[COMMITTEE PRINT]

A PRIMER ON CLIMATIC VARIATION AND CHANGE

PREPARED FOR THE

SUBCOMMITTEE ON THE ENVIRONMENT AND THE ATMOSPHERE

OF THE

COMMITTEE ON SCIENCE AND TECHNOLOGY

U.S. HOUSE OF REPRESENTATIVES

NINETY-FOURTH CONGRESS

SECOND SESSION

BY THE

CONGRESSIONAL RESEARCH SERVICE

LIBRARY OF CONGRESS

Serial OO

SEPTEMBER 1976

Printed for the use of the Committee on Science and Technology

[COMMITTEE PRINT]

A PRIMER ON CLIMATIC VARIATION AND CHANGE

PREPARED FOR THE

SUBCOMMITTEE ON THE ENVIRONMENT AND THE ATMOSPHERE

OF THE

COMMITTEE ON SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES
NINETY-FOURTH CONGRESS
SECOND SESSION

BY THE

CONGRESSIONAL RESEARCH SERVICE
LIBRARY OF CONGRESS

Serial OO

SEPTEMBER 1976

Printed for the use of the Committee on Science and Technology

U.S. GOVERNMENT PRINTING OFFICE
76-572 O WASHINGTON : 1976

COMMITTEE ON SCIENCE AND TECHNOLOGY

OLIN E. TEAGUE, Texas, *Chairman*

KEN HECHLER, West Virginia
THOMAS N. DOWNING, Virginia
DON FUQUA, Florida
JAMES W. SYMINGTON, Missouri
WALTER FLOWERS, Alabama
ROBERT A. ROE, New Jersey
MIKE McCORMACK, Washington
GEORGE E. BROWN, Jr., California
DALE MILFORD, Texas
RAY THORNTON, Arkansas
JAMES H. SCHEUER, New York
RICHARD L. OTTINGER, New York
HENRY A. WAXMAN, California
PHILIP H. HAYES, Indiana
TOM HARKIN, Iowa
JIM LLOYD, California
JEROME A. AMBRO, New York
CHRISTOPHER J. DODD, Connecticut
MICHAEL T. BLOUIN, Iowa
TIM L. HALL, Illinois
ROBERT (BOB) KRUEGER, Texas
MARILYN LLOYD, Tennessee
JAMES J. BLANCHARD, Michigan
TIMOTHY E. WIRTH, Colorado

CHARLES A. MOSHER, Ohio
ALPHONZO BELL, California
JOHN JARMAN, Oklahoma
JOHN W. WYDLER, New York
LARRY WINN, Jr., Kansas
LOUIS FREY, Jr., Florida
BARRY M. GOLDWATER, Jr., California
MARVIN L. ESCH, Michigan
JOHN B. CONLAN, Arizona
GARY A. MYERS, Pennsylvania
DAVID F. EMERY, Maine
LARRY PRESSLER, South Dakota

JOHN L. SWIGERT, Jr., *Executive Director*
HAROLD A. GOULD, *Deputy Director*
PHILIP B. YEAGER, *Counsel*
FRANK R. HAMMILL, Jr., *Counsel*
JAMES E. WILSON, *Technical Consultant*
J. THOMAS RATCHFORD, *Science Consultant*
JOHN D. HOLMFELD, *Science Consultant*
RALPH N. READ, *Technical Consultant*
ROBERT C. KETCHAM, *Counsel*
REGINA A. DAVIS, *Chief Clerk*
MICHAEL A. SUPERATA, *Minority Counsel*

SUBCOMMITTEE ON THE ENVIRONMENT AND THE ATMOSPHERE

GEORGE E. BROWN, Jr., California, *Chairman*

KEN HECHLER, West Virginia
MIKE McCORMACK, Washington
DALE MILFORD, Texas
RICHARD L. OTTINGER, New York
PHILIP H. HAYES, Indiana
JEROME A. AMBRO, New York
JAMES J. BLANCHARD, Michigan
JAMES H. SCHEUER, New York

MARVIN L. ESCH, Michigan
LARRY WINN, Jr., Kansas
GARY A. MYERS, Pennsylvania
DAVID F. EMERY, Maine

COMMITTEE ON SCIENCE AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES
SUITE 2321 RAYBURN HOUSE OFFICE BUILDING
WASHINGTON, D.C. 20515

LETTER OF TRANSMITTAL

September 3, 1976

The Honorable Olin E. Teague
Committee on Science and Technology
U.S. House of Representatives
Washington, D.C. 20515

Dear Mr. Chairman:

The Subcommittee on the Environment and the Atmosphere completed six days of hearings on HR 10013, a bill to authorize and direct the establishment of a coordinated national program relating to climate, to require an annual report of the program to the Congress, and for other purposes.

In connection with these hearings, the Congressional Research Service of the Library of Congress was requested to undertake a comprehensive study of various aspects of climate and related research, predictions, and impact analysis.

This document will provide background information for our colleagues as the Congress continues the legislative process on this important subject, and I especially commend the enclosed report to you and the other members of our Committee.

Sincerely,

George E. Brown, Jr.

George E. Brown, Jr.
Chairman, Subcommittee on the
Environment and the Atmosphere

The Library of Congress

Congressional Research Service

Washington, D.C. 20540

LETTER OF SUBMITTAL

August 24, 1976

The Honorable George E. Brown, Jr., Chairman
Subcommittee on the Environment and the Atmosphere
Committee on Science and Technology
U.S. House of Representatives
Washington, D.C. 20515

Dear Mr. Chairman:

Enclosed is a report entitled "A Primer on Climatic Variation and Change," which was prepared by the Congressional Research Service pursuant to your request.

Covered in the report are such topics as the impact and effect of climatic variation on agriculture, energy consumption, health, and the availability of water; the use of simulation models to explore climate and its variability; mechanisms and factors governing climatic variation and change; current research pertaining to climatic variation and change; Federal programs; and mobilizing for a national climatic research program. A selection of current readings bearing on issues discussed in the report; a selected bibliography; a list of some of the more frequently used acronyms that have developed out of the planning and implementation of large field experiments and the participation of various civilian and Government organizations in the area of weather and climate; and an inventory of current research pertaining to climatic variation and change comprise a four part appendix.

The study was prepared by: George N. Chatham (Chapter 2), Christopher H. Dodge (Chapter 3), and John R. Justus (Chapters 6, 7, 8, 9) of the Science Policy Research Division; A. Barry Carr and Harvey R. Sherman (Chapter 1), and Christopher K. Caudill and Warren Viessman, Jr. (Chapter 4) of the Environment and Natural Resources Policy Division; and Marvin Kornbluh (Chapter 5) of the Futures Research Group. Mr. Justus served as coordinator for this interdisciplinary effort and was responsible for composition of the Perspective, assembly of the appendixes, and collocation of the final text.

I trust that this primer will serve your committee's needs as well as those of other committees and Members of Congress concerned with climatic variation and change. On behalf of the Congressional Research Service, may I express my appreciation for the opportunity to undertake this timely and worthwhile assignment.

Sincerely,

Norman Beckman
Acting Director

CONTENTS

APPENDIXES

LIST OF FIGURES

LIST OF TABLES

THE LIBRARY OF CONGRESS

Congressional Research Service

WASHINGTON, D.C. 20540

A PRIMER ON CLIMATIC VARIATION AND CHANGE

Prepared at the Request of the
Subcommittee on the Environment and the Atmosphere
of the
Committee on Science and Technology
U.S. House of Representatives

by

George N. Chatham
Christopher H. Dodge
John R. Justus
Science Policy Research Division

Marvin Kornbluh
Futures Research Group

A. Barry Carr
Christopher K. Caudill
Harvey R. Sherman
Warren Viessman, Jr.
Environment and Natural Resources Policy Division

Coordinated and Edited by

John R. Justus
Science Policy Research Division

August 24, 1976

PERSPECTIVE

A growing fraction of current evidence suggests that the world may be entering a new climate regime. Amid recent expressions of concern that the Earth may be on the verge of entering a new ice age, a potential serious problem for mankind is perceived. However, this concern has been voiced by many, both within scientific circles, and through the mass media without the qualifications appropriate to any such venture into the realm of the predictability of climate.

Advance knowledge of long-term future changes of climate is not yet available. A thorough understanding of the behavior and the many processes involved in the interaction of the air (atmosphere), sea (hydrosphere), ice (cryosphere), land (lithosphere), and biotic (biosphere) components of the climatic system is considered a necessary, but perhaps not a sufficient, prerequisite to a predictive capability. That understanding is not yet at hand. When it is reached, it may conceivably be discovered that the behavior of the system is not inherently predictable, either because some climate-governing external influences are themselves unpredictable or because the system itself evolves in a non-deterministic manner. At present, not even enough is known about the problem of the predictability of climactic change to know whether long-term predictions are a realistic possibility. One thing, however, is certain: climate is not a fixed element of the natural environment, and the Earth's climate has always been changeable.

Important advances in quantitative paleoclimatology have confirmed beyond any doubt the tendency for past climates of the Earth to have been extraordinarily changeable. This characteristic, which

is apparently shared by climate on virtually all resolvable time scales of variation, from that of aeons down to those of millenia and centuries, indicates that climatic variation and change must be recognized and dealt with as a fundamental property of climate.

In between the persistence dominated realm of very short period climatic fluctuation and the seemingly quasi-periodic realm of extremely long-period change lies interannual and interdecadal climatic variation that appears to be neither persistent nor demonstrably periodic. Yet this is the time scale of climatic change -- hopefully capable of being projected a few years or a few decades in advance -- that becomes critically important as a useful tool for planners and policy makers attempting to prepare intelligently for future needs.

Agriculture is undoubtedly that sector of society most sensitive to climate fluctuations. In North America, for example, climate usually permits productive cultivation of the majority of potentially arable land. However, yields depend markedly on the distribution of precipitation, and crops are sensitive to extremes of temperature. Overall crop yields have been greatly increased in recent years by the introduction of selected hybrid varieties of many basic crops suited to an expected climate. Although these new varieties offer better yields than traditional varieties over a wide range of conditions, greater variations in yield are often experienced as a result of greater sensitivity to weather conditions. A return to more variable conditions would undoubtedly produce far greater year-to-year fluctuations in agricultural outputs than those to which world markets have become accustomed and have taken for granted in national and international planning.

Society is becoming increasingly dependent on energy intensive services. For example, society demands not only well-heated buildings in winter but air-conditioned buildings in summer. As a result, the demand for energy has greatly increased. Over the past 50 years in the United States, as winter weather conditions have fluctuated, seasonal total heating requirements adjusted to the present-day population have varied by as much as 10% above or below their average. 1/

Winter transportation can be impeded and made relatively costly by cold and especially by abnormally high snowfalls. Snow and ice control on urban streets and on local and national highways is expensive. A particularly snowy winter can be responsible for costs that greatly exceed planned budgets. Similarly, severe winters would, for instance, shorten the navigation season on the St. Lawrence Seaway, in northern rivers and harbors, and in Arctic seaports. On the other hand, however, an instance of climatic change characterized by a warming trend could auger favorably for the use of northern sea routes.

Our society depends on a good fresh water supply, not only for human consumption and industry but also for agriculture. The size, and consequently the cost, of waterworks, hydroelectric power developments and flood control structures are dependent on estimates of expected precipitation. A shift to greater or lesser precipitation leads to failure of the system in one case and needless overbuilding in the other. Water levels in the Great Lakes, for example, are to a great part dependent on both precipitation and evaporation, which, in turn,

---

1/ Living With Climatic Change. Proceedings of a conference/workshop held in Toronto, November 17-22, 1975. Ottawa, Science Council of Canada, 1976. p. 10.

are controlled by temperature. As water consumption increases there may be increasing demands for water diversion, demands that could be either negated or amplified by climatic change.

There are many other, perhaps less obvious, facets of society which could be affected to a greater or lesser degree by climatic variability. The tourism and recreation industry; petroleum refining and the production mix of fuel oil and gasoline; planning for the manufacture of snow tires, air conditioners, rain wear and other climate dependent products are but a few of the areas where climatic change makes a difference. The construction, performance and maintenance of pipelines is affected by climatic conditions. The architectural design of buildings should take into account climatic parameters. The performance of houses and many other types of structures are clearly affected by climate and climatic change.

In addition to natural climatic variations, the possibility also exists that man may be changing the climate by his own actions. Man's presence on the Earth cannot be assumed to go unnoticed by the atmosphere. As a result of human activities enormous amounts of gaseous and particulate materials have been emitted into the atmosphere through the combustion of fossil fuels (primarily carbon dioxide, sulfur dioxide, and fly ash) and through the manipulation of land for agriculture and commerce (primarily wind-blown dust, and forest and grass fire smoke). To an increasing extent, waste heat is also entering the atmosphere, both directly and indirectly (via rivers and estuaries), and in both sensible and latent form (as, for example, through evaporation in wet cooling towers). Moreover, large-scale land management programs

have been responsible for significant changes of surface albedo, moisture holding capacity, and aerodynamic roughness of the surface (primarily through deforestation, water impoundment by man-made lakes, slash-burn agricultural practices, urbanization, etc.). It is doubtful that these effects of man, and possibly others as well, are yet capable of impacting climate on a global scale to an important extent. But because of the growth of population, industry, energy generation, food production, and commerce in the years and decades ahead, the time is almost certainly not far off that human effects on large-scale climate will become appreciable in relation to natural climate-regulating phenomena.

Strides have been made in understanding the nature and the physical processes involved in globally coherent climatic change by means of advanced general circulation modeling experiments. Although these experiments have not yet clearly elucidated the mechanisms involved in climatic change, they have helped in an important way to describe the problem of how to go about identifying those mechanisms. The far-reaching consequences of a major, unanticipated change of climate in the modern world indicate the need not only for making climate research efforts more structured and focused but also for establishing an adequate, ongoing climate monitoring program to gain the information needed to clarify the mechanisms, causes, socio-economic and international implications of climatic change.

The following sections comprising this study are designed to shed light on some of the above mentioned topics. Chapters 1 through 4 examine the impact and effects of climatic variation on agriculture,

energy consumption, health, and the availability of water, respectively. The use of simulation models to explore climate and its variability is discussed in Chapter 5. Mechanisms and factors governing climatic variation and change are examined in Chapter 6. Chapters 7 and 8 discuss current research pertaining to climatic variation and change, and Federal programs, respectively. Finally, Chapter 9 presents some thoughts and recommendations on mobilizing for a national climate research program. Appended are a selection of current readings bearing on some of the issues discussed in the body of the report; a selected bibliography; a list of some of the more frequently used acronyms that have developed out of the planning and implementation of large field experiments and the participation of various civilian and Government organizations in the area of weather and climate; and an inventory of current research pertaining to climatic variation and change.

Society's growing sensitivity to climatic change, the anomalously favorable character of the climate to which the world has adapted, and the evidence that generally unfavorable fluctuations are in progress combine to portend distrubing consequences for the future. However, through a resulting loss of perspective on the matter of the impact, nature, and predictability of climatic change, a scientifically valid caution regarding a possible instability of present-day climate conditions has been allowed to degenerate in the eyes of many laymen into a prophesy of imminent climatic doom. It is hoped that this report will in some small way restore some of the lost perspective that has fostered the emergence of the "ice-age-is-coming" syndrome.

76-572 O - 76 - 2

****

CHAPTER I

IMPACT AND EFFECTS OF CLIMATIC VARIATION ON AGRICULTURE

by

A. Barry Carr
Specialist in Agricultural Policy

and

Harvey R. Sherman
Specialist in Environmental Policy
Environment and Natural Resources Policy Division

****

IMPACT AND EFFECTS OF CLIMATIC VARIATION ON AGRICULTURE

Land, technology and climate are the critical factors in the world's food production equation. The area of land suitable for cultivation is determined not only by soil type and topography, but also by the temperature and moisture conditions which prevail. The climate requirements of stable crop production include a good combination of light energy, heat and moisture. Yields are determined not only by the total amount of rainfall over a growing season, but also the timing of these rains over the season.

Climate has been defined as the average expression of all weather events over many years. Climatologists define normal weather as that which has been experienced over the 3 previous decades. Comprehensive records based on accurate instrumental observations of atmospheric variables extend back less than 300 years for most areas of the world. Yet from a historical perspective, 10,000 years is but a brief moment in the earth's climate age.

From an agricultural viewpoint climate can be defined as some combination of annual temperature, moisture and wind patterns that determines a region's ability to sustain the production of desirable agricultural commodities in economic quantities.

Modern agricultural technology, as exemplified by the "Green Revolution", has resulted in new crop varieties which are matched to the narrow spectrum of temperature and precipation conditions that have prevailed in the last few decades. Scientists are concerned about the impact of climatic change on these highly specialized crop strains; which are less tolerant than the older indigenous varieties.

New agricultural technology has increased crop yields over the past several decades, but it has been favorable weather that reduced the year to year variability in yields. Weather is capable of offsetting any increase in yields brought about by technological advances.

Increased variability in weather is a typical phenomena when long-term climatic changes are underway. Sudden and unusual events, such as drought, flood, unseasonable frost, or hot spells, may have a more disruptive effect on crops than the longer term trends. It has been these kinds of crop failures during the past few years which have stalled the advances of the green revolution and caused concern in many quarters about the ability of the world's peoples to feed themselves and survive in the decades ahead.

Alternative Climatic Scenarios

A significant body of agricultural scientists continue to predict steady improvements in crop yields and in world food production. This school of thought would dismiss recent weather-induced crop failures as short term anomolies which will correct themselves without man's intervention.

However a second group of scientists have expressed concern about the declining mean global temperature. Temperatures in the Northern Hemisphere have been dropping since the 1940's, and temperature regimes are now at about the level of 1900. This trend is seen as a return to the conditions of the 16th and 17th Centuries, a time known as the little ice age, and as the beginning of a declining weather cycle that will affect the yields of certain agriculturally productive regions.

The confusion over our future climate seems rooted in the statistical bases used by climatologists. Is the 1931-1960 period, one of recorded history's most favorable climatic phases for crop production, normal, or does it represent a temporary phenomenon not soom to be repeated?

There is general agreement on several points at least. In the past, significant climatic changes have occurred rapidly (within several decades) while the changed climate can last for centuries. If the present climatic trend continues for the rest of the century, our climate will become more unstable and climatically related disasters are more likely.

Location of Agricultural Production

The world's land area totals about 33 billion acres. Of this, 7.8 billion acres (24 percent) are theoretically arable--capable of producing crops. However less than half of this land, 3.4 billion acres, has soil and climate suitable for the production of crops or livestock with today's technology and price relationships. The western world has 45 percent of the potentially arable land and less than 20 percent of the world's population. Current trends in population growth will only increase this disparity.

Thermal and moisture conditions are the principal factors in determing the location of crop production. Most of the world's grain production is situated between the 30th and 55th parallels of the northern and southern hemispheres (see Figure 1), where the summer temperatures average 70 degrees to 75 degrees. These belts are limited in the lower latitudes by high summer temperatures and in higher latitudes by the length of the

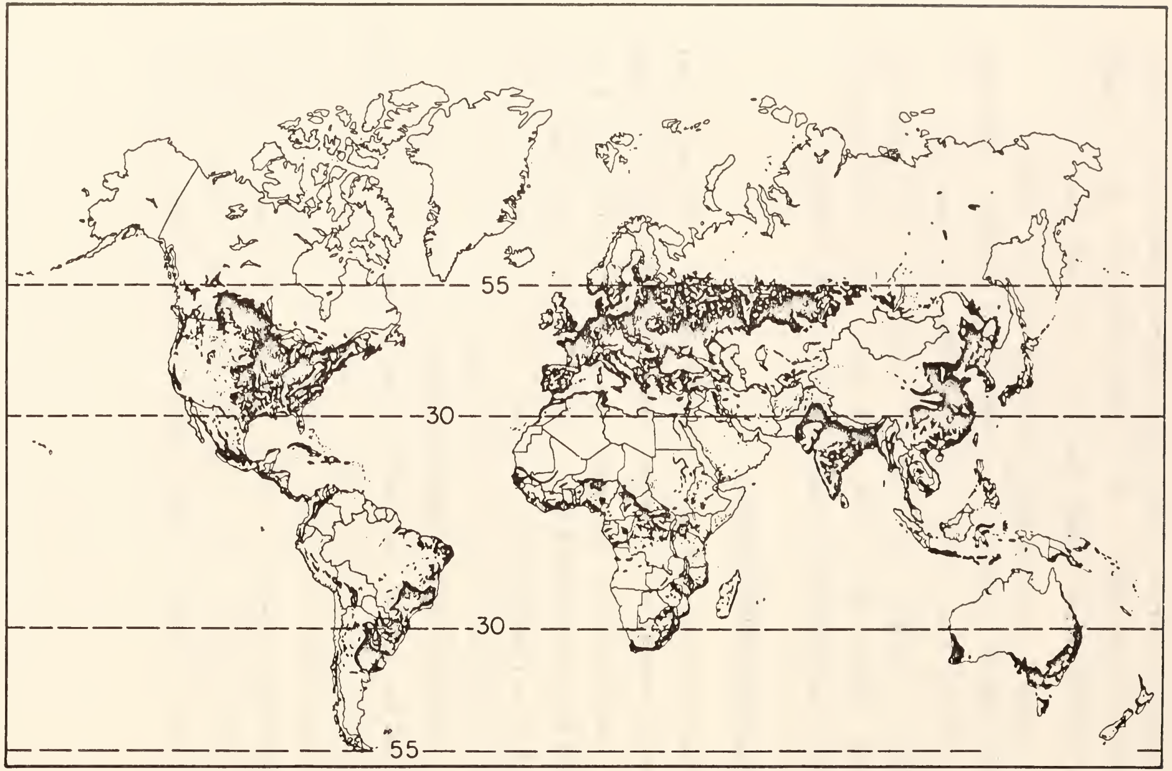


Fig. 1 Grain belts of the northern and southern hemispheres situated between the thirtieth and fifty-fifth parallels and characterized by similar soils, vegetation, and climate [*Thompson*, 1966]. The shaded portions represent the approximate arable cropland, including tree and bush crops as well as fallow. (Partly because sufficiently detailed data on land use are not available for some countries and partly because the map is small, the shaded portions include scattered areas of land not used for crops, and the unshaded portions, scattered cropland areas.)

growing season. In Canada and the U.S.S.R. the northern margin of significant agricultural settlement corresponds to the 120-130 degree month line, and the northern limit of corn for grain is the 200 degree month line. 2/ The lower limit of precipitation for non-irrigated agriculture is around 10"-11" per year, and the distribution of moisture over the growing season has a major influence on yields.

The major wheat producing areas are the grasslands of North America, South America, eastern Europe, Asia and Australia. Corn is grown in the wetter and warmer portions of these same regions. The important rice areas of India, southeast China and other countries of southeast Asia are largely confined to tropical (free from freezing temperatures) and subtropical monsoon climates. All of these climates have transitional zones or tension zones around them. Climatic fluctuations can strongly affect agricultural productivity in these marginal areas. As more and more marginal land is brought into production, in an effort to feed ever larger populations, the effect of climatic variation on food production is multiplied.

Impact of Climatic Change

If present global cooling trends continue for several more decades, high latitude areas such as Canada, the U.S.S.R. and northern China would experience shorter growing seasons and a drop in output. Helmut Landsberg, a climatologist at the University of Maryland, estimates that a drop in average temperature of 2 degrees centigrade in the region above

---

2/ The degree month value is the sum of the mean monthly temperatures in excess of 32 degrees Fahrenheit.

the 40 degree parallel would completely eliminate wheat and corn production in major regions of Canada. A decrease of 1 degree Centigrade in the mean annual temperature in Iceland has already reduced the number of degree days by 27 percent--a reduction in the growing season of 2 weeks.

In addition to shorter growing seasons from a cooling trend, there would be broad bands of excess and deficit rainfall in the middle latitudes. Europe can expect to be cooler and wetter. The western regions of the U.S. wheat belt--from Montana to Colorado--would experience increased wheat crop failures. The northern Great Plains would experience a 14-18 day reduction in growing season, but the southern plains would gain in crop yields due to increased rainfall. In general the existing crop belts of the U.S. would shift southward. Overall U.S. agricultural production would be unaffected or perhaps slightly increased.

The monsoon rain belt would also shift southward causing these rains to fall into the oceans rather than the traditionally fertile areas of sub-saharan Africa, India, Japan and south China. Production of rice would be seriously affected in the warm lands below 30 degree latitude.

Impacts on Agricultural Trade

Climatic changes of the order just described would drastically affect the capability of nations to feed their people and the availability of food from traditional exporting nations. In Europe the number of persons supported per hectare of land would fall from 3 to 2; in China from 7 to 4 according

to Reid Bryson, Director of the Institute for Environmental Studies, University of Wisconsin. Northern Europe would lose 25 to 30 percent of its productive capacity and the European Economic Community (EEC) would cease to export food. China, hurt by shorter growing seasons in the north and monsoon failures in the south, would require an external grain supply of about 50 million metric tons yearly. The Soviet Union would require a similar amount. India could expect a major drought every 4 years and could support only three-fourths of its present population. Canada, one of the world's traditional wheat exporters, would lose 50 percent of its productive capacity and 75 percent of its surplus for export. The importance of the U.S. in world food markets would be even greater than the present dominance of world petroleum supplies by mideast nations.

Measures to Alleviate Climate-Induced Food Shortages

Mankind can be expected to resist the adverse effects of climate change on the food supply. The alternative strategies available are many but can be categorized under 5 headings: production technology, availability of land, climate modification, food storage and distribution, population size and distribution.

A complex set of food production technology has come into use over the past 100 years. Regions have developed technology which includes genetic selection, methods of pest and disease control, tillage practices and machinery, synthetic fertilizers and irrigation, that responds well to their

particular climatic conditions. Although scientists can modify technology in response to changing climatic conditions, several decades are usually required for the research, development and adoption process.

Yield reductions can be offset by the use of additional land area or the improvement of land area already under cultivation. Irrigation of arid lands, protection of land from flooding, clearing and leveling of new land and even the preservation of existing agricultural lands are long-term measures to increase food production.

Direct manipulaion of climatic variables has long been a dream of man. On a local scale some success has apparently been achieved with rainfall or snowfall augmentation. More ambitious schemes on a global scale have been proposed, but have been stymied to date by insufficient knowledge and by the complexity of international agreements they would involve.

Regional fluctuations in agricultural production are often unavoidable, but can be offset by the availability of adequate food reserves. A world food reserve system, to be truely effective, must be coupled with a distribution system more effiicient than presently exists in many areas of the world.

The global production of food must increase by 2 percent yearly just to maintain parity with population increases. In many poor areas of the world the population growth rate is even higher than 2 percent. The impact of reduced food production will fall heaviest on poor nations with rapidly growing populations. In the past, large population migrations resulted from famine. This option is no longer available. If these people fail to voltarily control their populations, widespread starvation is likely.

All of the measures discussed above require time to develop and implement. To those who are starving, time is of the essence. The global institutional framework is presently unable to respond quickly to climatic change and to bring about the needed adjustments in the world food economy. Mankind can continue to ignore the issues or respond with short-term solutions only at considerable peril to its future.

Impact on National and International Food Policies

The world would become a smaller place for men and nations as a result of the possible future events described in this chapter. Nations will have increasing difficulty in pursuing their separate destinies. With respect to almost any policy decision, at both the national and international level, there will be winners and losers. The losers will be numerous and the losses final in the case of food policy decisions.

By the year 2000 the western world will still have more than one food producing acre for each person. Eastern countries will need to feed 4 to 5 persons per acre (more than double the 1960 level). The continent of North America will not be able to feed the world with its surplus. Will the world be willing to tolerate such vast discrepencies among regions in the adequacy of diets? Can the western reliance on animal agriculture continue in a world where people starve for lack of grain?

The United States now provides nearly 75 percent of the world's net grain exports. Should climatic changes impact on Canadian production, the U. S. role could grow to 90 percent. Massive U. S. exports in recent years

have had serious impacts on the domestic economy, caused violent price fluctuations and led to pressure for food export control policies. The domestic issues involve questions of how much to consume at home, how much to sell for export, and who to assist with food aid.

The food reserve question carries these same questions to the international level. The desirable level of food reserves must be balanced off with the carrying costs. A satisfactory way of sharing the costs and administration of resources among nations has yet to be found.

Many nations have not succeeded in achieving levels of food production sufficient to provide adequate nutritional levels for their ever-growing populations. Much of the present disparity in agricultural productivity is the result of policies which subordinate domestic agricultural production to other economic or political interests. Even food aid, supplied with the most humane objectives to food deficit regions, must be carefully handled to avoid adverse impacts on increased food production in recipient countries. Present trends in climate, food production and population growth clearly indicate the need for ambitious new programs to expand global food production, particularly in underdeveloped countries.

Proposals for global weather modification present mankind with uncertainties as awesome as those presented by the onset of the nuclear age. Modification activities could set into motion changes that would affect the welfare of all the world's people. Improvements in the condition of one region might be offset by adverse effects in other regions. Even if the outcome could be predicted with accuracy, the institutional framework does not exist to control the process and to distribute the gains and losses equitably.

Information Needs

Various elements of society view their climatic future from different perspectives and with different degrees of alarm. Most concerns about the future can be summarized by 3 questions:

-- What is happening to the climate?

-- What impact will these changes have on human existence?

-- What can be done to improve the outlook?

Governments need as much advanced warning as possible to prepare adequately for the welfare of their people. The public needs to be better informed, if it is to be wise enough to deal with issues and make appropriate decisions. Farmers and other agricultural scientists need time and information to operate and improve the food production system. Since small climatic changes can have catastrophic effects on the world's food supply, acceleration of climatological study would seem a matter of utmost urgency.

****

CHAPTER II

CLIMATIC VARIATION AND ENERGY CONSUMPTION

by

George N. Chatham
Specialist in Aeronautics and Space
Science Policy Research Division

****

CLIMATIC VARIATION AND ENERGY CONSUMPTION

Climate varies as a function of specific locations on earth and it varies at each location as a function the time of year as well as a function of specific weather conditions at a given time at that location. There are also long-term local weather cycles which cause seasonal, even yearly variations from a long-term norm in a given area, as well as other cyles which are worldwide.

It would be simple enough to assume that energy demand, worldwide, would increase as the ambient temperature moved higher or lower than some established comfort point. The energy would be used to preserve some sort of acceptable level of temperature within occupied dwellings or buildings. Of course this is nonense. Most people of the world do nothing about cooling themselves through energy using machines. As to heating, a tropical islander might build a small fire from which to enjoy some radiative effects but not to alter the ambient temperature. A Polar Eskimo might also take some measures to warm the inside of his igloo -- but with the caution that the inside air stay safely below freezing because he would otherwise cause his ice block igloo to suffer melting.

Climatic variation as an energy problem, however, involves only a specific portion of the Earth's population. This portion consists of those who heat, and in some cases heat and cool themselves with energy from fossil or nuclear fuels. These populations exist within a social and economic structure within which they interact in a reciprocal fashion to obtain goods and services e. g. energy, in exchange for other goods and services they provide. In other words,

these populations are totally dependent upon others for a supply of energy, and similarly the suppliers of this energy are obligated to assure that the energy supply, which is their responsibility, is adequate and dependable.

Since inventories of energy are not infinite, sources of energy can be depleted -- all variables effecting supply and consumption become vitally important matters to the society as a whole. In this section, only the relevance of climatic variation will be treated, however.

Once again, the simpliest assumption is that energy demand will rise as a function of the ambient temperature deviating away from some comfort point. At this comfort point, no energy would be needed to alter the indoor climate. Above or below this point, energy would be used to keep the indoor temperature at the comfort setting. Calculations of energy used based on a whole nation turns out have little meaning in terms of anticipating in specific regional or local energy demands. However, when a significant portion of nation's fuel must be imported, planning at the national level is essential.

Local variations average out and overall national requirements can be anticipated. Such an analysis can answer a vitally important question: "Disregarding all variables except climate, what is the maximum variation in energy demand we may reasonably anticipate in terms of national energy consumption as a function of climatic variability?"

This question was answered for the United States (coterminous) in 1974 by the National Oceanic and Atmospheric Adminstration. 3/

Using all available historical data in a complex statistical analyses NOAA defined an "average" year and determined that heating energy demands fluctuating between the coldest year in 100 years and the warmest year in 100 years would cause a plus or minus 10% variation in energy requirements from the "average" year. The coldest and warmest year using a ten year span showed an expected variation of plus or minus 5%.

It would therefore seem that the effect of climate variability on energy demand in the United States is not a severe problem. A 5% reserve supply of fuel over the average needed by a given region would seem to be a safe margin in all but the most unusual circumstances. In addition, there is a high degree of flexibility between regions. For example, should a supplier find his fuel reserves dangerously low due to a rare climatic event, he knows the chances are good that the supplies of adjacent regions were hit less severely and he can borrow energy or fuel from them until his emergency subsides.

However, at the regional and local level, a reserve of 5% isn't regarded as trivial. Such a reserve represents as very large volume of fuel. An exceptionally mild year for example, resulting in a year 5% below the average could mean a dead inventory of 10% of yearly

---

3/ National Oceanic and Atmospheric Administration, Special Task Group. Variability of Seasonal Total Heating Fuel Demand in the United States. Environmental Data Service, January, 1974, p. 5-9.

76-572 O - 76 - 3

consumption. Inventory of any kind is costly, not only in terms of tying up the capital costs of the fuel but also in storing it. Land, facilities, rental and interest expenses could exceed the cost of the stored fuel. Local regions have therefore found ways of greatly enhancing the accuracy of their expected fuel needs. They consider only the particular locality they serve and construct highly elaborate historical and statistical analyses of consumption patterns. The "degree day"--the number of days multiplied by degrees away from the "average" as used in the NOAA study is only a crude start in these analyses. They know that relative humidity, precipitation, snow cover, cloud cover during the day and cloud cover during the night are all significant variables, and these do not exhaust the list. Considering everything available, most regional firms conclude that an anticipation with an accuracy of plus or minus 1% is acceptable but a miss as high as 3% is cause for concern. 4/

Can the anticipated consumption of energy be refined still further? Apparently it can. Accuracy rises as the area studied becomes smaller and the advent of computerized consumption records and billings makes feasible the study of ever smaller increments of the consuming population. Energy firms are now introducing "flat rate" billings. This is a system in which each individual consumer is the subject of individualized statistical analysis. Working at this "atomistic" level,

---

4/ Leffler, L.G. Electric Load Estimating Experience at Public Service Electric and Gas Company. Paper presented at the Short-Range Load Forecasting in Electric Power Systems Conference, Saxtons River, Vermont, August 1, 1972.

consumption anticipations can be tailored so close that an averaged cost or "flat rate" can be billed to the user each month with a year-end adjustment for accumulated error. The error is, on the average a small fraction of 1%.

Reducing the anticipatory mathematics to individual, tailor-made, analyses enables the energy supplier to simplify his statistics to some degree. Since he is now dealing with actual consumption, he no longer needs a number of assumptions such as the effect of average insulation value, wind velocity, etc. on the average dwelling. Trends in climate, such as a generally cooler or warmer season are not eliminated. These conditions must be considered a weighting value to be added into the assumed consumption figures.

The actual analytical procedures and how they have evolved from region to region may be of interest to the reader. The following studies should provide an adequate sampling to provide the next level-in-depth for the study of the climate variable on energy consumption.

Barnett, C. V. Weather and the short-term forecasting of electricity demand. In Taylor, James A. (ed.) Weather forecasting for agriculture and industry, a symposium. Cranbury, N. J.: Associated University Presses, 1973. pp. 209-223.

Barr, Matthew D., and Gunderson, Walter J. Load forecasting and dispatching for distribution companies. American Gas Association, Operating Section, Production Conference, 1962.

Berrisford, H. G. The relation between gas demand and temperature: A study in statistical demand forecasting. Operational research quarterly, Vol. 16, no. 2 (June 1965) pp. 229 -246. CEP-62-16.

McQuigg, James D. Increasing sensitivity of energy demand to weather. Paper presented to American Association for the Advancement of Science 140th meeting, San Francisco, February 27, 1974.

****

CHAPTER III

IMPACT OF CLIMATIC VARIATION ON MAN

by

Christopher H. Dodge
Analyst in Life Science
Science Policy Research Division

****

IMPACT OF CLIMATIC VARIATION ON MAN

> "There is very important climatic change going on right now. And it's not merely something of academic interest. It is something that, if continues, will affect the whole human occupation of the earth-like a billion people starving. The effects are already showing up in rather drastic ways."
>
> Dr. Reid Bryson
> Institute for Environmental Studies
> University of Wisconsin

> "Most people, relying on their memories alone, insist that our climates are very different from what they used to be. Their fathers made similar statements about the climates of still earlier times, as did also their fathers' fathers...and the bulk of this testimony is to the effect that our climates are getting worse--evidence, perhaps that flesh has always been heir to ills."
>
> W.J. Humphreys
> U.S. Weather Service

Introduction

Man is the highest heir in the trophic chain of life to any change in global climate and the impacts thereof on his material existence. By virtue of his unique demands on the environment and his life style, man is among the most vulnerable of life forms to such change.

Current theory almost unanimously holds that the Earth's climate is, in fact, changing. Just exactly how it is changing is the domain of the other sections of this report. The purpose of this section is to assemble varying opinions as to what possible impacts of climatic varia-

tions on man wil occur. Of particular concern are impacts on health and nutrition.

Although it is almost unanimously held that the Earth is presently in a phase of climatic change, theories as to the future course and rate of the change vary considerably. Today, most experts agree that the Earth is in a cooling phase. Proceeding from that observation, the following scenarios for the future are commonly predicted:

1) that Earth is slowly (ever thousands of years) entering into a new ice age;

2) that Earth will rapidly (within 100 years or slighly more) enter into a new ice age wherein much the planet will be locked in glaciers;

3) that the present cooling trend is only a minor aberration due to cyclic sunspot activity and is not necessarily a harbinger of a new ice age;

4) that man's activities (release of CO_2, heat, and other substances into the world's weather machinery) will forestall the onset of a scheduled ice age; and

5) that man's activities will accelerate the ice age process

However, there are also some experts who hold that, contrary to the above, the earth is in a long-term warming phase. Proceeding from that theory, the following scenarios for the future are commonly predicted:

1) that the Earth is slowly (over thousands of years) emerging from the last ice age;

2) that presently, more areas of the world are warming than are cooling;

3) that cooling over the past three decades is but a minor regression in a longer-term warming phase;

4) that man's activities will precipitate either a slow or fast warming process; and

5) that so significant is man's impact on the weather, that a major warming trend will soon melt the ice caps triggering a global increase in sea level.

Finally, there are experts who attach little or no significance to the cooling and/or warming trends of the past century. These experts believe that the Earth's climate will change little over the next few thousand years.

Although the most popular theory appears to support a global cooling trend, it is almost unanimously agreed by most experts that any climatic change, even one resulting in a change of as little as $\pm 1^{\circ}C$ will have a profound effect on global human health and welfare. For that reason, in 1973, a special project was initiated under the International Federation of Institutes for Advanced Study (IFIAS) entitled, "The Impact on Man of Climate Changes". 5/ The purpose of this special project is to study the impact of climate changes and climate fluctuations on the quality and character of human life. Particular emphasis is being given to the effects of climate changes on world food supplies. The project joins specialists of diverse nations and disciplines in endeavors that explore the full social, ethical and humanistic dimensions of new advances that bear on problems surrounding the ways in which climate changes affect the lives of human beings.

The IFIAS Climate Project is a cooperative endeavor among IFIAS, the Aspen Institute for Humanistic Studies, and other participating organizations. The project is funded through grants from private foundations and organizations. Additional support for the project comes from IFIAS Member Institutes and other organizations electing to participate.

5/ IFIAS. Status Report of the IFIAS Special Project: The Impact on Man of Climate Changes. 10 Oct. 1975, 16 p.

Dr. Walter Orr Roberts, Director of the Aspen Institute Program in Science, Technology and Humanism is the Climate Project Leader. Several workshops and conferences are to be held under the project. In May, 1974, the first IFIAS Climate Project Workshop was convented in Bonn, Germany.

Past Effects of Climate Change on Man

There is strong historical evidence that past climatic changes have had profound effects on large populations. Before the advent of agriculture, man as a hunter is thought to have contributed to a reduction in the number of species of large mammals inhabiting the earth. With the advent of agriculture, abuse of soils and habitat began to occur. One of the best known examples was the conversion of the once fertile Tigris and Euphrates Valleys to desert through erosion and salt accumulation resulting from faulty irrigation practices. In essence, the downfall of the Mesopotamian civilization appears to have been the ultimate result of an environmental and subsequent climatic catastrophe caused by human activities.

Overgrazing of pasture lands and poor farming practices are believed to have contributed over the millenia to the expansion of the Sahara Desert, a process which continues today with disastrous consequences for some 24 million people. The people and livestock of the Rajasthan Desert in India are also the victims of chronic human carelessness with the environment and population pressure. 6/ Much of Europe and Asia were deforested

6/ Holdren, J.P. and P.R. Ehrlich. Human Population and the Global Environment. American Scientist, Vol. 62, 1974, 282-292.

by pre-industrial man, beginning in the Stone Age. Overgrazing by sheep of Navajo herdsmen destroyed large tracts of prime pasture land in the American southwest, which remains arid today. 7/

The common denominator in all historical climate changes described thus far has been human influence on the environment. It is compellingly argued that population size and the rate of population growth both in rich and poor countries have been and will continue to be important contributing factors in the degeneration of the human environment and subsequent climatic changes.

Little is understood about the dynamics of cycles of cold weather or ice ages. Before the little ice age, which held the world in its grip from the sixteenth century to about 1890, grapes were widely cultivated in England. Today this is no longer so and the growing season for crops is now decreasing once again during the present cooling phase. As early as the tenth century, the Vikings had established prosperous colonies in Greenland, having named the island for its verdant pastures. By the early fifteenth century, however, these colonies were wiped out by cold and hunger. Now, four-fifths of Greenland lies buried under hundreds of feet of ice cap. 8/

Recent Climate Changes and Man

Aberrant weather patterns over the past decade have had profound effects on man, particularly in poor countries in the southern hemisphere.

7/ Wade, N. Sahelian Drought: No Victory for Western Aid. Science, Vol. 185, 234-237.

8/ The Great Global Struggle of the Winds. Fortune, Feb. 1974, 91-95; 142-152.

The African drought, caused by an as yet unexplained southward shift of the monsoon rain belt lasted for six years and has not completely abated. The drought has brought on a devastating famine affecting some 24 million people while threatening to render permanently uninhabitable a large belt of sub-Saharan land. Similar dry weather conditions prevail in parts of India, China, Kenya, Bolivia, and scores of other countries on both sides of the Equator, raising the specter of even more serious drought and famine throughout Asia, Africa, and Latin America. Drought, which has affected the central United States regularly every 20 years, has already started a new cycle in the South-central part of the country as predicted. 9/

Meanwhile, wet weather has predominated in much of the United States in recent years bringing heavy flooding interspersed with drought to the upper Midwest, high water in the great lakes, rare snow and ice storms throughout the south, and winters that were unusually severe in the West while unseasonably mild in the East. The most severe series of tornadoes in some two decades hit the United States in the spring of 1974. 10/

Elsewhere in the world, unprecedented rains and flooding were experienced in Mexico, Korea, and Tunisia. An unseasonably cold spell damaged crops in Japan. The worst heat wave in a century hit Russia, devastating the 1972 wheat crop. Weather in Great Britain was unseasonably warm and dry. 11/

9/ Hamer, J. World Weather Trends. Editorial Research Reports, No. 2, 1974, 517-538.

10/ Is the Earth's Climate Changing? The Ecologist, Jan., 1974, p. 11.

11/ Ibid.

By far the most popular theory today is that the Earth is undergoing a cooling trend. Just how rapid this trend will be, and therefore, what its impact will be on man is the subject of much speculation. In any event it is widely held that the world climate was unusually stable between 1890 and 1945, but that since 1950, began taking a turn for the worse. According to Professor Hubert H. Lamb of the Climatic Research Unit in Great Britain, "The decline of prevailing temperatures since about 1945 appears to be the longest continued downward trend since temperature records began." 12/

Dr. Reid Bryson, director of the Institute for Environmental Studies at the University of Wisconsin, believes that the weather since 1950 has been the most abnormal period in at least a thousand years. He points, for example, to the fact that from 1918 to 1960 India experienced far fewer droughts that would have been expected from previous records. The comparative absences of famine during this period played a large role, in his view, along with improved medical care, in causing the population of such regions as India to more than double in this century. 13/

From the above, two facts are clear: 1) that from 1890 to 1945, global weather was generally favorable enough to support a spectacular increase in the world's population; 2) that from 1950 to present, weather patterns have been capricious and unpredictable with the result that huge populations now present and still increasing are threatened with famine and disease should present climatic trends continue.

12/ Is the Earth's Climate Changing? Op. Cit.

13/ The Great Global Struggle of the Winds. Op. Cit.

Effects of Man on Ecology and Climate

A controversial theory which has gained considerable attention in recent years is that human activity has caused climatic change--specifically, that man-made atmospheric pollutants have inadvertently changed the global climate. The primary mechanism responsible according to some experts is the increased amount of dust, or particulate matter in the atmosphere brought about by the burning of fossil fuels, mechanized agricultural operations, man-made forest fires, and the primitive slash-and-burn method of clearing land for crops in the tropics. It is held that particulate matter in the atmosphere reduces the amount of solar energy which reaches the Earth's surface and thus lowers the temperature.

Quite to the contrary, however, in the first half century, fossil fuel burning may have accelerated the global warming trend by a mechanism popularly known as the "greenhouse effect". Carbon dioxide yielded by the burning process is transparent to sunlight which has a short wave length. But when sunlight hits the Earth, much of it is converted to heat which has a longer wavelength and cannot easily escape the carbon dioxide layer. Thus, it is held in this school of thought that a large share of solar energy was trapped, rather than being reradiated back into space, increasing the sun's warming effect.

Most recently, it has been speculated in some circles that man's release of fluorocarbons and exhaust emissions from high-flying supersonic aircraft may be reducing the thickness of the stratospheric ozone layer. The ozone layer acts as a shield against the damaging biological effects of excessive ultraviolet radiation. There is some inconclusive evidence that the ozone layer has already been decreased by 0.5-2 percent. It is

believed by some experts that if no more fluorocarbons were released into the stratosphere, there might be a 1.3-3 percent further decrease in the layer. Other calculations predict an eventual reduction of about 7 percent in the equilibrium ozone concentration, presuming a continuation of fluorocarbon release at the 1972 rate. A 5-10 percent decrease persisting and measured for several years would be required before a change could be attributed to human activity with any reasonable statistical reliability. 14/

Some scientists postulate that changes in stratospheric ozone levels would cause changes in temperature, wind patterns, precipitation, and other weather elements. The nature and extent of these changes and their effects on Earth's climate cannot be predicted on the basis of present knowledge. 15/

Speculation about the impact of ozone reduction on man, animals, and agriculture is as inconclusive as speculation about the phenomenon itself. The direct hazard to humans would be caused by an increase in the cumulative amount of damaging ultraviolet radiation received. Although it is believed that effects would be delayed for decades, for each one percent decrease in ozone, the expected increase in skin cancer incidence would be on the order of 2 percent. Other major effects would be increased incidence of sunburn, premature aging and other structural changes in the skin, and varying degrees of eye damage. 16/

14/ Federal Task Force on Inadvertent Modification of the Stratosphere (IMOS). Fluorocarbons and the Environment. June, 1975, 109 p.

15/ Ibid.

16/ Ibid.

Possible biological and agricultural effects might include changes in physiological, biochemical, anatomical, and growth characteristics of certain plant and animal species; health effects on livestock; disturbances in the balance of aquatic and terrestrial ecosystems; and changes in the stability and effectiveness of agricultural chemicals. Any significant changes resulting from reduction in stratospheric ozone levels might be expected to have some agricultural effects, such as reduction of the yield of some crops, particularly in areas where production is marginal. 17/

While the influence of man's activities on climate has not been conclusively demonstrated, circumstantial evidence continues to support theories that man is at least exerting subtle influences on climatic patterns. Certain experts favoring the theory that man ultimately affects climate through ecological disruption contend that world policy makers make three false assumptions related to population growth, environmental deterioration, and resource depletion. The first is that the absolute size and rate of growth of a population has little or no relationship to ecological problems. The second is that environmental deterioration consists primarily of pollution which is regarded as a local and reversible phenomenon of concern mainly for its effects on human health. The third false assumption is that science and technology can make possible the long continuation of rapid growth both in rich and poor countries have and will continue to be important contributing factors in the de-

---

17/ Ibid.

generation of the human environment, including climate. It is further argued that the most serious human threat to environment and climate may be of subtle, indirect nature. 18/

It has been suggested that as a global, geological, and biological force, man is becoming comparable to and even exceeding many natural environmental processes. For example, oil added to the oceans, assuming all forseeable precautions, is estimated to reach 30 times the level of natural seepage by 1980. Civilization is now contributing half as much as nature to the global atmospheric sulfur burden and will be contributing an equal amount by the year 2000. Combustion of fossil fuel has already increased the global atmospheric burden of carbon dioxide by 10 percent since the turn of the century and will further increase the burden by as much as 5 percent by the end of the century. Civilizations contribution to the global atmospheric burden of particulate matter is estimated to range from 5 to 45 percent of the total annual input from natural processes. Roughly 5 percent of all energy captured by photosynthesis on Earth flows through agricultural ecosystems supporting the metabolic demands of human beings and their domestic animals. Most of the waste heat from Civilization's energy use is discharged directly into the atmosphere to the extent that there is concern of major climatic changes both locally and globally. 19/

18/ Holdren, J.P. et al. Human Population and the Global Environment. Op. Cit.

19/ Ibid.

It has been estimated by one expert at the current 1.9 percent yearly growth, the world's population of about 4 billion people will double to 8 billion by 2012, to 16 billion by 2048, and to 32 billion by 2084. 20/ What impact this rapid population growth rate will have on climate is a matter of continuing speculation. At the same time, the impact of naturally or artificially changing climate on the same population equation is currently a matter of urgent speculation.

Climate and Food

The possibility of widespread famine caused by an increased incidence of bad weather is increasingly troubling many climatologists, sociologists, and policy makers. For example they note that the Indian monsoon has failed twice in the 1970's compared with only once in the 1960's. Such failures disastrously affect the nutritional status and ultimate health of millions of people. 21/

That the influence of climate on food is profound is underlined by statistics on world grain production in 1974. Between 1950 and 1972, there were steady and consistent increases in grain production associated with favorable weather patterns. However, in 1972 and 1974, both years of poor weather conditions, grain production declined. In 1974, the world grain harvest was two percent less than the preceding year's harvest. With 70 million more people to feed that year, the decrease was a serious one. 22/

20/ Echols, J.R. Population Versus the Environment: A Crisis of Too Many People. American Scientist, Vol. 64, 1976, 165-173.

21/ Concern Over Climate: Researchers Increasingly Go Public. Science, Vol. 192, 1976, p. 246.

22/ Grim Reaping: This Year the Whole World is Short of Grain. N.Y. Times, Sept. 15, 1974, p. 6.

Worldwide demand for grain products has reduced reserves below 30 days. At the same time, it is estimated that half a billion people in the world are now suffering from some form of hunger. Ten thousand people die of starvation each week in Africa, Asia, and Latin America. There are food shortages in the sub-Sahara, Brazil, India, and Bangladesh. India alone needs 8 to 10 million tons of food or more from outside sources, or else as many as 30 million people might starve. 23/

Only slightly less serious are nutritional situations in Honduras, Burma, Burundi, Rwanda, the Sudan, and Yemen. Poor harvests caused by bad weather threaten food supplies in Nepal, Somalia, Tanzania, Zambia, and even the Phillipines and Mexico. 24/

Human nutrition is not exact enough to estimate exactly how many calories a human being needs to survive. Many factors in such an estimate depend on the individual, his environment, his activity, and his general condition. In a northern industrial country, a 30 year old, 150 pound man needs at least 3000 calories a day. In the tropics, where people do not need many calories to maintain body heat, the figure is lower. If caloric intake drops below the daily expenditure of energy for too long, starvation is the result.

A nutritional map of the world reveals that only in the industrialized countries does caloric intake exceed substantially metabolic demand. In all other parts of the world, caloric intake is marginal or substandard. Therefore, any change in climate of a magnitude which would negatively

---

23/ The World Food Crisis. Time. Nov. 11, 1974, 66-83.

24/ Ibid.

76-572 O - 76 - 4

affect crop production has the most profound effects in the less developed countries where the nutritional status is marginal, even when the climate is favorable. Population increases alone are already exceeding the ability of agriculture to nutritionally satisfy the added burden. The consequences of any climatic change on man's nutritional equation, then, are all too grimly plain.

Prognoses and Possible Solutions

Even the most optimistic speculations hold that a slight variation in climate can have a profoundly negative effect on the health and welfare of man. A major change would therefore have truly catastrophic effects unparalleled in the history of man.

If one accepts the popular scenario that Earth is rapidly entering into a new ice age, then the danger of that event must be related to the living population. Simply stated, if the population were small and mobile, it could survive by moving southward toward the warm climate. If world populations of men and animals were large, which all estimates predict they will be, a large proportion would have to die even if it was mobile. For a major ice age could well extend its glaciers to the fortieth parallel or beyond. If they extended another ten degrees below this parallel, the climate in that area would approximate that of Canada, Northern Europe, and Siberia, with relatively short crop growing periods. In other words, the foodbasket of the world would have been destroyed, because below the thirtieth parallel there is only 28 percent of the world's land surface and much of this would become desert. Perhaps 10 to 20 percent of the world's land surface would remain within the agriculturally productive zone.

The first casualties of such an event would be populations of animals, wild and domestic, since competition for productive land surface would be quickly felt by man. The raising of food animals would be too inefficient in an era of land scarcity and man would have to exist on a vegetarian and/or synthetic diet. The management of four or more billion people on the productivity which would become available below the fortieth parallel would require the highest forms of technology. Without disciplined worldwide planning, it is estimated that half of the world's population could die through war, fighting on a smaller scale, starvation, or cold. 25/

Similarly, if one accepts scenarios which suggest that rapid warming of Earth will occur, melting the polar ice caps and inundating the Earth with 240 more feet of water, the prognosis is equally grim. Enormous displacements of populations would be obviated by that event with the similar result that the same number of people would have to be supported by a significantly smaller area of land.

In between the extreme scenarios are those that suggest that climate changes will be more moderate, but nonetheless profoundly affect the health and welfare of man. Most experts agree that over the next two decades, that the present "stressed" climate will continue. During this time, the population will continue to increase and the chance of severe food shortages, particularly in the tropical regions, is great. 26/

25/ Kaplan, I.E. The Threat of A New Ice Age and Some Possible Defences. Science Forum, No. 2, 1975, 7-10.

26/ Decker, W.L. Unsettled and Variable Climate Uncertain Food Supply. Industrial Research, Nov. 15, 1974, 51-55.

It can safely be concluded that even the most optimistic scenarios about the future climate of Earth have disturbing implications for the health and welfare of man. After pointing out the high probability of major, climate induced crop failures within a decade, the 1974 Bonn International Workshop on Climate and its Effects on Human Life suggested that the following anticipatory measures be taken:

> ". . . If national and international policies do not take these near-certain failures into account, they will result in mass deaths by starvation and probably in anarchy and violence that could exact a still more terrible toll. It would be irresponsible in those circumstances to continue passively in our present condition of helplessness: without food reserves or alternative technologies to produce food and without adequate means to redistribute food from the more favored nations or more favored groups within nations to the less favored in time of urgent need.
>
> "The most obvious and immediately practicable steps to reduce that helplessness are to encourage the production and storage of food in excess of current consumption. This should be the policy not only of the breadbasket nations but so far as is possible of the most vulnerable themselves to climate catastrophes. At best even modest reserves will need some years of grace in good growing weather to accumulate. For the longer run . . . there must be intensified research into the causes of climatic change and intensified research on new sources of food (from conversion of cellulose or marine farming, for instance).
>
> "New, or at least newly urgent, ethical problems loom in perhaps unavoidable decisions to allocate food supplies that are grossly inadequate to keep everyone alive. Age-old problems of social justice inherent in the current distribution of wealth among economic classes will at the very least be sharpened. These furthermore may now have practical as well as ethical significance; one way to find reserves could be to eliminate wasteful and physiologically excessive consumption among the affluent of the world; another might be to improve food-handling processes to plug the holes through which so much grain now goes to waste; finally further reform is still needed in the land-holding systems of some of the poorest countries that too often have discouraged farmers from increasing production.
>
> "In view of the importance of climate to all mankind, we urge the dedication of the climatic system to peaceful purposes. In recent years, there have been efforts to try to develop techniques to change weather and climate conditions. We need to take the necessary measures to ensure that such techniques, if developed, are not used for hostile purposes. Moreover with

> the present lack of flexibility any change of climate, natural or induced by man deliberately or inadvertently, is very likely to involve stress and suffering in various regions of the earth before the human economy becomes adjusted to the new conditions."

As articulated by Dr. Walter Orr Roberts, "Climate change and its consequences, in a new age of scarcity, have risen to a position near the top of the agenda of humankind." 27/

Summary

Much uncertainty exists about the character and imminence of future climate patterns, and therefore about their impact on man. However, the consensus of worldwide expert opinion is that future climate patterns will, at best, be of a variable and unpredictable nature and that a return to the generally beneficial weather patterns characteristic of the 1890-1945 period is not to be expected. It is believed that the greatest negative impact of future climate on man will involve food supply. The high probability of crop failures as a result of aberrant weather patterns which are predicted to occur in the next decade are held to pose the most serious threat to the nutritional status and ultimate health of millions of people throughout the world. The implications of predicted crop failures are all the more serious when viewed against almost non-existent grain reserves and rapidly increasing human populations in regions of the Earth where the nutritional and health status is marginal even under the most optimum weather conditions. Panels of experts who have examined these trends have strongly recommended that all nations of the Earth, individually and collectively, plan and act to establish the technical, social, and political means to meet this most serious challenge to man (See Appendix).

27/ Roberts, O.R. Towards A Global Food Policy. Die Zeit, April 4, 1975, 1-9.

****

CHAPTER IV

CLIMATIC CHANGE AND WATER AVAILABILITY

by

Warren Viessman, Jr.
Senior Specialist in Engineering and Public Works

and

Christopher K. Caudill
Research Assistant
Environment and Natural Resources Policy Division

****

CLIMATIC CHANGE AND WATER AVAILABILITY

Climatic variations affect water supplies through changes induced in the global atmospheric circulation system. Evaporated moisture is carried from the oceans by the winds and is condensed over the continents. Variations in ocean and air temperatures change the amount of evaporation and wind direction causing changes in amounts of precipitation, thus water supply, around the world. Temperature changes further affect the form of precipitation which also plays a modifying role in relation to climate.

In this section, the machinery involved in furnishing water supplies and the effects of climatic variations upon it are discussed. Also included is a discussion of the effects of climatic variations on the polar regions.

The Winds of the Earth

Due to unequal solar heating of the earth, inequalities in air density occur in the atmosphere. Colder air sinks forming high pressure areas horizontally along the Earth's surface. Warm air rises forming low presure areas and spreads over the colder underlying air. As cold air moves over the surface of the Earth, it is warmed by radiant heat from the sun and rises. Conversely, warm air cools and descends completing the circulation pattern. Air mass movements created by this process generate the prevailing winds which act to redistribute the Sun's heat. In the northern and southern hemispheres, three distinct circulation zones exist. Attention will be focused on the northern hemisphere, since most of the world's population resides therein.

At the equator, a slim band of light and irregular winds prevail. These are known as the doldrums. Air is heated by intense solar radiation and becomes supersaturated with water evaporated from the ocean. The warm-moist air rises rapidly creating a strong low pressure zone along the equator. It then flows northeastwardly at high altitudes into the subtropical high pressure zone. As the humid air passes through the cooler temperatures of the upper atmosphere, it loses heat to its surroundings and loses some of its capacity to retain water vapor. The excess water vapor condenses and falls as rain with the release of additional heat to the atmosphere. Once cooled, the air decends creating a high pressure region on the Earth's surface. At this point, the air has lost most if not all of its moisture and is consequently very dry (deserts exist in areas where dry air consistently reaches the surface). After the air has descended, it flows back towards the low pressure system of the doldrums creating the "trade winds". These are the dominant winds of the surface and lower atmosphere of the subtropical high pressure zone.

North of the subtropical high pressure zone, lying between the 35th and 55th parallels, is a region of prevalent winds known as the westerlies. Although these winds blow predominantely from the west, there are many irregular currents caused by migrating centers of high and low pressure. Further disturbances are caused by land masses of North America, Europe, and Asia. Mountain chains and large lakes block the flow of air forcing rapid cooling effects along with movement in avoidance of these obstacles. In North America and Asia, large areas of ice and snow reflect much of the Sun's heat during the winter. Consequently the air is not warmed and large high pressure systems result over these continents. Because of flunc-

tuations between the subtropical high pressure zone and the westerlies, some areas are under the influence of high pressure during the entire year. Climates of California, the Mediterranean area, and south Africa are examples.

Topping off the globe are the polar easterlies. Because of the presence of ice and snow on the polar cap, much of the Sun's energy is reflected back into space and a large high pressure system is developed. Due to the anticyclonic spin of such systems, winds blow easterly or southeasterly. This pattern is complicated by the fact that the largest glaciated land mass, Greeland, is not centered on the pole, and the winters of Siberia and northern Canada are colder than the Artic Ocean. These conditions oppose the influence of the polar region and create northwest winds over the Canadian archipelago. Winds over Franz Josef Land and Spitzbergen are usually easterly, although changes often occur.

As altitude increases, air pressure decreases more rapidly over cold air masses than over warm air masses. At an altitude of several miles, lows are found over the polar region, while high pressure is found over the equator. Since the trade winds diminish with altitude, winds at high altitudes prevail from the west. These winds are especially pronounced near the 30th parallel during the winter and the 40th parallel during summer. They are known as the "jet stream" and attain speeds up to two hundred miles an hour, although sixty miles an hour is the average. Disturbing influences of land formations and traveling centers of high and low pressure cause the jet stream to travel in a zigzag fashion around the Earth. During the summer months, the jet stream moves northward and becomes weaker due to the decrease in contrast between the temperatures in the tropics and the poles. The stream repositions itself from Oklahoma in the winter to the Canadian border in the summer.

The jet stream affects weather by creating high pressure areas as it moves towards the tropics and low pressure areas as it turns towards the pole. Interrupting the normal weather flow, these pressure areas may create a blocking effect which is usually centered over Scandinavia. This bars movement by Atlantic storms. Results of this occurance vary from heat waves to record snowfalls and droughts to floods. The jet stream can further interrupt weather patterns by forming pools of stationary warm air which can divert the jet stream from that area for weeks.

The small wandering storms that frequent the region of the westerlies are created by movements of the jet stream. These storms correspond to areas of upward suction created by movements of the jet stream. Each storm moves eastward following the path of the jet stream, but moves slower and is affected by changes in the land topography.

The Winds As Water Bearers

In addition to redistributing tropical heat, the wind system also carries water to all parts of the world. Water is injected into the wind system mostly by oceans and to a lesser extent lakes and rivers.

Through absorbtion of solar radiation, the oceans are about 0.8 degrees Centigrade warmer than the atmosphere. Heat flow, therefore, is from the oceans to the air. Some of this heat is transferred as sensible heat (heat which can be felt) while the majority is released as latent heat of evaporated moisture. Although the difference in temperature between the oceans and the atmosphere is relatively small, it must be remembered that because of the individual specific heats, the same amount of heat that would

raise the temperature of sea water (35% salinity) one degree Centigrade, would raise three thousand times the same volume of air one degree Centigrade at standard temperature and pressure.

With the water supply carried on the wings of the wind, one can see how vunerable it is to change. Changing influences can be exerted on wind patterns by variations in ocean temperature, thermal conditions of land areas, sea ice, volcanic dust, or solar disturbances.

Variations in ocean temperatures are considered likely to be the largest influence in causing long term weather anomalies. These changes are seen as a predictor of atmospheric circulation behavior for at least a month.

During the period between 1890 and 1920, the mean surface temperature in the mid-Atlantic fell more than 1 degree Centigrade, while the temperature south of Newfoundland rose by 2 degrees Centigrade. These temperature changes spurred an intensification of the "Iceland" low, the "Azores" high and the westerlies which lie between them. Results of this change displaced both the strengthened westerlies and intensified subpolar and subtropical high pressure zones. The circulation features which appeared tended to intensify the situation which caused it.

The northeastern winds of the subtropical high pressure zone and the westerlies of the middle latitudes carry most of the moisture to the populated areas of the northern hemisphere. Changes affecting the direction of these winds can cause droughts in some areas and floods in others.

The northeastern winds of the subtropical high pressure zone bring the monsoons to Southern Asia. Resulting rains supply the farmlands which feed the largest concentration of people in the world. The hugh land mass of Asia distorts the global wind pattern. During the winter, the air pumped to high altitudes over the Indian Ocean flows exclusively northwards and re-

turns at surface level by the trade winds as the cold and dry winter monsoon. The Himalayas prevent the cold of Siberia from accompanying the air on its return to India. In summer, though, Asia rivals the equator as a warm zone. Over the mountains of Tibet and the Himalayas, the air is much warmer at 15,000 feet than it is elsewhere at that altitude. Consequently, the warm air rises more vigorously than at the equator and flows towards the southern hemisphere high above India and her ocean. The winds return as the trade winds of the southern hemisphere. These winds blow to the northwest, but at the equator they make a right turn and sweep over India from the southwest. Although these winds do not possess enough moisture to make rain, the mountains of Burma wall in the moisture and force it to spill back on India and Bangladesh.

Many climatologists have tried to develop ways to predict monsoon adequacy. Most predict that if the climate is cooler in the north, weaker monsoons will occur. As the Asian land mass becomes cooler, its advantage over the equator's temperature lessens, weakening the monsoons. Other theories state that changes in the temperature of the cold upwelling of water off the coast of East Africa varies the temperature differential between the oceans and the continent strengthening or weakening the monsoons accordingly.

Miniature monsoons occur over Africa. Along the coasts of Sierra Leone to Nigeria, rainfall is abundant, but it lessens considerably towards the north. The rains are not penetrating as far north as they did two decades ago and as a result, the Sahara desert is moving southward. The tide of the Sahara has moved southward and northward according to the temperature of the middle and polar latitudes. During the Sahara's recession around 1931, cattlemen followed by farmers settled the reclaimed area. The cur-

rent drought is forcing them along with thousands of starving refugees back towards Central Africa.

The general theory explaining the recession of the rains from North Africa is that it is due to the cooling of the northern latitudes, in progress since 1950. As the artic high enlarges, the westerlies and subtropical high pressure zone moves southward taking its rain with it. A colder mean temperature in New England may forecast weak monsoons for India, China, and Africa. [28/] Clearly this demonstrates that the problem of climatic change is global in nature.

Others have suggested that the desert reflects much of the solar radiation back into space due to its surface structure. If this is true, the desert perpetuates itself as it moves southward.

The climate in the area of the westerlies is much more variable than that of the subtropical high pressure zone. Due to the influences of polar high pressure, subtropical low pressure, and the mixing effect of the jet stream, the weather is characterized by a repeating pattern of stormy, then clear weather.

Water-rich low pressure systems are pumped in by the upswing of the jet stream from warm areas such as the Gulf of Mexico, the Gulf Stream, and the Pacific Ocean. On the downswing of the jet stream, cold high presure systems are flung into the westerly winds of the region. Interaction of these systems supplies rainfall to the continents of North America, Europe and Asia.

Variations in the path of the jet stream cause an increase or decrease in the amount of both high and low pressure systems entering the westerlies

---

28/ Calder, Nigel The Weather Machine, Viking Press, New York 1974 pp. 45-46.

region. Since major land formations rarely change drastically, temperature variations in the polar region and the subtropical region exert the most important disturbing influence upon the jet stream. Colder temperatures in the polar region force the jet stream southward. The increase in contrast between temperatures of the polar and the westerlies regions would increase the strength of the jet stream. Because of its southerly location, the jet stream would pull more cold high pressure systems farther south than at present and fewer low pressure systems would reach northern latitudes. The climate would be characterized by longer and colder winters with shorter and cooler summers. Much water would be invested in snow and ice lowering the amount of readily available water. As a result of increased storage of water in snow packs, spring and summer melts would release large quantities of water from storage increasing the likelihood of flooding.

Warming in the polar climates would allow the jet stream to move northward. Contrast between polar and westerlies temperatures would decrease weakening the jet stream. The weakened jet stream would pump a lesser number of high pressure systems into the westerlies region making the warm low pressure the dominant feature. The climate would be characterized by warmer and wetter weather year around. The increased precipitation could result in greater flooding, however due to the amount of time needed to complete the temperature change, some river beds would be able to adjust to increased flows through natural geomorphic processes.

Ice Cap Melt and Expansion

Warming and cooling trends in the Artic and Antartic regions have occured frequently. At least five times in the Earth's history, the cooling process produced ice ages. Less frequently, warming trends have been sufficient to entirely melt the ice caps. Either occurance, now or in the future, would be a catastrophy. Because of this, scientists are striving to understand the mechanisms which promote melting and glaciating processes.

About 90,000 years ago, the Earth experienced a warm period similar to the one during this century. Then, in about 100 years, the Earth plunged into severe cold conditions beginning the last ice age. A thousand years later, the ice sheets receded to the poles and the Earth warmed again.

To explain the sudden cooling, scientists formulated the Antartic ice surge theory. Scientists believe the Ross Ice Shelf, a large floating mass of ice the size of France, is actually a climatic time bomb. After a thousand years of ice and show buildup, it is theorized that the sheer weight of the formation would melt the underlying ice. Lubricated by the melt water, the ice sheet would move outward into the ocean raising the sea-level as much as 60 meters. The seaborn ice would cool the ocean lowering the mean temperature in the southern hemisphere and allowing further formation of ice and snow. Winds would distribute the temperature decrease around the world and lower temperatures in the Artic region would trigger the expansion of its ice sheets.

However, some scientists feel that this method of ice generation does not explain why the temperature in the northern hemisphere dropped so quickly.

Two other theories have been proposed to explain ice age generation. The first suggests that ice sheets form and grow until an ice age is set in

process. As the ice and snow build up vertically, glacier-like movements occur. This theory, like the previous one, does not account for the quick temperature decrease, however, since it is estimated that the glacier-like expansion of the ice sheet would take between 15,000 and 30,000 years.

A final theory proposes that the ice sheet is formed by snowfall. It considers that as a large area of land is covered by winter snows, reflected solar heat lowers temperatures and prevents or decreases spring melt. During following winters, added snowfalls occur perpetuating the process. As air temperature decreases due to increased reflection of solar radiation, snowfall is increased in outlying areas and the resultant ice sheet is expanded and continuously reinforced. Evidence shows that ice sheets reach half their volume in 5000 years. This does not mean that the climate takes that long to deteriorate, however, since in the process, temperature drops, large land areas become inundated with snow, and ice sheets gradually increased in thickness, by about half meter per year.

Although the formation of an extensive ice sheet does not present an immediate problem, associated temperature changes and conditions that sustain snowfall could make life very uncomfortable. Once an ice sheet is established, it persists for a very long time.

Water resources would be affected during the development of an ice age as ocean levels decrease and fresh water supplies freeze. For example, during the ice age, it was calculated that ocean levels decreased as much as 200 meters.

Another problem would be the need to melt large quantities of ice to furnish fresh water supplies.

Warming trends in polar regions also have worldwide repercussions. As temperatures increase in these areas, as they did in the early part of

the century, ice sheets melt and recede. In the planet's history, warming trends have completely melted the ice caps. If such a warming trend occured today, the sea-level would rise accordingly. If the Ross Ice Shelf melted, the sea-level would rise about five meters worldwide. Total melting of the poles would raise sea level 60 meters, inundating much of the coastlines of the world. This would include the major cities of New York, Baltimore, Washington D. C., Paris, Berlin, and London.

Warming of the poles is also related to still another theory on the ice age. Warm and most air is essential in snow making. The theory suggests that as the ice caps melt, more warm and most air is made available to outlying lands via polar easterlies. Ice sheets form by heavy snow falls and decreasing temperatures.

Many timetables have been suggested predicting the next ice age. They range from 100 years to 10,000 years. Even if it started tomorrow, we would probably just tell our grandchildren to move farther south. But the destructive force of the ice sheet would eventually level cities and rearrange the topography and climatic changes would clear the land of present flora and fauna and establish new regimes indigenous to colder climates. Once an ice age is set in motion, it persists for 10,000 to 100,000 years. Thus it is important for man to understand the forces involved and preventing such occurrences.

Summary

Variations in climate affect water supplies through temperature change. Causative elements (both natural and man-induced) could include particulate matter, ozone destruction, solar radiation variation, cold water upwelling, and changes in established courses of warm water such as the Gulf Stream.

76-572 O - 76 - 5

Warming trends would tend to increase rainfall and raise the temperature of the northern latitudes. Under these conditions, the middle latitudes would acquire a semi-tropical climate while the equatorial region would become warmer with increased humidity. Cooling trends would establish colder temperatures in the northern latitudes. The middle latitudes would experience colder and longer winters while summers would be cooler and shorter. More water would be stored in ice and snow during the longer winter, decreasing the quantity of readily available water. Spring melts could increase due to expanded snow packs and greater flooding might result. Monsoons in Southeast Asia would be weaker and less frequent, consequently, food production in that area would decrease.

Warming in the polar regions could melt the ice caps. Depending on the extent to which this occured, the sea-level could be raised as much as 60 meters inundating coastal cities worldwide.

Colder temperatures could generate an ice age by contributing to the spread of ice sheets. The destructive effects of these are well known and in time they could destroy many natural and man-made land forms including cities. Previous ice ages have persisted for 10,000 years or more.

The impact of climatic change on global and regional water resources must be understood if such effects are to be dealt with or modified. The basic mechanisms of water vapor transport are fundamental to this understanding and have been reviewed in this chapter.

****

CHAPTER V

THE USE OF SIMULATION MODELS TO EXPLORE CLIMATE AND ITS VARIABILITY

by

Marvin Kornbluh
Analyst in Futures Research
Futures Research Group

****

THE USE OF SIMULATION MODELS TO EXPLORE CLIMATE AND ITS VARIABILITY

Introduction

Recent years have seen an upsurge of research in the fields of weather prediction, weather modification and climate control. Substantial improvements in the accumulation and analysis of environmental data, coupled with a better understanding of the nature and interrelationship of climatic processes have provided meteorological and climate researchers with meaningful insights. These insights concern the possibilities of predicting and deliberately influencing the earth's climate in both the short and long run. Furthermore, as a result of these insights, both researchers and policy-makers are becoming aware of the inherent danger of attempts to modify weather and climate phenomena. The danger lies in the fact that such modification experiments could lead to inadvertent and irreversible changes in the environment that are potentially harmful to its inhabitants. One illustration is the burning of fossil fuels for heating and energy production. This common procedure releases large quantities of carbon dioxide (CO_2) and particles into the atmosphere. These emissions can potentially alter the workings of critical physical processes and permanently alter the local, regional,

or global climate. 29/ Another possibility that has been seriously suggested is to remove the ice in the Arctic Ocean to radically improve the climate of Siberia. However, in addition to improving the Siberian climate, at least one logical chain of argument suggests that the ice might not return for several thousand years and that its absence might precipitate a new ice age. 30/

There is at least one major conclusion that can be drawn with respect to the uncertainty of weather prediction and modification and climatic control efforts. This is the conclusion that purposeful management of resources devoted to these areas may eventually become necessary to prevent undesirable changes. This chapter discusses one type of technology -- computer simulation modeling -- and how it can facilitate purposeful management of climatic resources. Specifically, such models may be developed to represent and experiment with systems via a computer before actual field experiments are attempted and climate modifications made. Simulation models may be designed to accept man-induced

---

29/ This possibility was mentioned in Beltzner, Klauss, ed. Living With Climatic Change. Ottawa, Canada, Science Council of Canada (March 1976) p. 11 (The conference proceedings were held in Toronto, Canada on Nov. 17-22, 1975).

30/ This suggestion was mentioned in Greenfield, S.N. Weather Modification Research: A Desire and an Approach. Santa Monica, Calif., Rand Corp. (February 1969) p. 4 (No. P-4027).

changes and disturbances as input and provide as output, information that is relevant and meaningful for a more comprehensive understanding of weather, climate and climatic change. This knowledge can encourage a rational approach to the control of climatic variations and provide a means for making more accurate weather forecasts - both short and long range.

Nature of a Model

A model can be regarded as a representation or likeness of specific aspects of a physical system. It is both an idealization of and a substitute for such a system. By working with a model, we can study and experiment with the reference system as it was yesterday, as it is today and as it may become tomorrow. A model does not - and in fact cannot - duplicate all the features of a system. Rather, it tries to reflect only those system details felt to be necessary to attain the objectives set for the study.

Some model-builders declare that researchers use models whenever they think logically about a system and its operation. When they apply their unique experience, knowledge and intuition to the study of a systems problem, they may be constructing a "mental model" without consciously realizing it. This subjectivity, some declare, is what severely limits mental models. One eminent model-builder said the

following about mental models: 31/

> Our mental processes use concepts which we manipulate into new arrangements. These concepts are not, in fact, the real system that they represent. The mental concepts are abstractions based on our experience. This experience has been filtered and modified by our individual perception and organization processes to produce our mental models that represent the world around us.

Types of Models

Mental models can be a natural and useful capability in certain circumstances. However, for a number of other situations, a formal model of a given system may be more beneficial. This is particularly true when we are dealing with large complex systems. A formal model makes the implicit mental model explicit. Formal models vary in their modes of expression and three basic ones can be distinguished:

1. Schematic models which use pictures of some sort to represent the essential features of a system. These pictures can be different geometric shapes, lines, maps and other schemata. Familiar examples are flow charts, scheduling charts and meteorological charts which denote pressure fields, wind fields, temperature distributions, etc.

2. Physical models which employ tangible materials to depict the reference system. Relevant examples here are a wind tunnel used to test the effects of wind on objects and a scaled-down river basin built from plastic or concrete according to topografic maps.

31/ Forrester, Jay W. Principles of Systems. Cambridge, Mass., Wright-Allen Press, Inc. (1968) p. 3-1.

3. Symbolic models which use symbols to designate major system features. Verbal symbols or narratives such as English or Chinese and mathematical symbols depicted in equations, form very common symbolic models.

Probably the most concise form of symbolic model is the mathematical model which utilizes mathematical symbols. Three characteristics of mathematics make the use of these models attractive: 32/

1. They are very precise. Very few nuances are present in most interpretations of mathematical symbols.

2. They are very concise. A small number of symbols, properly interrelated, can express organization and activity in large, relatively complex systems.

3. They are very manipulatable. Mathematical symbols require relatively few rules to operate upon features of large complex systems.

Mathematical models are developed by formulating equations which represent and interconnect system features and activities. They relate variables, constants and parameters. Variables are system features whose values vary within some range. Variables normally assume different values as a mathematical model is solved or experimented with. Constants represent system

---

32/ This list was mentioned in Chapter III, The Nature of a Computer Simulation Model. U.S. Congress. House. Committee on Merchant Marine and Fisheries. Subcommittee on Fisheries and Wildlife Conservation and the Environment. Computer Simulation Methods to Aid National Growth Policy. Washington, D.C. U.S. Govt. Print. Off., 1975, p. 31.

features which do not vary, that is, they maintain assigned values as the system operates. Parameters are variables that are consciously made constants for the purposes of experimentation. There are probably hundreds of variables and constants to contend with in the complete climatic system which consists of the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere. 33/

For example, some variables that are responsible for our climate and its variations are temperatures of the air, water, ice and land, the speeds of wind and ocean currents, the air's moisture or humidity, the cloudiness and cloud water content, the lake levels and the water content of snow and of land and sea ice. These variables are interrelated to form various system processes such as precipitation, evaporation, radiation, heat transfer as well as momentum by advection, convection and turbulence. For a time-scale of thousands of years, the shape of ocean basins, the distribution of continents as a result of sea floor spreading and continental drift and the sun's radiation can be considered constant.

If the value of a variable is determined by conditions external to the system, it is known as an "exogenous variable". Alternatively, if the model (system) is largely responsible for the value a variable takes, that variable is called

---

33/ Definitions of these terms are given in United States Committee for the Global Atmospheric Research Program, National Research Council. Understanding Climatic Change: A Program for Action. Washington, D.C., National Academy of Sciences (1975) p. 15.

an "endogenous variable". To illustrate, we may regard the underlying ground and the space surrounding the Earth as the external climatic system and the gaseous, liquid and ice envelopes surrounding the Earth as the internal system. Thus, the variables which produce changes in solar radiation, atmospheric composition, land features, orography, vegetation and albedo can all be regarded as exogenous variables. On the other hand, variables which form couplings of the ice and air, ice and ocean, atmosphere and ocean and wind stress can be called endogenous variables.

Simulation Models

A special class of mathematical models is referred to as simulation models. A simulation model is a dynamic model in the sense that it incorporates time as its most critical dimension -- directly or indirectly. When time is incorporated directly, the simulation model is referred to as being "period-oriented". A period version produces results at regularly spaced intervals of time in the reference system such as days, months or years. Dynamic models constructed to explore climate and its variability are susceptible to a wide variety of time intervals depending on the particular aspects of the climate problem being investigated. For studying the atmosphere, years seem to be the most appropriate interval; for long-term weather forecasting, weeks appear to

be the best selection; for investigating the oceans, centuries look most fruitful. Time is incorporated indirectly into a simulation model by an "event-oriented" approach. An event-oriented version does not progress evenly in terms of time in the reference system. Rather, it produces a result only when an event occurs in the system represented by the model. Each event, in turn, influences the occurrence, timing, nature and impact of subsequent events. A simulation of short-term weather forecasting relating temperature, motion, pressure, clouds, water vapor and other variables may conveniently be event-oriented.

A system -- and the model used to manipulate it -- is said to be stable when its measured output varies within a previously established and acceptable range despite likely changes to its parameters. A system and its model may also yield results which fall outside some desired and perhaps safe range. The system may then be referred to as unstable. The permanency of this unstableness may be tested by "feedback". A feedback mechanism either amplifies an output value -- called positive feedback -- or dampens it -- called negative feedback. There are a large number of feedback mechanisms present in the ocean and in the atmosphere and between the ocean and the atmosphere -- especially during the shorter range time periods of climatic change. Some of the more prominent ones relate to the radiation balance over land and the energy balance over the ocean. Feedback can make a large contribution to the dynamics of a simulation model.

Some simulation models are referred to as "deterministic" in nature because they yield the same results in every model run with the same assumptions about the reference system. A "probabilistic" or "stochastic model", on the other hand, uses random numbers to assign values to the model variables according to the probabilistic effects built into the model. In stochastic models, different results follow from the use of different sets of random numbers without any change to the model. For example, a simulation model developed to yield forecasts of the direction and the force of an already formed hurricane is likely to be deterministic. However, the model involved in forecasting the number and the locations of hurricanes over the forthcoming year is likely to be probabilistic in nature.

We see then, that a model attempts to imitate the operation of the reference system by time intervals or event-by-event in a deterministic or probabilistic manner. Because of these features, a simulation model is said to be"run"rather than "solved"as are most other mathematical models. With the assistance of a computer, a simulation model may be run many times with different values assigned to the parameters. These computer runs are called experiments; they are directed at answering two kinds of "what if" questions:

1. What if we set the values of the critical and controllable parameters at certain levels? What would happen to the model outputs?

2. What if certain variables which are not very controllable take on certain values? What would happen to the model outputs?

The various outputs from a set of computer simulation runs must be organized, analyzed and interpreted. It is these interpretations rather than the specific outputs per se that may properly be called solutions of a simulation model.

Role of Computers in Simulation Modeling

The computation and manipulation capabilities of the modern electronic digital computer have important implications for simulation models that represent climate and climatic change. One authority felt this was primarily due to two computer capabilities: 34/

1. It can replicate experiments rapidly under the same or different conditions.
2. It can handle a large number of variables and constants and relationships among them in a single computer run.

Increasingly, computers used in simulation modeling, are functioning "on-line" and operating in "real-time". The former term refers to the fact that data is entered directly into the computer from some point of origin and/or output data is transmitted directly to where they are used. There

---

34/ See Barton, R.F. A Primer on Simulation and Gaming. Englewood Cliffs, N.J., Prentice Hall, Inc. (1970) p. 20.

need be no human intervention between the source recording of data and their ultimate processing by the computer. Real-time implies a very quick response from the computer. It means that required computations and logical manipulations are performed fast enough to influence ongoing computer controlled processes. A wide variety of devices have been developed to facilitate on-line real time processing of system activities -- with or without the incorporation of a model. These devices, referred to as computer terminals, can enter and receive data from computerized data banks located near to or far away from the terminals.

Putting computers to work manipulating variables, constants and parameters contained within mathematical equations (via a simulation model) usually calls for a costly and time-consuming programming effort. To make a computer function, it must be programmed. Programming means formulating a set of instructions which can tell the computer what to do and how to do it. These instructions must be extremely precise and follow a logical pattern. 35/ Fortunately, many flexible programs having wide applicability can be purchased from computer manufacturers, management and systems consultants and from other computer users. These "packaged programs" are referred to as "software". This is in contrast

---

35/ This logical pattern is frequently referred to as an algorithm. Essentially this can be defined as a fixed step-by-step procedure which, when properly performed, will yield a definite, proven result.

to the term "hardware" which signifies the main computer and associated terminals and other devices attached to it.

One of the more fundamental problems in the study of weather and climate is how to obtain a quantitative understanding of the general circulation of the atmosphere, the oceanic heat transport and the ocean/atmosphere heat exchange. The development of computer simulation models in these areas would likely require the formulation of a large number of equations, the calculation or the assignment of values for their elements, the programming of these equations and running experiments on the model many times. A large-scale computer system, aided by knowledgeable programmers, possesses the capability to perform these tasks and quickly deliver the results to researchers and policymakers in diverse locations. Furthermore, the computer output is likely to yield more climatic details than we now observe in nature itself.

Some Benefits to Using Simulation Models to Study Climate

We can conjecture as to the benefits of using simulation models for the study of climate and its variations. These potential benefits are grouped below into eight major areas:

1. They impose a consistent and logical discipline for precisely describing the elements and the processes involved in a climatic system. This, in turn, makes possible

the identification of important system variables and significant chains of relationships that may have been inadvertently overlooked utilizing other research methods.

2. They provide an expedient vehicle for conducting a great number of diverse experiments not possible in the field or in the traditional laboratory. The sensitivities of various climatic resources of particular regions to changes in the magnitudes of its variables and to changes in relationships among these variables and the resulting influences on the global climatic system can be tested. A variety of possible future climates can be explored as a result of man-made and natural changes.

3. They permit experimentation in circumstances where it may be impossible or impracticable to experiment with the real situation. For example, we can test whether the by-products of a nuclear war would permanently interfere with the dynamical, hydrological and radiational processes in the atmosphere.

4. They permit verification of past climates, obtained from climatilogical dating methods and historical records, to be made. A simulation model can reconstruct selected events and periods in the climatic history of the earth and infer time-dependent evolution of the coupled atmosphere -- hydrosphere --cryosphere climatic system.

5. They not only facilitate explorations of system

structures and functions but can compress the time for this type of investigation. Actual time, depicting projected future events in a global climate system, can be compressed into brief intervals of computer time. For instance, a million years of future climate may be run on a computer in a matter of minutes or perhaps an hour or two depending on the size and complexity of the model.

6. They can clarify the nature and intensity of the various risks entailed in modifying the structure or the functioning of a system. This is possible because such models can be programmed to output statistical averages, ranges, probabilities, and deviations -- in graphical form, if desired. Thus, research and policymaking with respect to climate and climate modification can be formulated with greater awareness of the potential risks.

7. They can be viewed as educational tools for teaching both researchers and policymakers concepts in logical analysis, model building and experimental methods. Some declare that intense involvement in model development and interpretation can provide insights not previously grasped and greatly encouraged the occurrence of serendipity. This appears to be especially true with respect to the influence of climate on the social and economic stability (as well as the physical stability) of regions and nations.

8. They serve to facilitate more open communications among all parties engaged in climatic research and forecasting and

76-572 O - 76 - 6

associated program formulations. This includes universities, private businesses, government at all levels, trade and professional associations and others. Different perspectives may be uncovered and compared and areas of agreement and disagreement more precisely delineated.

Some Sources of Error in Simulation Modeling

Like all research methodologies, simulation modeling is subject to a number of sources of error. However, if these sources are known and understood, allowances can be made for their influence on the results yielded by the model and on the reference system itself. Some of the major error sources mentioned with respect to climate oriented simulation modeling include the following:

1. A simulation model is always a simplified version of the system it represents. This simplification arises because the model-builder has to make assumptions with regard to the nature and values of the system variables, constants and interrelationships and because he may not recognize, and thus not incorporate, all the details of the reference system into the model. A model-builder may also purposefully exclude some system elements and relationships or aggregate them because he lacks resources -- data, manpower, money, and computing facilities -- to adequately handle them. The term

"validation" refers to tests devised to judge if the model is in fact, an adequate representation of the "important" elements and relationships in the reference system. Importance is judged in terms of the experiments planned with the model and the desired nature of its outputs. Validation is an indication of the level of confidence we can place in the model's behavior under the conditions we have specified. There is no uniform procedure for validating a simulation model. All models are invalid to the extent they are simplifications of the reference system. We may increase our confidence in a simulation model of climatic conditions (i.e., its validity) by determining how well it reproduces past climates by judging how reasonable its responses to experimental modifications of climate are and by critically judging the adequacy of the theory of climate on which the model is based. These tests, however, can only reveal the presence of error; they are unable to prove the absence of errors.

2. Most simulation models require accurate and relevant data for their equations. Unfortunately, however, such data may be unavailable, incompatible, misreported, altered to fit circumstances, inaccessible, or even self-contradictory. Furthermore, the accuracy of data sometimes declines as its detail increases. For instance, it may be easier to make reliable statements about broad climatic conditions on a global scale than about detailed climatic conditions within a small region. This confusing data situation calls for the

model-builder to exercise special care in obtaining, storing, verifying and applying data for insertion into simulation models. In this regard, climatological data bases are maintained and climatological statistics are prepared by a number of government agencies.[36/] However, atmospheric data are not always compatible. Moreover, the observational data bases for the oceans appear to be much less developed than for the atmosphere. Climatic summaries for the ocean are based largely on observations that are more widely scattered in time and space. In addition, data obtained from isotopic dating methods used to infer the chronology of climate over the past several hundred thousand years are far from infallible.

3. Experimentation with a simulation model may be inefficient, incomplete, or inaccurate. As previously described, model experimentation means designing sets of computer runs to determine the sytem's sensitivity to potential changes in the values of its variables and parameters and to potential changes in the types and strengths of system interrelationships. If small changes in these items result in a proportionate or greater change in the model outputs, then these outputs are said to be sensitive to the specified changes. Even with a relatively simple model, the total number of runs required to test all combinations of possible values can be quite large. Further,

---

36/ Some of these government organizations are NOAA's National Climatic Center, and National Meteorological Center, the Air Force's Environmental Technical Application Center, the Navy's Fleet Numerical Weather Central, the National Marine Fisheries Service, and the U.S. Geological Survey.

a number of runs are required to impart reliability to each combination. One special committee appointed to study climate expressed some ideas of sensitivity analysis in the following way: 37/

> To study the relative contribution of individual physical processes to the overall "equilibrium" climatic state, one approach is to test the sensitivity of the statistics generated by a climate model to perturbations in the parameters that influence that particular physical process. In such a modeling program, the effects of changes can first be tested in isolation from other interacting components of the system and then in concert with all known processes in a complete climatic model.

A Brief Conclusion

Man is highly dependent upon his climate. Climatic changes affect patterns of food production, availability of timber, energy consumption, land use, population density, and other important resources. With a greater understanding of weather, climate and climatic variation, we may be able to reduce this dependency. Greater understanding can occur through comprehensively pre-testing potential man-made and natural modifications to existing climatic conditions. This, in turn, requires the coordinated use of all applicable research tools -- including observation and testing in the field, theoretical analysis in the laboratory and operation upon simulation models in a computer center.

37/ United States Committee for the Global Atmospheric Research Program, op. cit.,p. 29.

References

1. Barton, R.F. A primer on simulation and gaming. Englewood Cliffs, New Jersey, Prentice Hall, Inc. [1970] .

2. Daetz, Douglas and Richard H. Pantell, ed. Environmental modeling. Stroudsburg, Pennsylvania, Dowden, Hutchinson and Ross, Inc. [1974] 407 p.

3. Forrester, J.W. World dynamics. Cambridge, Massachusetts, Wright-Allen Press, Inc. [1971] 142 p.

4. Fromm, Gary, William L. Hamilton and Diane E. Hamilton. Federally supported mathematical models: survey and analysis. Washington, D.C., National Science Foundation [1974] 293 p.

5. Greenberger, Martin, Martin Crensen and Brian Crissey. Models in the policymaking process: publication pending. New York, Russell Sage Foundation [1975].

6. Reports of a workshop held at Brookings Institution on February 10-12, 1975. Modeling large scale systems at national and regional levels. Washington, D.C. National Science Foundation 40 p. (Grant No. ENG 75-00738 to M.I.T., Cambridge, Massachusetts).

7. House, Peter W. and John McLeod. Models for strategic analysis and policy evaluation. Pending publication. New York, Wiley-Interscience.

8. Leontief, W.W. Environmental repercussions and the economic structure: an input-output approach. Review of economics and statistics, v. 52: 1972.

9. U.S. Congress. House. Committee on Merchant Marine and Fisheries. Subcommittee on Fisheries and Wildlife Conservation and the Environmnet. Computer simulation methods to aid national growth policy. Washington, D.C., 1975. At head of title: 94th Congress, 1st Session. Serial No. 94-B.

10. U.S. Environmental Protection Agency. A guide to models in governmental planning and operations. Prepared for the Office of Research and Development. Environmenta Protection Agency, Washington, D.C. [1974] 415 p.

****

CHAPTER VI

MECHANISMS AND FACTORS GOVERNING CLIMATIC VARIATION AND CHANGE

by

John R. Justus
Analyst in Earth Science
Science Policy Research Division

****

MECHANISMS AND FACTORS GOVERNING CLIMATIC VARIATION AND CHANGE

The Climatic System

The term climate usually brings to mind an average regime of weather. The climatic system, however, consists of those properties and processes that are basically the same as those responsible for weather and in turn for climate and its variation. The properties of the climatic system may be broadly classified as follows: thermal properties, which include the temperature of the air, water, ice, and land; kinetic properties, which include the wind and ocean currents, together with associated vertical motions, and the motion of ice masses; aqueous properties, which include the air's moisture or humidity, the cloudiness and cloud water content, groundwater, lake levels, and the water content of snow and of land and sea ice; and static properties, which include the pressure and density of the atmosphere and ocean, the composition of the (dry) air, the salinity of the ocean, and geometric boundaries of the system. These variables are interconnected by the various physical processes occurring in the system, such as precipitation and evaporation, radiation, and the transfer of heat and momemtum by advection, convection, and turbulence.

In general terms, the climatic system consists of five physical components: (1) the atmosphere, comprising the Earth's gaseous envelope; (2) the hydrosphere, comprising the liquid water distributed over the surface of the Earth, including the oceans, lakes, rivers,

and the water beneath the Earth's surface, such as groundwater and subterranean water; (3) the cryosphere, comprising the world's ice masses and snow deposits, including the continental ice sheets, mountain glaciers, sea ice, surface snow cover, and lake and river ice; (4) the lithosphere, consisting of the land masses over the surface of the Earth, including the mountains and ocean basins, together with the surface rock, and sediments, and soil; and (5) the biosphere, including the plant cover on land and in the ocean, man himself, and the animals of the air, sea, and land.

While the above may describe the processes, properties, and major actors responsible for the maintenance of climate, the concept of climatic change entails a wide range of complex interactions, with a disparity of response times, among the components of the climatic system. Climate is not a fixed element of the natural environment. Indeed, the Earth's climate has always been changeable. Distinctions are often drawn between short-term, relatively transient regional "anomalies," "variations," or "fluctuations" between one decade and the next (such as the droughts that struck the North American "Dust Bowl" in the 1930s and the Sahel region of Africa in the 1970s) and long-term "changes" on the scale of centuries and millennia (such as transitions between glacial and interglacial periods). Between these two extremes are intermediate-term fluctuations (such as the "Little Ice Age" roughly 1550 to 1850 A. D.).

Short-Term Variations

Day-to-Day Variability. The day-to-day changes in the weather experienced at any locality are associated with weather systems such as those shown on the familiar daily weather maps. These maps are drawn from more or less synchronous observations sent from surface and upper air stations around the world. Data from satellites are increasingly useful in completing the definition of these systems.

Variations Over 10- to 30-Day Periods. Large scale hemispheric patterns in the atmospheric circulation can persist, or change slowly, and consequently cause spells (or runs) of anomalous weather. During a 20- to 30-day period, these persistent or slowly changing circulations may produce specific patterns of precipitation and temperature.

Montly and Seasonal Variability. There seems to be little persistence in the anomalies of temperature or rainfall from one month to the next at any given location. The same is true for the change from one month or season to the same period a year later. However, historical records show runs of several years in succession that may be abnormally cold, warm, wet, or dry. Such successive runs may occur even when there is little more than chance likelihood, for example, that a cold winter will be followed by a cold spring.

Annual and Decadal Variation

Months, seasons, and years of rather persistent unusual weather resulting in runs of abnormally hot or cold, wet or dry months and years do occur from time to time. The Dust Bowl era of the 1930s

is probably the most oft-remembered such period in North America. Elsewhere on the globe, periods of drought in the African Sahel have been a rather common occurrence in historical times. In India, records of rainfall over the past 120 years reveal changes in the frequency of monsoon failure and in monsoon intensity.

Changes Over Centuries and Millennia

Paleoclimatic information from various types of evidence shows that major and prolonged episodes of climatic change, on the order of centuries or millennia, occurred in the distant past. These changes were global in nature, although not necessarily identical in kind or direction, because, for example, wetter conditions in some regions correspond to drier conditions in others.

Frequency and Patterns of Past Variations

Climatic variations of the last thousand years or so, which are relevant to understanding the climate of our own century and its impact on food production, are fairly well documented by historical records and proxy data sources such as records of harvest dates and vineyard yields. Long-term climatic changes, on time scales of more than a millennium, have been reconstructed on the basis of paleoclimatological and geological evidence.

Attempts to reconstruct the past record of climate have produced the conclusion that the prevailing temperature level has varied on every time scale. The prevailing patterns and strength of the global wind circulation also appear to have varied considerably over the years

and centuries. Variations in precipitation are more difficult to establish. Even now, total global precipitation and its yearly variations are not unequivocally documented, due to large and often complex variations in rainfall between different areas on a local scale, uncertainty about rainfall at sea, and instrumental problems in accurately measuring both rainfall and snowfall. However, variations in precipitation indicated by available records appear logical in terms of the changes in atmospheric circulation that were recorded at the same time. Thus, they may be fairly good indicators of trends and large fluctuations if not of precise amounts of precipitation of particular times and places.

The most obvious aspect of climatic change appears to be variations in temperature near the Earth's surface. When changes in temperature occur worldwide they tend to be larger in high northern latitudes. However, smaller changes in temperature in low-latitude ocean areas probably have disproportionately large effects on the atmosphere, and the increased contrast between temperatures at high and low latitudes appears to affect the large-scale atmospheric circulation in significant ways. High-altitude temperature changes are directly related to the extent of ice and snow cover, altered albedo, and variations in the amount of energy absorbed at the Earth's surface. These in turn affect the circumpolar westerly circulation and the development and movement of cyclonic and anticyclonic weather systems. Ocean temperatures and circulations are closely coupled to those of the atmosphere.

Variations in this Century

The most obvious and clearly documented global climatic fluctuation in the twentieth century has been in temperature levels. It is generally agreed that global annual mean temperatures have been relatively warm since the early decades of this century, rising to a maximum in the 1940s. From the 1940s to the present, there has been a cooling trend that is most evident in northern hemisphere temperatures at latitudes of 55 °N and above. Even in that region, however, annual mean temperatures are still higher than the average for the past several centuries.

Temperature. Between the 1880s and the early 1940s, the global mean temperature apparently increased by about 0.5 °C, and it appears to have dropped by about 0.2 to 0.3 °C since then. Both changes were greatest in the Arctic, especially over the Norwegian and Barents Seas. The sharpest decrease in temperature, about 5° C, has occured near Franz Josef Land, at 80° N 53° E, since the early 1950s. 38/

There are suggestions that opposite trends in temperature may have occurred in the southern hemisphere, possibly because cooler conditions in the northern hemisphere displaced the meteorological equator -- the intertropical convergence zone -- southward, reducing the northward transport of heat by winds and ocean currents across the geographical equator. The formation of Antarctic sea ice may

---

38/ Climate Change, Food Production, and Interstate Conflict. Working papers from a conference held at the Bellagio Study and Conference Center, Italy, June 4-8, 1975. New York, The Rockefeller Foundation, 1976. p. 3.

also have been reduced by changes in cyclonic storm tracks. Further study is needed to understand past temperature fluctuations in various parts of the southern hemisphere.

Although the average northern hemisphere temperature fluctuations have been relatively small, they have changed the length of the growing season appreciably in some regions. In the English lowland districts, for example, the average length of the growing season in different decades has varied by 10 to 20 days since 1870. It has shortened by 9 to 10 days since the warmest decades of the 1930s and 40s, owing to colder springs and, in the last year or two, colder autumns, as well. 39/

Europe, the southern part of North America, and parts of the Far East experienced a series of mild winters in the 1970s. However, most of the northern hemisphere did not share this experience, and the warm winters in these areas do not seem to have raised the annual mean temperature. They appear to have been caused by the spread of Arctic cooling to northern Canada, which has increased the temperature gradient between Canada and the warm North Atlantic waters and strengthened the atmospheric circulation patterns which have resulted in mild winters in certain areas.

Atmospheric Pressure and Circulation Patterns. Atmospheric pressures and large-scale circulation patterns have also varied considerably during the twentieth century. During the first half of the century, circulation tended to be zonal, characterized by strong

---

39/ Ibid., p. 4.

west-east movement. Since 1950, this zonal circulation has decreased in strength, and since the late 1960s there has been an increased frequency of blocking situations, in which stationary or very slow-moving weather systems impede the west-east movement. Both northern and southern hemispheres are more prone to blocking situations, resulting in periods as long as a year or two when the controlling weather sytems tend to be considerably north or south of the positions typical of the first part of the century. In mid-latitude regions, this tends to produce long dry or wet spells, with abrupt changes between the two extremes.

The frequency of westerly wind situations over the British Isles, which seems to be a useful index of global circulation patterns, has decreased in recent years in response to the increased frequency of blocking situations. The average number of days when westerlies dominate the weather situation over the British Isles has declined to levels that have not occurred during the last century. Periods with such circulation characteristics have generally been characterized by highly variable conditions of temperature and precipitation.

During the warming period of the first part of the twentieth century, rainfall generally increased in the interiors of continents in the mid-latitudes of both hemispheres, except in the lee of north-south mountain ranges and toward the east coasts. This increase was produced by the vigorous zonal atmospheric circulation, which carried increased amounts of moisture inland. Rainfall decreased in the zones of the subtropical anticyclones, where many of the Earth's

major deserts are found, but increased south of this region in the northern hemisphere, where the monsoon rains reached farther north into the Sahel -- the southern fringe of the Sahara Desert -- and were more dependable in northern India.

Since the 1940s, as large-scale atmospheric circulation patterns become more meridional -- dominated by north-south movement -- and smaller scale weather systems have transported less moisture, all these tendencies seem to have reversed. The Arctic influence has increased, and the patterns of weather systems that had become established were either interrupted by blocking situations or pushed further toward the equator. The equatorial rains did not move as far north and south, which resulted in reduced rainfall in some regions such as the Sahel and parts of India. The dominant position of the rainbelt seems to have moved farther south.

Two major results of these changes in circulation and precipitation patterns have been observed during the last decade. These are droughts resulting from monsoon failures in latitudes of 10° to 20° N and 12° to 20° S, and abrupt transitions between drought and flood situations and prevailing warm and cold conditions in many mid-latitude regions of the northern and southern hemispheres. 40/

Variations from 1000 to 1900 A. D.

The climate of the last millennium was characterized by two temperature extremes. A warm period in early medieval times was

---

40/ Ibid., p. 5, 6, 7.

centered roughly on the thirteenth century. The cold period commonly known as the Little Ice Age reached its peak around the seventeenth century. The temperature history that has been reconstructed for central England appears to be fairly representative of global temperature as far as these two broad fluctuations are concerned, and correlates fairly closely with data from California and New Zealand. However, there are some interesting differences between the English record and those of the Far East, Greenland, and some other locations that should be examined more carefully.

Ocean Current Fluctuation. Recent studies of data from the Faeroe Islands, located north of Scotland about midway between Iceland and Norway, have suggested that anomalies in sea-surface temperature played an important role in amplifying the severity of the seventeenth century cooling in that region. The Faeroe Islands data include continuous records of sea-temperature measurements from 1867 to the present, and these measurements have been extended back to about 1600 on the basis of records of cod fisheries, which are highly responsive to drops in sea temperature below 2° C. The Faeroe Islands studies indicate that the magnitude of the seventeenth century cooling was amplified in that region by changes in ocean currents which brought incursions of extremely cold polar water down from the north. This suggests that further studies of the amplification of climatic fluctuations in the North Atlantic region by variations in ocean currents flowing in and out of the Arctic region may provide a better understanding of regional variations in the magnitude of temperature

fluctuations during the Little Ice Age and other historic periods of climatic variation. 41/

Some climatic researchers have minimized the value of apparent periodicities in trying to understand climatic change. However, the climatic record of the last 100 years and beyond appears to reveal some quasi-periodicities, particularly on scales of approximately 50 and 200 years, that may be of importance in understanding recent climatic fluctuations.

Understanding Climatic Variation

So far, there is no single comprehensive theory, or even a combination of a small number of theories, that completely explains -- much less predicts -- climatic fluctuation or change. Nevertheless, there are some factors that clearly should be taken into account, either in terms of observed correlations in the past or of theoretical assumptions about what should be important. These factors include such things as: changes in the atmospheric dust content, fluctuations in solar emission, variations in the Earth's orbit and axis of rotation; changes in levels of carbon dioxide in the atmosphere; major changes in the cryosphere -- the ice mass of the Earth; changes in the character of the land surface; and quasiperiodic or anomalous ocean surface temperature patterns. Furthermore, enough is understood about the Earth/atmosphere system to recognize that man and

41/ Ibid., p. 7, 8.

his activities may affect it, and probably have already, by pushing on certain leverage points that control the heat balance of the system.

The climatic system includes large numbers of both positive and negative feedback loops that may act to amplify or damp the value or anomaly of one of the interacting climatic system components. It is often difficult to separate causes and effects. For example, the wind can drive an ocean current which alters the distribution of sea surface temperatures, influencing the atmospheric circulation which determines the strength and direction of the wind. It would be arbitrary to label one factor the cause and another the effect in such a dynamically coupled system with chains of causality that are essentially circular. In consequence, the climatic system is a highly nonlinear, interactive system that has defied a complete quantitative description (see Figure 2).

Although the system is characterized by nonlinearity, trigger mechanisms, and instabilities, there exist some negative feedback loops that tend to stabilize certain parts of the system. However, there is considerable uncertainity about which parts of the system may be essentially self-regulating and which ones may have the potential for "runaway" reactions in response to certain stimuli.

It is particularly important to consider potential human impacts on the climatic system, as the scale of human activities is rapidly increasing. The 0.5- to 10-year time scale of atmospheric behavior, which has often been neglected because it falls between the time domains that are of primary interest to most meteorologists and climatologists, appears to be of great importance in assessing human impacts on the atmosphere. 42/

42/ Ibid., p. 9.

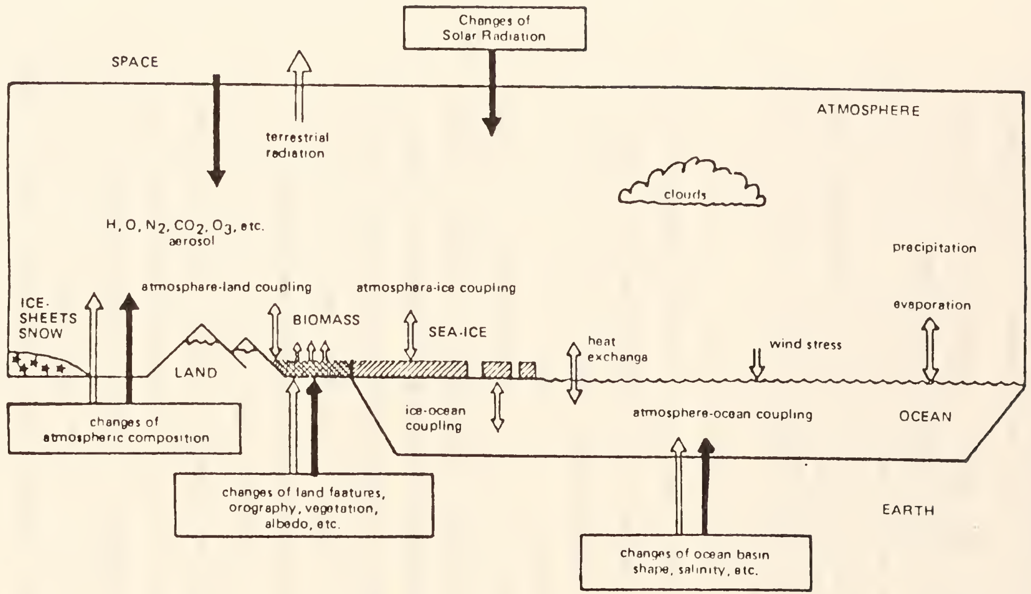


Figure 2. Schematic illustration of the components of the coupled atmosphere-ocean-ice-land surface-biota climatic system. The full arrows (➡) are examples of external mechanisms, and the open arrows (⇨) are examples of internal mechanisms of climatic change.

Source: Living With Climatic Change. Proceedings of a conference/workshop held in Toronto, Nov. 17-22, 1975. Ottawa, Science Council of Canada, 1976. p. 85.

Inferences About Future Climate: Climate System Theories

In spite of what could be characterized as a very meager understanding of the dynamics of climatic fluctuation and change, one may at least refer to the observed climatic history to draw certain empirical inferences about future climate.

Consideration of Central Tendency. Not only is the present-day climate much warmer than the average of the past several centuries, but the latter, in turn, has been much warmer (and more ice-free) than the glacial stages of the past million years. This suggests that a return of the Earth to cooler conditions is a possibility over the long run. Precisely when such a cooling could begin, and how rapidly the cooling would proceed if it begins, are by no means obvious from the record of past climates. 43/

Inferences Based on Random Transition Theory. One theory has been proposed which views the atmosphere as a "quasi-intransitive" system with two or more conditionally stable states in which the climate system can find itself at any given time, with the transition from one state to another set off by a random fluctuation of a certain amplitude. After the transition has occurred, the system will remain in that state until it is triggered into another state or perhaps back to the first state, with the pattern of the transitions occurring at random. One

43/ U.S. Federal Council for Science and Technology. Interdepartmental Committee for Atmospheric Sciences. Report of the Ad Hoc Panel on the Present Interglacial. Washington, National Science Foundation, 1974. p. 4, 5. (ICAS 18b-FY75)

implication of this theory is that, if human influences triggered a transition from one state to another, it is unlikely that the transition back to the original state could be accomplished by halting whatever human activity had caused the first transition. If transitions from very warm climates such as today's to more glacial conditions are assumed to occur at strictly random intervals of geologic time, the mean number of such transitions per unit time in the past may be used to infer the risk that the next such transition will occur within an arbitrarily specified number of years in the future. According to this random model:

(1) The probability of occurrence of a transition associated with the fundamental 100,000-year glacial-interglacial cycle is about 0.002 in the next 100 years, and about 0.02 in the next 1000 years.

(2) The probability of one or more modest transitions back to cooler conditions associated with the 2,500-year "neoglacial" cycle (to which the "Little Ice Age" presumably belongs) is about 0.08 in the next 100 years and about 0.5 in the next 1000 years.

(3) The probability of one or more transitions of smaller magnitude, with characteristic wavelengths on the order of 100 to 200 years, is about 0.1 to 0.2 in the next 10 years, about 0.6 to 0.8 in the next 100 years, and approaches 1.0 with waiting times greater than 300 years. 44/

44/ Ibid., p. 6, 7, 8.

Inferences Based on Quasi-Periodic Recurrences. The possibility remains that climatic fluctuations are -- at least in part -- quasi-periodic in nature. If future climatic changes are assumed to be dominated by the future continuation of quasi-periodic components detected in the past record (having characteristic wavelengths previously noted), the direction of future change would continue to be one of cooling for at least another decade, but will yield to a warming in later decades. It is clear that the shorter wavelength fluctuations will play a dominant role in determining the course of climate in the next 100 years; these, however, need not persist into the future with the same phases and amplitudes that have characterized them in the recent past. 45/ While a number of quasi-periodic components of long-term climatic change, with characteristic wavelengths of change, may be said to have stood out above the "noise" of climatic variations of differing wavelengths, it seems apparent that (1) these quasi-periodic components do not account for all of the systematic variability of climate, and (2) none of them is sufficiently consistent and regular to form the basis for firm predictive statements of future climate.

Clear evidence would seem to be lacking that, on a scale of 10 or even 50 years, the climatic system restores itself to some equilibrium state. By international convention, 30-year averages of climatic conditions are defined as "normals," and this definition of a 30-year period as normal by the World Meteorological Organization (WMO) has resulted in some confusion on this point. Aside

---

45/ Ibid., p. 8, 9.

from the scientific merits and the practical justification for choosing such averages as an appropriate measure to central tendency of climatic statistics, the concept of "normal" climate can be very misleading. The adoption of the 30-year "norm" was an administrative device designed to provide an international standard that would be useful to national weather services. However, it is not a scientific premise based on an assumption that 30-year averages have some rational basis as parameters of the normal state. Moreover, modern 30-year "normals" are revealed by a knowledge of conditions in the remote historical and geological past to be not at all normal but, in fact, extremely abnormal.46/

Similar semantic confusion has resulted from the tendency of some climatologists to refer to the climate of the first half of this century as "benign" for agriculture; yet almost any farmer can point to major climatic anomalies during the period. The 1930's were notorious among the northern hemisphere's grain and livestock farmers because of recurrent drought (e.g. the North American "Dust Bowl" years of the 1930's) when conditions could only be viewed as malign from the point of view of the farmers who were affected by them. But bad weather, like good, tends to strike the world unequally, for there were whole regions for which it was an excellent decade.

46/ Climate Change, Food Production, and Interstate Conflict, p. 11.

Causes of Climatic Change

There have been numerous theories concerning the mechanisms of climatic change, based on various combinations of interacting physical factors and processes.

One group of processes reponsible for climatic variation and change consists of internal mechanisms. These involve "feedback" interactions between the atmosphere and the oceans, the cryosphere, the land surface, and the biosphere. The other group of processes responsible for climatic variations consists of external mechanisms. These include all geophysical changes outside the climatic system, terrestrial, or anthropogenic in origin. Such changes are said to produce external forcing of the climatic system. It is not clear to what extent the observed variability of the climatic system originates from internal mechanisms, and to what extent from external mechanisms. It appears likely that the answer depends upon the time scale of the variability, with internal mechanisms probably important on the scale of months and decades, and external mechanisms becoming increasingly important on time scales beyond a century (see Figure 3).

Climatic Change Due to External Mechanisms.

Solar Effects: Since the sun is the basic energy source of the climatic system, it is natural to expect that changes in the sun's radiative output could affect climate. For example, changes of the distribution of solar radiation have been invoked to explain the major glacial/interglacial cycles of order 10,000 to 100,000 years. Aside from the question of variations of the sun's radiative output, variations

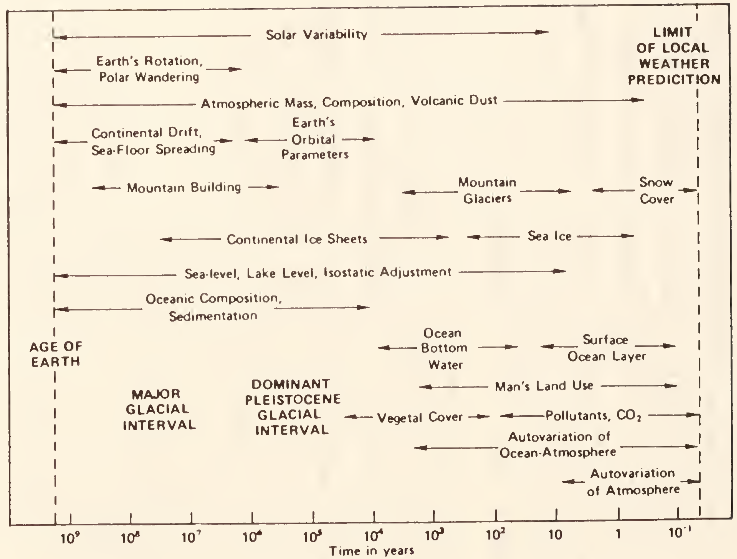


Figure 3. Characteristic climatic events and processes in the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere and possible causative factors of global climatic change.

Source: National Research Council. U.S. Committee for the Global Atmospheric Research Program. Understanding Climatic Change: A Program for Action. Washington, National Academy of Sciences, 1975. p. 22.

of the Earth's orbital parameters produce changes in the intensity and geographical pattern of the seasonal and annual radiation received at the top of the atmosphere and in the length of the radiational season in each hemisphere. These effects, which are known with considerable accuracy, have resulted in occasional variations of the seasonal insolation regime several times larger than those now experienced. These orbital parameters (eccentricity, obliquity, and precession) vary with periods averaging about 96,000 years, 41,000 years, and 21,000 years, respectively.

The possible connection between solar activity and climate remains one of considerable controversy as well as one of considerable interest. Variations in the total solar output, of all parts of the solar spectrum, and of corpuscular radiation 47/ have been suggested as possible causes of climatic variation. Variations in certain regions of the solar spectrum (particularly in the ultra-violet) and of corpuscular radiation have been detected. The difficulty in relating these phenomena to climatic change resides in the lack of continuous observations of such variations and in a lack of understanding of how such energetically weak forcing can significantly affect climate.

Sunspot activity occurs in cycles which have been well studied and are widely recognized. Three of these cycles of solar activity may be considered in relation to climatic fluctuations: the 11-year sunspot

47/ Radiation consisting of atomic ions or nuclear particles.

cycle, the double or 22-year sunspot cycle, and the longer secular cycle alternately of approximately 100, and 80 years' duration. Complete quantitative explanations for the relationship between solar cycles and climate remain to be given, though some hypotheses have been suggested in the absence of the right kind of solar observational data and physical research. But a fair argument for the solar-climatic hypothesis of climatic fluctuation can be made, resting squarely on observed, historical relationships between solar and climatic cycles. 48/

Lunar and Solar Tidal Effects: Analyses of weather data have shown relatively small but highly consistent relationships between weather and the phases of the moon. For the most part, these relationships appear to involve atmospheric tidal effects on the timing of heavy rainfall events, which are destined by other meteorological circumstances to occur anyway.

Airborne Particulate Matter and Atmospheric Turbidity: Particulate matter in the atmosphere may significantly affect climate by influencing the Earth's radiation balance (see Figure 4) and/or cloud nucleation and precipitation.

It has already been noted that the average annual global temperature has been decreasing. The question is: Could this lowering of temperature be a result of a reduction of soalr radiation reaching the surface of the Earth because of particles and aerosols that have been scattered into the atmosphere by man's activities, among them: the burning of

---

48/ Willett, Hurd C. The Sun as a Maker of Weather and Climate. Technology Review, v. 78, Jan. 1976: 49.

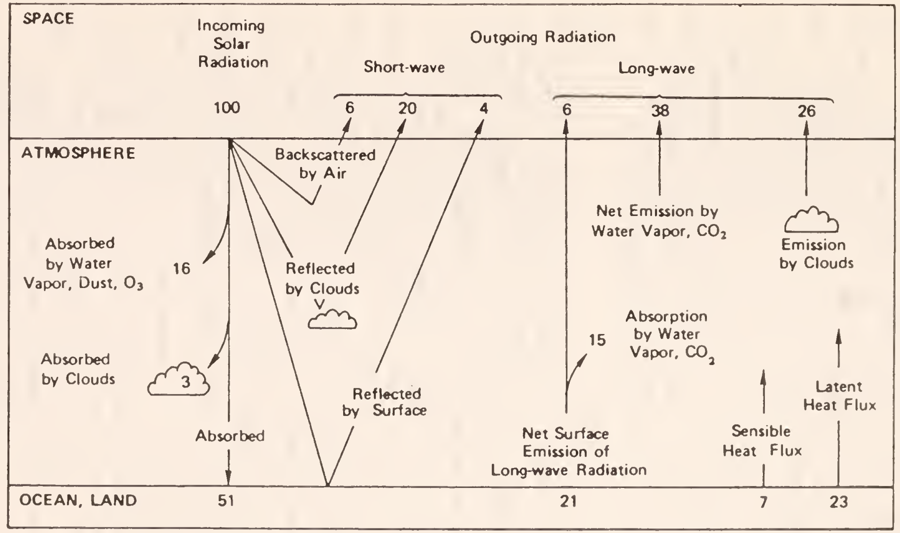


Figure 4. The mean annual radiation and heat balance of the atmosphere, relative to 100 units of incoming solar radiation, based on satellite measurements and conventional observations.

Source: National Research Council. U.S. Committee for the Global Atmospheric Research Program. Understanding Climatic Change: A Program for Action. Washington, National Academy of Sciences, 1975. p. 18.

fossil fuels, mechanized agricultural operations, over-grazing of arid lands, man-made forest fires, and the slash-and-burn method of clearing land for crops which is still widely employed in the tropics. If man started his polluting processes in the last century, and the decrease of global temperature were due to alteration in the transparency of the atmosphere, then why has a decrease in temperature not been observed earlier? It is possible that instruments are measuring a natural climatic trend that may be only somewhat augmented by the byproducts of resource development, power generation, and industrial activities.

Particle pollution contributes to changes in the thermal balance both directly and indirectly. Small particles in the atmosphere decrease the transparency of the atmosphere to solar radiation. This decrease in solar radiation may lead to somewhat lower temperatures, but these small particles also affect the outgoing long-wave radiation with possible implications for short-term temperature increases. Therefore, the net effect of a given aerosol on the radiation balance and hence on climate depends in large part upon the number, size, location of the particles in the atmosphere, and how long they remain in the atmosphere. Some aerosols, such as lead from auto exhaust, are rapidly scavenged by precipitation. Others may remain for months or years, mostly organic particles such as pesticides. While short-term aerosols such as lead may affect weather on a local scale, it is the aerosols that remain and accumulate in the atmosphere that will have long-term effects on climate.

Of course, not all aerosols in the Earth's atmosphere, or even a major proportion, are attributable to human activity. In fact, dust from volcanic eruptions, sea salt from evaporated ocean spray, smoke from lightning-caused forest fires, debris from meteors which burn up in the atmosphere, wind-blown dust or sand storms, and organic compounds emitted by vegetation are much larger sources of atmospheric particulates than human activity. Scientists at Standford University estimate that natural processes produce about 2,312 million tons of aerosols a year, which amounts to 88.5% of the total. Man and his activities account for only 296 million tons, the remaning 11.5%. At present, it is unlikely that man's activities and man-made aerosols will affect global temperature and cause significant cooling of the planet. It is important to note, however, that while aerosols from natural sources are distributed fairly evenly across the planet, man, in contrast, contributes high concentrations mostly from industrial centers. Atmospheric scientists at the National Oceanic and Atmospheric Administration's Atmospheric Physics and Chemistry Laboratory found that the 296 million tons of man-made aerosols are produced every year on only about 2.5% of the surface of the globe. Within these limited areas, man-made aerosols account for nearly 84% of the total. It follows, then, that these aerosols may be expected to have noticeable effects on local weather and urban climates.

Everyday, particles of soot, smoke, dust, and chemicals from industrial combustion and other activities are emitted into the urban

atmosphere. About 80% of the solid contaminants are small enough to remain suspended in the air, sometimes for several days. 49/ Even though these tiny particles reflect and scatter sunlight ostensibly keeping its heat from reaching the ground, they also can act as a lid to prevent the outflow of heat from the land surface to the atmosphere. In a sense, this turbidity acts as an insulator. It reduces the amount of sunlight at the top of the city in the daytime and cuts down on a source of heat. However, at night urban aerosol pollutants retard the departure of radiant energy from the heated city air, encasing the heat in the city's closed atmospheric system. Certain aerosols may undergo chemical change when they combine with water vapor in the presence of solar radiation. There are many complicated processes that can generate aerosol gas-to-particle conversions, and the particles can then grow by surface chemistry and physical accretion. 50/

Perhaps the most sensitive atmospheric processes which can be affected by air pollutants are those involved in the development of clouds and precipitation. The formation and building of clouds over a city can be influenced by the presence of pollutants acting as nuclei upon which water vapor condenses and by the hot dry air with which these aerosols are swept into the base of the clouds. The structure

---

49/ Do Cites Change the Weather? Mosaic, v. 5, summer 1974: 33, 34.

50/ Hobbs, P.V., H. Harrison, E. Robinson. Atmospheric Effects of Pollutants. Science, v. 183, Mar. 8, 1974: 910.

of clouds with temperatures below 0° C (defined as cold clouds) can be modified, and under certain conditions precipitation from them altered, by particles which are termed ice nuclei. 51/ The concentrations of natural ice nuclei in the air appear to be very low: Only about one in a billion atmospheric particles which are effective as ice nuclei at temperatures above about -15 °C have the potential for modifying the structure of clouds and the development of precipitation. If the concentration of anthropogenic ice nuclei is about 1 in 100 million airborne particles, the result may be an enhancement of precipitation; however, if the concentration is greatly in excess of 1 in 100 million, the result may be a tendency to "overseed" cold clouds and reduce precipitation. Certain steel mills have been identified as sources of ice nuclei. Also of concern is the possibility that emissions from automobiles may combine with trace chemicals in the atmosphere to produce ice nuclei. 52/

Precipitation from clouds that have temperatures above 0 °C (warm clouds) may be modified by particles which serve as cloud condensation nuclei (CCN). A source that produces comparatively low concentrations of very efficient CCN will tend to increase precipitation from warm clouds, whereas one that produces large concentrations

---

51/ National Research Council. Committee on Atmospheric Sciences. Weather and Climate Modification: Problems and Progress. Washington, National Academy of Sciences, 1973. p. 41-47.

52/ Hobbs, P.V., H. Harrison, E. Robinson. Atmospheric Effects of Pollutants, p. 910.

76-572 O - 76 - 8

of somewhat less efficient CCN might decrease precipitation. Modifications in the structure of clouds and precipitation have been observed many miles downwind of fires and pulp and paper mills. Large wood-waste burners and aluminum smelters have also been identified as major sources of CCN. 53/

La Porte, Indiana, is located east of major steel mills and other industries south of Chicago. Analysis of La Porte records revealed that, since 1925, La Porte had shown a precipitation increase of between 30 and 40 percent. Between 1951 and 1965, La Porte had 31% more precipitation, 38% more thunderstorms, and 246% more hail days than nearby weather stations in Illinois, Indiana and Michigan. 54/ Reporting on this anomaly at a national meeting of the American Meteorological Society in 1968, Stanley Changnon, a climatologist with the Illinois State Water Survey pointed out that the precipitation increase in La Porte closely followed the upward curve of iron and steel production at Chicago and Gary, Indiana. Furthermore, La Porte's runs of bad weather correlated closely with periods when Chicago's air pollution was bad. Stated simply, Changnon's theory was that if this effect did not occur by chance, then the increase in precipitation could be caused by the excess particles as well as heat and moisture produced by the industries upwind of La Porte. Pollutants from the

53/ National Research Council. Committee on Atmospheric Sciences. Weather and Climate Modification: Problems and Progress, p. 50.

54/ Lansford, Henry. We're Changing the Weather by Accident. Science Digest, v. 74, Dec. 1973: 21.

industrial sources, it seemed, were serving as nuclei to trigger precipitation, just as silver iodide crystals are used to seed clouds in deliberate efforts of weather modification.

Although Changnon's case for the reality of this phenomenon, which he called the La Porte Weather Anomaly, was convincing, it was based on circumstantial evidence. Some climatologists have attacked its validity on grounds ranging from possible errors by the weather observer to the lack of corroborating physical evidence to support the circumstantial link between Chicago's pollution and La Porte's bad weather.

However, at the 1973 annual meeting of the American Meteorological Society, Changnon and a colleague, Richard G. Semonin, also of the Illinois State Water Survey, presented the results of two years of work in a project known as the Metropolitan Meteorological Experiment (METROMEX), 55/ a five-year field investigation of urban effects on weather still being conducted in the vicinity of St. Louis, Missouri. According to Semonin, the Illinois State Water Survey undertook its part of Metromex to test the hypothesis that grew out of the La Porte Study and similar situations.

55/ METROMEX, a component of the National Science Foundation's Research Applied to National Needs (RANN) program in atmospheric science, is being conducted to investigate the inadvertent weather effects caused by an urban industrial complex. The summer of 1975 was the final effort in the field (the fifth year), to be followed by a year of data analysis and report preparation.

Researchers found that rain, thunderstorms and hail actually do maximize within cities and nearby areas, particularly in those downwind. Such locations have more storms, and they are more intense, last longer and produce more rain and hail than storms in the surrounding region. Apparently, air heated and polluted by a city does move up through the atmosphere high enough to affect clouds. This urban-modified air, according to Semonin, clearly adds to the strength of convective storms and increases the severity of precipitation. A light cumulus formation could conceivably turn into a heavy thunderstorm.

Carbon Dioxide and Water Vapor: The constituent gases of the atmosphere that are important variables affecting the distribution of temperature within the atmosphere are carbon dioxide and water vapor. Capable of absorbing important quantities of infrared radiation, they both have a role in modifying the vertical distribution of temperature in the atmosphere by controlling the flux of infrared radiation. The absorption of incoming solar radiation by these gases is so small that their concentration has no appreciable effect on the amount of incoming solar radiation reaching the Earth's surface. Carbon dioxide and water vapor are, however, opaque to major portions of the long-wave radiation emitted by the Earth's surface. The greater the content of these gases the greater the opacity of the atmosphere to infrared light and the higher its temperature must be to radiate away the necessary amount of energy to maintain a radiation balance. It

is this absorption of long-wave radiation emitted by the Earth, with the subsequent re-radiation of additional infrared radiation to the ground and consequent elevation of air temperatures near the surface that is known as the "greenhouse effect."

There is observational evidence that the combustion of fossil fuels has increased the average annual concentration of carbon dioxide by 3% from about 310 to 320 parts per million (ppm) between 1958 and 1970. Indirect evidence suggests that the carbon dioxide content of the atmosphere is currently 10% higher than at the beginning of the industrial revolution in the 19th century. An extrapolation for the concentration in the year 2000 indicates a value of 380 ppm, or almost 20% higher than the present concentration. 56/ Such an extrapolation is based on certain assumptions, a critical one being, for example, that the ocean and the biosphere will continue to absorb a large fraction of the carbon dioxide in the atmosphere. It has been estimated that half of the carbon dioxide that enters the atmosphere/ocean system is stored in solution in the ocean. Some oceanographers see increasing evidence that the upper mixing layer of the ocean, where most of the carbon dioxide is stored, is rapidly becoming saturated. This situation might result in an increase in the concentration of carbon dioxide by a factor of five or even ten, in contrast to estimates that the level of atmospheric carbon dioxide might double during the

---

56/ Anthes, Richard A., Hans A. Panofsky, John J. Cahir, and Albert Rango. The Atmosphere. Columbus, Charles E. Merrill Publishing Company, 1975. p. 204.

next century. However, this prediction is far from certain; for example, carbon dioxide absorption in the ocean could turn out to be greater than expected because of mixing between ocean layers or other factors. 57/ Also, this prediction ignores the worldwide energy shortage, which may accelerate a transition from oil and natural gas to atomic energy and renewable sources of energy thus decreasing the emission of carbon dioxide.

A change in the carbon dioxide content of the atmosphere upsets the Earth's radiation balance by holding back departing infrared light. All things being equal, if no other change were to occur in the system, the net amount of energy accumulated by the Earth would raise its surface temperature until the enhanced infrared emission re-established balance between incoming and outgoing radiation. The problem, however, is greatly complicated by the fact that other changes will certainly take place. For example, if the Earth's temperature rises, the water vapor content of the atmosphere is likely to rise. More water will have the same effect as more carbon dioxide creating positive feedback in the system and hence forcing temperatures to climb even higher. A rise in water vapor would quite likely increase the fraction of the globe covered by clouds. Such an increase would cause the amount of primary solar radiation absorbed by the Earth to fall. Some combination of increased temperature and cloudiness will balance the enhanced absorption of infrared radiation by the added carbon dioxide and water vapor.

57/ Climate Change, Food Production, and Interstate Conflict, p. 11, 12.

It should be noted that since a substantial portion of the carbon dioxide change has occurred during the last three decades, the increase in global temperatures prior to 1940 can only in part be due to changes in the concentrations of carbon dioxide and, to a much lesser extent, water vapor. If this were the only cause of climatic change, the mean global surface temperature should have risen steadily and smoothly at an increasing rate. It has not and, what is more, since 1940, temperatures have decreased in spite of further warming contributions by carbon dioxide content in that period due to man's activities. This indicates that other mechanisms are evidently required to account for part of the warming observed between 1880 and 1940, as well as for the cooling observed since 1940, and, all in all, that changes in global temperatures cannot be solely attributed to changes in the composition of the atmosphere. 58/

58/ National Research Council. Committee on Atmospheric Sciences. Weather and Climate Modification: Problems and Progress, p. 155.

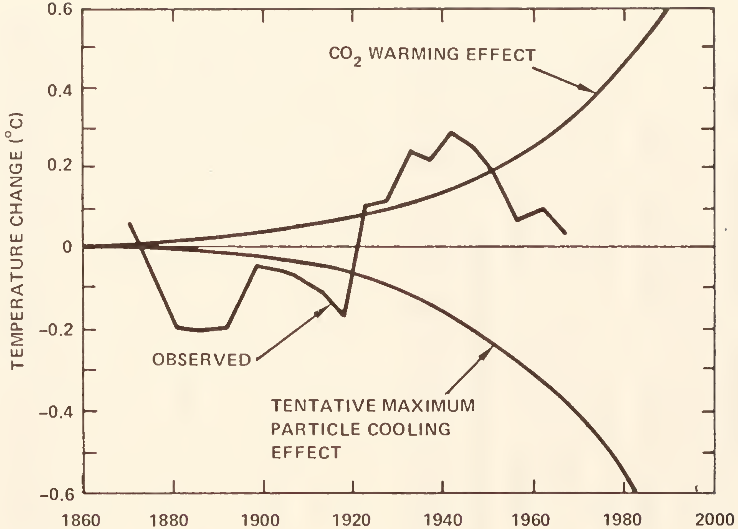


Figure 5. Trends of global mean temperature, 1860-2000 A.D. Upper smooth curve represents warming contribution by carbon dioxide growth in the atmosphere. Lower smooth curve represents probable maximum cooling contribution by particle increases. Broken curve is the observed temperature change in the Northern Hemisphere.

Source: U.S. Federal Council for Science and Technology. Interdepartmental Committee for Atmospheric Sciences. Report of the Ad Hoc Panel on the Present Interglacial. Washington, National Science Foundation, 1974. p. 15.

Ozone Depletion: Prediction that some human activities will lead to depletion of the atmospheric ozone shield have received considerable attention recently.

Ozone (O_3), a toxic, colorless, unstable molecule of oxygen absorbs quantities of harmful ultraviolet radition (UV). The average natural variation of UV intensity is 25 percent at a given point during a day. Equatorial intensities are roughly three times the polar intensities. A world-wide cycle variation of about 10 percent also occurs, apparently correlated with the eleven-year sunspot cycle. Without some UV penetration, natural vitamin D would not be formed and therefore would not confer protection against rickets.

On the other hand, too much UV has been associated with an increased incidence of skin cancer. (Among fair skinned people, there is more skin cancer in the south than in the north).

The idea that the natural density of ozone might be diminished by man's activity -- that is, certain man-made pollutants might increase the rate of destruction beyond the rate it is created -- leads to a fear of a corresponding increase in the incidence of skin cancer. In 1969, during the congressional debate over the U. S. supersonic transport, several scientists predicted that water insertions, created by the burning of jet fuel in the stratosphere, would seriously deplete stratospheric ozone. The threat from water vapor was later dimissed by most scientists, as empirical evidence demonstrated that the opposite (a slight increase in O_3 density) occurred when water vapor was injected.

Then, other substances were identified as potential O_3 destroyers. The first of these was the oxides of nitrogen, followed by compounds

containing chlorine, such as from propellants and refrigerants. Other compounds have also been suggested, such as bromine from agricultural fumigants. A number of scientists have verified to their satisfaction the destructive effects of these compounds.

Since empirical proof may not be available for a decade, due to the necessity of determining natural concentrations of the various chemicals in the stratosphere and of observing long term natural ozone density fluctuations, the scientists who believe that ozone density can be reduced by man-made pollutants, or is controlled by these same pollutants released by nature but added to by man, necessarily rely on theoretical models of the atmosphere. The best available data on chemical reaction rates are inserted into computerized atmospheric models. The results from the models vary but all predict a destructive interaction with ozone.

The Climate Impact Assessment Program (C. I. A. P.) of the Department of Transportation developed and studied a large number of atmospheric models which indicated that NOx (created by the heat of aircraft engines flying in the stratosphere) could diminish ozone. An interagency task force, I. M. O. S. (Inadvertent Modification of the Stratosphere) studied the C. I. A. P. data as well as models not included in C. I. A. P. and also concluded that there are grounds for serious concern. Study panels at the National Academy of Sciences concurred with the I. M. O. S. opinion.

In opposition are other scientists who state that all of the models predict a world wide distribution of ozone which is exactly opposite to that found in nature. They further state that the uncertainties and unknowns used in the models are so great as to reduce them to

subjective exercises. A number of others claim that such empirical evidence as is available indicate that O_3 destruction does not occur when these pollutants are inserted.

Thus, the issue of ozone depletion, brought to the forefront by the emotionally laden issue of cancer, is highly topical and controversial at both a scientific and an emotional level.

A suggested laboratory for analysis of the linkage between skin cancer and higher intensities of UV is the large metropolitan areas which have recently undergone large increases in average sunlight intensity resulting from decreases in turbidity brought about by laws requiring cleaner air. In some cases, increases in average sunlight intensity in excess of the maximum change related to a decline in ozone density might be found. 59/

While the effect of a significant build up in the concentration of chlorofluorocarbons and chlorocarbons on the chemical balance of the Earth/atmosphere system is currently a subject of concern, their impact and effect on the Earth's overall thermal energy balance must also be considered. The chlorofluorocarbons and chlorocarbons have strong infrared absorption bands, thus allowing these compounds to trap long-wave radiation emitted by the Earth and, in turn, enhance the atmospheric "greenhouse effect." This enhancement may lead to an appreciable increase in global surface and atmospheric

---

59/ The previous section on the ozone depletion issue was contributed by George Chatham, Specialist in Aeronautics and Space, Science Policy Research Division.

temperature if atmospheric concentrations of these compounds reach values of the order of 2 parts per billion (ppb). 60/

Furthermore, ozone itself is important to the Earth's climate because it absorbs some quantities of both solar and terrestrial infrared radiation, thereby affecting the energy balance of the Earth/atmosphere system that determines the Earth's temperature. Exactly how changes in the ozone concentration might affect climate are far more difficult to determine, since changes in surface temperature from variations in ozone depend on such diverse factors as whether the total amount of ozone is increased or decreased, whether the height at which the maximum amount of ozone occurs is altered, or whether the latitudinal distribution of ozone is disturbed. James Coakley of the National Center for Atmospheric Research (NCAR), Boulder, Colorado, has found that a uniform reduction in the total amount of atmospheric ozone would lead to a cooling of the Earth's surface, but that a decrease in altitude in the stratosphere where ozone has its maximum concentration can warm the surface. Similarly, an increase in total amount of ozone warms, but an increase in the altitude of maximum ozone concentration can cool the climate. If it were known that an atmospheric pollutant, such as chlorofluorocarbons, acted to reduce the amount of ozone in the atmosphere, then before one could conclude that this would lead to a global cooling, it would still also have to be known if the chlorofluorocarbons moved the altitude of maximum ozone concentration up or down. If the maximum moved up, this would

---

60/ Ramanathan, V. Greenhouse Effect Due to Chlorofluorocarbons: Climatic Implications. Science, v. 190, Oct. 3, 1975: 50, 51.

enhance the cooling effect of a decrease in ozone, but if the maximum move down, that situation would oppose the cooling attributable to the decrease in total ozone. Thus, while it is conceivable that a large change in ozone could significantly affect climate, it may be seen that the direction of any potential ozone-climatic effect is difficult to determine. 61/

Waste Heat: Another man-generated pollutant that could affect the climate is waste heat generated by combustion, automobiles, home heating, industrial processes and power generation -- all produce heat that eventually is emitted into the atmosphere. In addition to its direct effect on atmospheric temperature, in specific situations waste heat can enhance convection, the vertical motion so important in precipitation processes.

On a regional scale, thermal effects may become important by the turn of the century. However, on a global scale, climatic effects of thermal pollution today and for the near future appear to be insignificant. Some scientists, however, believe this impact may grow with increased energy production and conversion. Research meteorologist James T. Peterson of the Environmental Protection Agency states that a long-term view reveals that continued growth of energy use could lead to large-scale climatic change in 100 years or more. Of particular concern, says Peterson, are present-day nuclear power plants, which will produce about 55% more

---

61/ Schneider, Stephen H. The Genesis Strategy: Climate and Global Survival. New York, Plenum Press, 1976. p. 183.

waste heat than a fossil fuel plant for a given amount of electricity generated. 62/

On a local scale, the climatic effects of energy use and heat production are significant and well documented. Obviously, urban areas are experiencing thermal effects. The most evident feature of city climate is its excess warmth, which is commonly referred to as the "urban heat island." Cities are prodigious sources of heat. Factory smokestacks, air conditioners and heating systems of offices and homes, vehicle engines and exhausts -- all contribute waste heat to the outside atmosphere, particularly in winter. Summer temperatures in the city are 0.6°C to 1.1°C higher than in nearby rural areas; and 1.1°C to 2.2°C higher in winter. Also, the building materials of brick, asphalt, mortar, and concrete readily absorb and store more heat from the sun than the soil and vegetation of a rural area, and give it up more slowly after sundown. While rural areas are rapidly cooling after sunset, the building materials gradually release their stored heat to the urban atmosphere, tending to keep it warmer than the countryside.

Another factor that retains high temperatures and makes the atmosphere dry is the way a city disposes of its rainwater or snow. During any shower or storm the water is quickly drained from the roofs by gutters and drainpipes, and from the sidewalks and streets by gutters and storm sewers. The winter snows are removed as quickly as possible by shovels and plows, and often hauled away in trucks. These methods of removing precipitation not only take

---

62/ Peterson, James T. Energy and the Weather. Environment, v. 15, Oct. 1973: 4, 5, 8.

away sources of moisture but also remove the cooling effect of evaporation. In the country, evaporation can cool the area where the rain and melting snow stay on the surface or seep into the ground. A large fraction of the absorbed heat energy is used in evapotranspiration as vegetation transpires water vapor.

An advantage of urban heat emissions is that they decrease the likelihood of surface-based air temperature inversions (air temperature increases rather than decreases with height) and increase the height of the mixed layer near the surface. Inversions inhibit turbulent air motions which diffuse and dilute pollutants. Heat emissions at the city surface create a relative decrease in temperature with height which in turn aids the mixing and dispersion of pollutants. Observations of urban and rural temperature-height profiles have shown this effect of thermal emissions. Thus, urban pollutants emitted near ground level, such as carbon monoxide from auto exhaust, will be diffused through a greater volume of the atmosphere with a consequent reduction in concentration.

Other major features of urban climates that are related to thermal pollution include:

- A longer frost-free growing season;
- Less snowfall because snow melts while falling through the warmer urban atmosphere and less snow accumulation because snow melts on contact with warmer urban surfaces.
- Lower relative humidity;
- Decreased occurrence and density of fog because of the lower relative humidity, a feature which may be offset by more particulate matter which serves as condensation nuclei;
- A slight component of the wind direction toward the city center as a result of the horizontal temperature contrast;

- o Apparent enhancement of precipitation downwind of cities, a phenomenon partially due to increased convection (vertical motion).

Migration of Land Masses: On time scales of tens of millions of years there may have been changes in the shapes of the ocean basins and the distribution of continents as a result of sea-floor spreading and continental drift. Over geologic time, these processes could have resulted in substantial changes of global climate. Applying climatic models to the systematic reconstruction of the Earth's climatic history prior to about 10 million years ago is important if it is to be ascertained just how much of the recorded paleoclimatic variations may eventually be accounted for by such effects. In such climatic reconstructions, the oceans would be simulated along with the atmosphere, and eventually the ice masses must also be reproduced. Accompanying the migration of the land masses are the processes of mountain building, epeirogeny, isostatic adjustment, and sea-level changes, all of which must also be taken into account.

Other Possible Causes: Additional effects of climate may follow from alterations to the energy and hydrological cycles due, for instance, to land use practices, to irrigation, and to alterations of natural waterways. Yet another external cause of climatic variation is the changes in the composition of the atmosphere resulting from the natural chemical evolution of the nitrogen, oxygen, and carbon dioxide content in response to geological and biological processes, as well as from the gaseous effluents of volcanic eruptions.

Climatic Change Due to Internal Mechanisms. In addition to being influenced by external forcing mechanisms, climate is also

influenced by internal mechanisms within the atmosphere/ocean/land/cryosphere/biosphere components of the climatic system. In this system, the atmosphere by and large has a shorter reaction time scale than the other components. It is thus conceivable that climate changes on time scales shorter than the characteristic time of the slower varying components of the climatic system could be a result of internal changes, or "self-fluctuations," of the system. 63/

The internal climatic system consists of numerous interactive processes that adjust simultaneously with changes of climatic state. If an external parameter were to be changed by a specific factor, the response of the climatic system to that change could be modified by the actions of these internal processes which act as "feedbacks" on the climatic system and modify its evolution.

There are some feedbacks which are stabilizing, and some which are destabilizing (i.e., they may intensify deviations of weather from its long term norm). In this way destablilizing feedbacks may amplify the effects of external forcing functions on the climatic system. Some of the more prominent feedback effects operating among the shorter-period processes of climatic change are identified below.

Water Vapor-Greenhouse Feedback: The atmosphere is believed to maintain a somewhat uniform distribution of relative humidity over a large range of lower atmosphere temperatures,

---

63/ Living With Climatic Change. Proceedings of a conference/workshop held in Toronto Nov. 17-22, 1975. Ottawa, Science Council of Canada, 1976. p. 88.

even though the absolute humidity varies strongly with temperature. 64/ The absolute humidity determines, to a large extent, the opacity of the lower atmosphere to infrared radiation. Increased temperatures at constant relative humidity lead to increased absorption of long-wave radiation by water vapor, which gives rise to further increases in the temperature of the lower atmosphere. In this manner, the external forcing that may have led to a temperature increase initially is amplified by this positive feedback process.

Albedo: The albedo is a numerical indication of the percentage of the incoming solar radiation that is reflected by the land, ocean, and atmosphere back into space. Another important manner for altering the Earth's heat budget, albedo can be changed by the process of urbanization, agricultural activities, changes in the character of the land surface, and by increasing or decreasing cloudiness.

Most clouds are both excellent absorbers of infrared radiation and reflectors of solar radiation. Therefore, clouds are a major factor in determining the Earth's energy balance. An increase in clouds could warm surface temperatures by tending to reduce the

---

64/ The term humidity simply refers to the degree to which water vapor is present in the air. For any specified temperature, there is a definite limit to the quantity of moisture that can be held by the air. This limit is known as the saturation point. The proportion of water vapor present relative to the maximum quantity is the relative humidity, expressed as a percentage. While relative humidity is a statement only of the relative quantity of water vapor with respect to a saturation quantity, the actual quantity of moisture present is denoted by absolute humidity, defined as the weight of water vapor contained in a given volume of air.

flux of long-wave (i.e., infrared) radiation to space; or cool surface temperatures by reflecting incoming solar radiation back to space. The net effect of increased cloudiness is to either warm or cool the surface, depending on cloud type, latitude and season. 65/ The effect of cloud condensation nuclei (CCN) on the formation of fog and clouds could alter the albedo of a region if the fog or clouds were sufficiently persistent or extensive. P.V. Hobbs and H. Harrison, both professors of atmospheric science at the University of Washington, and E. Robinson of Washington State University's Air Pollution Research Unit contend that perhaps the most sensitive atmospheric processes which can be affected by air pollutants are those involved in the development of clouds and precipitation. Apart from effects on precipitation processes, inadvertent modification of the microstructure and distribution of clouds, with attendant consequences for radiative properties, could have profound effects on atmospheric temperature distributions and global climate. 66/ Whether a variation in terrain on temperature or other factors would have a negative or positive feedback interaction with clouds is a major question in climate theory that will be answered by extensive analyses of observations and model studies.

The high reflectivity of snow and ice, as compared to water or land surfaces, provides positive feedback if the average year-round temperature decreases and the extent of ice and snow coverage

---

65/ Living With Climatic Change, p. 89.

66/ Hobbs, P.V., H. Harrision, and E. Robinson. Atmospheric Effects of Pollutants, p. 910, 911.

increases and reflects more of the incoming sunlight back to space. The result is to lower the rate of heating still more, particularly in the regions closest to the poles. Columbia University scientists observed from a study of satellite photo-maps that snow and ice-pack cover were more extensive and of longer duration in the early 1970s than in previous years. The result, they reported, was to increase the Earth's albedo, reflect more sunlight back into space, and reduce the planet's heat balance. It was pointed out that normally vegetated ground reflects about 15% to 20% of sunlight and a calm ocean reflects 5% to 10%, while snow-covered grassland or pack ice reflects about 80%. They also found that snow and ice covered twice as much ground in October 1972 as in October 1968 and correlated that situation with a drop in global air temperatures. They warned that the potential for fast changes of climate evidently does exist and should be kept in mind. 67/

There's yet another contributor to the planet's albedo: airborne particles, particularly the extremely fine dust particles that have been carried too high in the atmosphere to be scavenged and washed out by precipitation processes. Many of these particles remain aloft

---

67/ Kukla, George J., and Helena J. Kukla. Increased Surface Albedo in the Northern Hemisphere. Science, v. 183, Feb. 22, 1974: 709, 713, 714.

A growing fraction of current evidence seems to suggest, however, that this has not been the case in North America. Analysis of satellite data for the last decade has led scientists with the National Environmental Satellite Service to conclude that North American snow cover showed no significant change during the entire period of record. Rather, the North American total winter snow cover appears to be remarkably similar year to year. Eurasian snow cover on the other hand was reported to be much more variable.

for months or years. Dust of various kinds may initiate short-term cooling trends with characteristic time spans of decades or centuries. This depends on the optical properties of the particles, which in turn depend on particle composition and size distribution. Furthermore, particles radiate in the infrared, and therefore can alter the outgoing long-wave radiation.

Densely populated regions tend to have higher albedos than do forests or cultivated soils. The deserts of the world have a higher albedo than, for example. grass-covered fields. Urbanization, agriculture, transportation networks -- all act to alter the surface albedo. While local changes in albedo have been determined, however, the overall integrated global variation is still unknown. Even local net effects of surface changes may not be fully understood, since changes in the nature of a surface are generally accompanied by changes in surface roughness. Surface roughness alterations can affect the manner and rate of heat and momentum exchanges with the atmosphere through modification of small-scale turbulent processes.[68]

A factor such as roughness of the ocean should not be overlooked in ocean/atmosphere exchange mechanisms. Ocean-surface pollution may also figure in the alteration of the albedo as well as the sea-surface characteristics: an oil slick forming a surface film on the sea, for example.

Quasi-Periodic or Anomalous Ocean Surface Temperature Patterns: Climatically significant sea surface temperature anomalies

---

68/ National Research Council. Committee on Atmospheric Sciences. Weather and Climate Modification: Problems and Progress, p. 156.

tend to occur as large, spatially coherent patches or regions of the order of 1000 km or more across and a million square kilometers or larger in area. Here sea surface temperatures depart, appreciably and systematically, from their long-term average values for periods of weeks, seasons, and years. These anomalies are among the most frequently postulated factors influencing the behavior of the atmosphere, and they represent changes large enough to have significant effects on climate. Indeed, many oceanographers believe that the oceans may be the best place to look for indications of shifts in climate, because they change much more slowly than the atmosphere and are less affected by seasonal fluctuations that tend to mask climatic changes. 69/

Ocean Salinity Variations: Significant climatic changes could be introduced by widespread salinity variations, as caused, for example, by the melting of ice. Decreases, for instance, in salinity in the North Atlantic or the Arctic Ocean could lead to increased sea ice formation.

69/ Hammond, Allen L. Long-Range Weather Forecasting: Sea Temperature Anomalies. Science, v. 184, June 7, 1974: 1064, 1065.

Table 1: POSSIBLE CAUSAL FACTORS IN FUTURE CLIMATIC CHANGE TO THE YEAR 2000 A.D.

ORIGIN	FACTOR	CONFIDENCE* THAT FACTOR WILL CHANGE APPRECIABLY	CONFIDENCE* THAT A CHANGE IN FACTOR WOULD APPRECIABLY AFFECT CLIMATE	ESTIMATED PRINCIPAL CLIMATIC EFFECT(S) #	TIME SCALE(S) OF CLIMATIC VARIATION INVOLVED
SOLAR	1. Total solar output	Low	High	Warming-cooling (not clear	Months & longer
	2. Ultraviolet & other variations	High	Low-moderate		Days & longer
LUNAR/SOLAR	3. Tidal perturbations	High	Moderate	Rainfall/cloudiness changes (1-10%)	Two weeks & longer
VOLCANIC	4. Stratospheric particle injections	High	Moderate-high	Cooling (0.1-1°C)	Years & longer
ANTHROPOGENIC	5. Carbon dioxide increase	High	Moderate-high	Warming (1°C**)	Trend
	6. Particle increase	Moderate	Low-moderate	Warming-cooling	Days & longer
	7. Chlorofluorocarbon (CFC) increase	Moderate@	Moderate	Warming (0.1°C**	Temporary trend
	8. Ozone depletion by CFC, NO_x, etc.	Moderate@	Moderate	Ultraviolet radiation increase (10%**)	Temporary trend
	9. Thermal pollution	High	High (local effects)	Warming; local clouds/storms	Trend
	10. Land use changes	Moderate	Moderate (regional effects)	Temperature/precipitation changes	Decades & longer
OCEANS	11. Sea surface temperature variations	High	Moderate-high (regional effects)	Temperature/precipitation changes	Months & longer
CRYOSPHERE	12. Sea ice/snow cover variations	High	Moderate (regional effects)	Temperature/precipitation changes	Months & longer
	13. Polar ice sheet surges	Low	High	Rise in sea level, possible glaciation	Years & longer
BIOTA	14. Vegetation changes	Moderate	Moderate (regional effects)	Temperature/precipitation changes	Years & longer

*Confidence based on intuitive judgment of many atmospheric scientists, considering state-of-the-art knowledge.
#All numberical values are order-of-magnitude estimates for earth as a whole; regional effects may differ substantially.
@Assumes that controls on CFC and other emissions are put into effect by 1980 A.D.
**Cumulative effect by year 2000 A.D.

Source: Draft report of North American Phase I Conference on "Living with Climatic Change", Toronto. November 1975.

Table 2: CHRONIC LOW-LEVEL POLLUTANTS

POLLUTANT AND SOURCE	OBSERVED TREND	POTENTIAL ATMOSPHERIC EFFECT	STATUS of ASSESSMENT CAPABILITY	TIME SCALE of IMPORTANCE
Carbon Dioxide (CO_2) from combustion of fossil fuels.	Up more than 20% in last 100 years.	Increased global temperatures leading to melting of polar ice caps, sea level increase, perturbations of marine biology.	Numerical model assessments of the global average effect on temperature differ by about a factor of 2; consequence chains need more study.	Thorough assessment needed in the next five years - may be a problem over next 50 years.
Fluorocarbons (e.g., freon) from aerosol cans, refrigeration systems, etc. Nitrogen oxides from high flying aircraft (and perhaps from fertilizers).	Fluorocarbons are now detectable throughout the atmosphere. Nitrogen oxides are a natural component. Stratospheric measurement program being established to determine levels and trends.	Reductions of the global stratospheric ozone layer and perturbation of the atmosphere's radiation balance. Analysis of current trend in ozone is not yet definitive due to natural variability.	Numerical models are capable of assessing the order of magnitude of the various effects, with uncertainties related to lack of basic information on reactants, reactions, and reaction rates; the natural chlorine and nitrogen balance; and the limitations in simulating simultaneously global chemistry, transport, seasonal, and diurnal processes.	Initial assessment in progress by National Academy of Sciences action probably needed within several years.
Krypton-85 from nuclear fuel reprocessing and power plants.	Building up proportionally with nuclear power generation.	Modification of the atmosphere's electric field, which may cause modification of the hydrologic cycle.	Not adequate.	Thorough assessment needed, may be a problem over next 100 years with growth of nuclear power industry.
Sulfur compounds from fossil fuel combustion.	Not well-established, but concentrations may already be too high on occasion.	May affect regional precipitation chemistry and acidity on regional to sub-continental scale.	Sulfur balance not well understood.	May presently be a problem which would be aggrevated by further coal burning.
Dust from combustion, slash/burn agriculture, and improper land conservation.	Not well-established because of evolution of sources and particles sizes with controls.	Initial response is temperature change (sign dependent on location and source type), precipitation modification. Problem mainly on sub-continental, but possibly up to global scale.	Theoretical capability is improving, but inadequate knowledge of both trends and consequences exists.	Further evaluation needed as improved data available.
Heat and water releases to the atmosphere from the energy generation process (thermal pollution, cooling towers, etc.)	Increasing with energy generation.	Temperature and precipitation modification on local and regional scale.	Models of atmospheric boundary layer are being developed.	Evaluation needed in regions of concentrated energy generation (e.g., energy parks, etc.)
Oceanic oil slicks from tanker cleaning, etc.	Not known.	By changing the reflectivity and evaporation characteristics of large oceanic areas, the earth's energy balance might be perturbed in an unknown way.	Further research needed.	Assessment needed as capability for evaluation improves.

The author is happy to acknowledge permission of the following organizations to reprint some figures and tables appearing in certain of their publications:

1. The Interdepartmental Committee for Atmospheric Sciences; Federal Council for Science and Technology (Figure 5)

2. American Meteorological Society (Figure 2, Table 1)

3. United States Committee for the Global Atmospheric Research Program; National Research Council; National Academy of Sciences (Figure 3, 4)

appreciable, can only be properly assessed when the natural forces at play are understood. 70/

Numerical Models

Large-scale numerical models of the atmosphere have the potential for treating the various interactive properties of this complex system in a way that they cannot be treated term by term. The models incorporate as much physical insight as possible into an algorithm -- a set of instructions -- and use the computations to show what these interactions and nonlinearities will produce. This simulation is generally only approximate in form, necessitated by a limited ability both to observe the system and to compute its behavior. The problem of modeling climate is best approached by constructing a hierarchy of models of varying complexity, each model suited to the physical processes dominant on a particular time or space scale. These would include, but not necessarily be limited to: statistical-dynamical models; three-dimensional explicit dynamical models (general circulation models); and thermodynamic models. 71/

It is possible to gain some physical insights with such models by considering relatively simplified systems, but to verify the validity of these insights, it is probably necessary to test them in the complex system. Since it is not possible to run climate experiments in

---

70/ Kellogg, W. W. and S. H. Schneider. Climate Stabilization: For Better or for Worse. Science, v. 186, Dec. 27, 1974: 1163.

71/ Living With Climatic Change. Proceedings of a conference/workshop held in Toronto, Nov. 17-22, 1975. Ottawa, Science Council of Canada, 1976. p. 94, 95.

the real atmosphere, the next best thing is to run them on a model that to some extent approaches the compexity of the real atmosphere.

However, even the most sophisticated models that have been developed fall far short of matching the complexity of the atmosphere itself. For example, no model of atmospheric/oceanic/cryospheric behavior has been developed that deals adequately with the problem of clouds in the atmosphere. Clouds are either held fixed in space or time, or are computed very crudely from a few parameters such as humidity. But when a very basic element of the system such as the heat budget is considered, it is clear that clouds are tremendously important, not only in transferring and releasing latent heat, but also in radiative processes. Thus present models have very substantial limitations. 72/

Predictive models can be divided into two categories. One class of models is used for short-range weather prediction. With these models, empirical adjustments are used to get the best possible predictions. Sophisticated modeling of processes is secondary to good prediction; if an approximation improves the accuracy of the prediction, then it is used. Such models are not really dependable beyond two or three days because they deviate from actual weather patterns. A basic problem in current research with such models is to extend this limit.

72/ Climate Change, Food Production, and Interstate Conflict. Working papers from a conference held at the Bellagio Study and Conference Center, Italy, June 4-8, 1975. New York, The Rockefeller Foundation, 1976. p. 16.

For climate prediction models, it is necessary to be extremely careful in dealing with physical processes, so that meaningful simulation beyond the limits of the short-range forecast can be made. The purpose of climate simulation or prediction is to simulate normal or average conditions rather than detailed day-to-day changes. Present models have not yet achieved a high degree of trustworthiness in terms of the sophistication and realism of their treatment of physical processes, but progress is being made.

For example, cumulus and mesoscale convection, the principal process by which moisture and energy are transported upward in the atmosphere, are handled in current models by parameterization -- that is, an approximation is used to specify the average effects of convection in the system. Therefore any result obtained with the model that relates closely to convection must be regarded as based on approximations rather than on precise details of atmospheric behavior, such as what happens to each individual cloud. Even though the answer that is obtained looks reasonable and may even be correct, the results cannot be regarded as reliable proof of the correctness of the hypothesis being tested. 73/

In spite of the substantial limitations on the present capabilities of atmospheric models, favorable results from modeling work over the past three or four years indicate that good climatological models may be developed during the next 10 or15 years.

In the meantime, although present models cannot predict the weather more than a few days in advance, it is possible that they

---

73/ Living With Climatic Change, p. 95, 96.

might be used to make cruder forecasts, perhaps of average conditions rather than specific details of the weather, a week, two weeks, or a month in advance. This possibility is being investigated.

Thus two points emerge: good, sophisticated climate models are probably at least a decade in the future; and the potential usefulness of present models for predicting certain limited aspects of climate could be explored.

Statistical and Empirical Approaches

Although numerical modeling appears to offer the ultimate long-term solution to climate prediction, statistical and empirical studies of past and present climatic fluctuations and their relationships to various features of the geophysical system may yield useful results much sooner in terms of prediction of certain features of climate on different time scales. Short-range forecasting deals with the deterministic prediction of individual weather systems, while long-range forecasting and climate prediction must deal with systems not yet born. At present, forecasts beyond a week are made using statistical information in some form.

Much long-range prediction utilizes the concept of persistent recurrence of anomalous atmospheric patterns within a given month or season and sometimes even within successive years. Persistent recurrence refers to a tendency for similar atmospheric patterns to recur after being temporarily interrupted one or more times. It is believed to arise from physical influences which tend to restore and maintain certain anomalous states. There is no general agreement

as to what these physical influences are. Suggested mechanisms include variations in solar activity, varying surface conditions (e. g., sea surface temperature anomalies, snow and ice cover, characteristics of land surfaces), and internal atmospheric phenomena.

Methods of prediction vary according to the time scale of the phenomena being studied. On the medium time range (up to one week) numerical predictions are used in conjunction with a variety of subjective and objective statistical techniques. In a number of countries, detailed predictive statements based on numerical methods are able to provide four to five forecasts. As numerical prediction models improve, . the time range of detailed weather prediction can presumably be extended.

At ranges up to a month, a variety of statistical techniques is used. Trends, periodicities, or singularities are sought with the help of maps, graphs, harmonic analysis, or spectrum analysis. For the most part, such techniques are studies in time-series -- an established form of long-range forecasting. 74/

Much empirical research has been concerned with teleconnections -- time-dependent correlations between large-scale climatic anomalies such as those of 1972, when a major drought in the Soviet

---

74/ Ibid., p. 92.
Harmonic analysis allows one to find a set of periodic functions which when multiplied by the proper coefficients can be summed to give a non-periodic function, e. g., an observed climatic record. Spectrum analysis is applied when a phenomenon may be considered as a set of periodic components, each contributing to the final output -- e. g., a climatic trend -- but at different intensities, frequencies, and wavelengths. Usually, only discrete sets of frequencies are involved.

Union occurred simultaneously with widespread failure of the Indian monsoon and the peak of the Sahelian drought. An improved understanding of space and time correlations between such anomalies is highly relevant to understanding climatic behavior on the scale of 0.5 to 10 years. There are strong indications that such anomalies are not distributed randomly, but have interrelationships that can be discerned by rigorous analysis of existing data. For example, time-averaged maps may be studied synoptically, occasionaly with the help of harmonic analysis. Energy budgets are occasionally employed. Indices reflecting the strength of the temperate westerlies or subtropical easterlies are also considered. Regional and temporal variations in persistence, combined with studies of teleconnections, could be employed to arrive at predictions for varying time intervals up to seasons and years.

Interactions between anomalous ocean and continent surface conditions, and the overlying atmosphere, have been given increasing weight in long-range forecasting. The philosophy behind this approach is that the ocean and cryosphere provide a memory, so to speak, for the atmosphere, thereby inducing quasi-periodic patterns of recurrence in the behavior of the atmosphere or, in a manner of speaking, restoring it from time to time to a preferred state of abnormality. An important research strategy in current studies of climate is to try to understand the complex coupling that exists between the atmospheric, oceanic, and cryospheric systems.

Weather forecasters seeking to utilize solar-weather relationships are attempting to prove, and improve, their methods with

the help of new indices of corpuscular or ultraviolet enhancement, indices of geomagnetic activity, and especially radiation measurements that are planned to be made by satellite. Here again, with a wide gap between theory and practice and a lack of adequate physical understanding, relationships are investigated by statistical analysis.

Analogue methods of long-range prediction attempt to discover a past situation in which conditions correspond as closely as possible to present conditions. Several meteorological and oceanographic elements maybe examined in the process of finding the "best analogue." Attempts are sometimes made to use the phases of the solar cycle as one of the criteria for analogue selection. Procedures for selecting analogues may be either objective or subjective.

Regional centers of activity that interact with other areas geographically far removed from them appear to be of interest. For example, both the onset and the end of the Sahelian drought teleconnected with changes in atmospheric patterns over western Europe. During the U.S. drought of the 1930's, a huge upper-level anticyclone that dominated the central United States teleconnected with similar anticyclones over the North Atlantic and Pacific Oceans. 75/

At present, numerical models are being tested to determine the primary mechanisms in the atmosphere which account for its characteristic time and space scales and also for the variability of the atmosphere on each of these scales. Now that large-scale characteristics of the atmosphere may be reasonably simulated in the short

---

75/ Climate Change, Food Production, and Interstate Conflict, p. 18, 19.

term, detailed results are being sought. These details require more exact knowledge of such physical processes as the evolution of cloud systems, exchanges of momentum and water vapor, internal turbulent exchanges, radiation transfers, and, in fact, the entire gamut of meteorological processes. It is possible that some of these processes can be approximated or even omitted. If only for this reason, the statistical/empirical approach should be pursued. It appears likely that empirical knowledge will still be necessary to make optimum practical use of any physically based long-range forecasting model from the standpoint of verification, calibration, and the offering of clues for further investigation.

****

CHAPTER VIII

FEDERAL PROGRAMS

by

John R. Justus
Analyst in Earth Science
Science Policy Research Division

****

FEDERAL PROGRAMS

The tables in this section categorize pertinent Federal and federally sponsored projects, on-going and proposed, according to the function they perform, the objective they serve, and the agency in which the responsibility for program direction resides.76/ Each program or project is assigned a code number according to the following scheme. The first letter indicates the agency which supports the project: Energy Research and Development Administration = "C"; Department of Defense = "D"; Interior = "I"; Agriculture = "A"; Commerce = "N"; Transportation = "T"; National Science Foundation = "S"; Environmental Protection = "E"; National Aeronautics and Space Administration = "M"; Federal Energy Administration = "F". The numbers following the agency designator specify a project of that agency. A letter "P" following the number indicates the project or program is proposed and not funded at present.

76/ Information on programs in progress and tables provided by the Office of Environmental Monitoring and Prediction, National Oceanic and Atmospheric Administration, April 1976.

Table 3

SURVEY BY FUNCTION OF ONGOING AND PROPOSED (P) FEDERAL PROGRAMS

		AGENCY						DOD DOI EPA FEA
		ERDA	DOA	DOC	DOT	NASA	NSF	
MONITORING	Extraterrestrial			N10,N11, N13		M6	S29P,S40	
	Upper Atmosphere	C2		N20P,N34P, N39P	T1	M2-M5	S40	
	Troposphere	C1,C3, C4	A1-A3	N7P,N12, N15,N16, N19,N33, N35P,N37P, N38P	T2		S30P,S37P, S39P,S40, S42,S43	
	Cryosphere			N17			S2,S3,S11, S5-S8,S23, S14-S17, S19-S21	
	Hydrosphere			N7P,N9P, N21-N23			S2,S30P, S42-S46	
	Other (1)				T3		S4	
RESEARCH: Descriptions	Paleoclimate			N40			S1,S7-S14, S16,S18-S24, S32P,S33P,S44	
	Recent			N3P,N8P, N9P,N10- N16,N21, N25-N33, N40			S1,S24-S26, S31P,S32P, S34P-S36P, S38P,S40, S42-S45	
	Prediction			N25-N28, N32,N39P		M1	S1,S24 S31P,S44	D1
RESEARCH: Assessments of factors influencing climate	Extraterrestrial						S1	
	Anthropogenic			N20P,N36P, N38P			S1,S25,S26, S32P,S37P	
	Other (2)			N17,N19		M1	S1-S3,S5,S6, S24,S25,S27, S28,S44	

(1) Lithosphere, Biosphere
(2) Troposheric, Stratospheric, Cryospheric, Hydrospheric

Table 3

SURVEY BY FUNCTION OF ONGOING AND PROPOSED (P) FEDERAL PROGRAMS

(cont'd)

AGENCY

		ERDA	DOA	DOC	DOT	NASA	NSF	DOD DOI EPA FEA
Assessment of Climate Change Upon:	Agriculture			N2,N4P, N5P			S41	
	Energy							
	Environment						S32P, S41	
	Fisheries			N24				
	Water Resources			N6P, N7P			S37P	
	Other (3)						S37P	
Services	Agriculture		A2,A3	N1,N2, N4P, N5P				
	Energy							
	Environment	C2,C3						
	Fisheries							
	Water Resources		A1	N8P				
	Other (4)	C1,C3,C4			T4			

(3) Land Use, Transportation, etc.
(4) Urban Regional Planning, Transportation, Air Quality, etc.

AGENCY	PROGRAM CODE	PROGRAM TITLE
ERDA	C1	Radioactivity and Trace Elements in Surface Air
	C2	Radionuclides in Stratospheric Air
	C3	Global Distribution and Inventory of Sr-90, Other Radionuclides, and Trace Elements
	C4	Base Line Radioactivity and Chemical Pollutants Measurements
DOA	A1	Barometer Watersheds Program
	A2	Agricultural Climatology
	A3	Fire Weather Measurements
DOC	N1	Agricultural Weather Support Service
	N2	Environmental Study Service Center (ESSC)
	N3P	Solar Radiation Network
	N4P	World Agricultural Weather Watch
	N5P	Environmental Study Service Center
	N6P	Establishment of National Hydro-Climatological Network
	N7P	Climatic and Hydrologic Benchmark Basins
	N8P	Coordinated Precipitation, Runoff and Water-Loss Maps for the United States
	N9P	Hydrometeorological Data for Mountainous and Remote Areas
	N10	Studies of Global Distribution of Radiative Heating Using Satellite Radiometry
	N11	Earth Radiation Budget (ERB) Experiments for Nimbus F and G
	N12	Large-Scale Circulations Over the Tropics and their Interactions with Temperate-Latitude Circulations
	N13	A Satellite System for Continuous Measurement of the Global Radiative Heating
	N14	Meteorological Satellite Laboratory (MSL) Climatological Unit
	N15	Long-Term Monitoring of the Tropical Circulations
	N16	Long-Term Monitoring of the Radiative Energy Budget and Sea-Surface Temperature for Critical Ocean Areas
	N17	Heat Budget of the Polar Regions and the General Circulation
	N18	Models of the Climatic Effects of Variations in the Earth-Atmosphere Radiative Heating
	N19	Particulate Loading of the Atmosphere and the Radiation Budget
	N20P	Development of a Satellite Stratospheric Monitoring Program
	N21	NOAA Data Buoy Office (NDBO)
	N22	National Oceanographic Instrumentation Center (NOIC)
	N23	Engineering Development Laboratory (EDL)
	N24	Studies of Bio-Environmental Interactions
	N25	The Global Circulation and its Regional Components
	N26	Ocean-Atmosphere Interaction
	N27	The Upper Atmosphere

AGENCY	PROGRAM CODE	PROGRAM TITLE
DOC (Cont.)	N28	Global Modeling
	N29	Phenomenological Studies
	N30	The World Ocean
	N31	Regional Flows - Tracer Studies, Equatorial Dynamics, Current Systems
	N32	Observational Studies
	N33	Air Quality Observations and Analysis
	N34P	Radiation Climatology Monitoring from the Stratosphere
	N35P	Monitoring Climatologically Important Aerosol Parameters
	N36P	Mathematical Modeling of Climatic Effects of Atmospheric Aerosols
	N37P	Solar Radiation Research
	N38P	Regional Transport
	N39P	Stratospheric Research
	N40	Climatic Variation
DOD	D1	DOD/ARPA Climate Dynamics Program
DOT	T1	Monitor Stratosphere (WMO/NOAA/NASA/AEC)
	T2	Monitor Troposphere (WMO/NOAA/NASA)
	T3	Monitor Biosphere (WHO/USDA/HEW)
	T4	Air Quality Standard (EPA)
NASA	M1	Stratospheric/Mesospheric Models of Minor Constituents
	M2	Survey of Stratospheric Trace Constituents
	M3	Balloon and Lidar Measurements of Concentrations of Atmospheric Constituents
	M4	Rocket Measurements of Mesospheric Constituents
	M5	Aircraft Measurements of Airborne Particles and Gaseous Pollutants
	M6	Laboratory Studies of Interactions of Pollutants and Atmospheric Constituents
NSF	S1	NCAR Climate Project
	S2	Polar Meteorology and Oceanography
	S3	Polar Glaciology and Remote Sensing
	S4	Earth Sciences
	S5	Greenland Ice Sheet Project (GISP)
	S6	AIDJEX - Dynamics and Thermodynamics of Artic Sea Ice
	S7	Glaciology and Glacial History in Antarctic Peninsula
	S8	Study of Peruvian Ice Cap
	S9	Dust Concentrations in Ice Cores Compared with Climate
	S10	Gas and Particle Extraction From Ice for Dating
	S11	Ice Drilling on Ross Ice Shelf Antarctic (Ross Ice Shelf Project)
	S12	Late Cenozoic Glacial History of Antarctic
	S13	Circum-Antarctic Paleoclimate from Tree-Ring Analysis

AGENCY	PROGRAM CODE	PROGRAM TITLE
NSF (cont.)	S14	Glacio-Climatology of the Baffin Bay Region
	S15	Coordination of Ice Core Drilling
	S16	Ice Core Drilling, Ice Core Analysis and Geophysical Investigations in Greenland
	S17	The Physical and Chemical Analysis of Polar Ice Cores and Geophysical Investigations
	S18	Geochemical and Isotope Bore Hole Studies as Part of Polar Ice-Drilling Projects
	S19	Studies of Glaciers in the South Shetland Islands
	S20	Glaciology and Glacial History of James Ross, Deception, King George, and Livingston Islands
	S21	Study of the Quelccaya Ice Cap, Peru: A Possible Cold, Tropical Glacier
	S22	Dust Concentrations in Byrd Core Compared with Climate Over the Last 100,000 Years
	S23	Ice Core Drilling, Ice Core Analysis and Geophysical Investigations in Greenland
	S24	Global Climatology
	S25	Local and Regional Climatology
	S26	Inadvertant Weather Modification
	S27	Submarine Geology and Geophysics and Physical and Chemical Oceanography
	S28	Geochemistry
	S29P	Astronomical and Space Techniques for Research on the Atmosphere
	S30P	Abundance of Carbon Dioxide in the Atmosphere and Its Exchange with the Oceans
	S31P	Theory of the Global Macroclimate
	S32P	Interdisciplinary Research Program in Climatology
	S33P	Densitometric Analysis of Annual Rings of Trees: A New Paleoclimatic Tool
	S34P	Ice, Water, and Heat Balance of the McCall Glacier, Brooks Range, Alaska
	S35P	Doctoral Dissertation Research in Meteorology (Climate Statistics for Rocky Mountain States)
	S36P	Some Characteristics of the Rainfall Regime at Douala, Cameroun
	S37P	Climatic Changes Through Urbanization
	S38P	External and Internal Synoptic-Dynamic Influences on the West Indian Rainfall Distribution
	S39P	Aerosol Concentrations on a Global Scale
	S40	Upper Atmosphere Project
	S41	Biome Studies and Primary Productivity Modeling
	S42	International Southern Ocean Studies (ISOS)
	S43	North Pacific Experiment (NORPAX)
	S44	Climate/Long Range Investigation, Mapping and Prediction (CLIMAP)
	S45	Mid-Ocean Dynamics Experiment (MODE)
	S46	Geochemical Ocean Sections Study (GEOSECS)

A few programs are designed to examine the overall global climatic forecasting problem, for example, the Department of Defense Advanced Research Project Agency (ARPA) Climate Dynamics Program(D1); the NOAA Geophysical Fluid Dynamics Laboratory climate modeling programs (N25-N32); and the National Science Foundation, National Center for Atmospheric Research (NCAR) Climate Project (S1).

Many of the physical bases of climatic change are (or plan to be) examined in research programs which include: NASA project (M1) -- monitoring upper atmospheric temperature changes; the NOAA program (N36P) to model the effects of atmospheric particulate matter on incoming solar radiation and climate; the National Science Foundation (NSF) sponsored research on air-sea exchange of carbon dioxide (S30P), the International Southern Ocean Studies (ISOS) project (S42), the North Pacific Experiment (NORPAX) (S43), the Climate: Long-Range Investigation, Mapping and Prediction (CLIMAP) program (S44), and the Mid-Ocean Dynamics Experiment (MODE) (S45).

Research on descriptions of past climates (paleoclimates) is sponsored by the NSF in the Office of Polar Programs and conducted in such projects as the Circum-Antarctic Paleoclimate from Tree-Ring Analysis (S13), the Greenland Ice Sheet Project (S5), the global climatology programs (S24) and the Interdisciplinary Research Program in Climatology (S32P).

Climate monitoring activities have been increased of late with significant contributions stemming from NOAA's Global Monitoring of

Climatic Change (GMCC) program (N33). GMCC continues to move toward a necessary objective of establishing a comprehensive air quality/climatic conditions baseline-monitoring network. Various modes of climate monitoring are either planned or in progress utilizing: (1) satellites, as in the NSF-NCAR Upper Atmosphere Project (S40), the proposed Satellite Stratospheric Monitoring Program (N20P), and the Energy Research and Development Administration air sampling programs (C1-C4) and the NASA monitoring program using commercial 747 airliners in routine service (M5); (3) balloons (M3); (4) rockets (M4); (5) ships (S43); (6) ocean data buoys (S43 and N21).

Assessments of the effects of climate change on agricultural production are carried out primarily by NOAA's National Weather Service Environmental Study Service Center at Auburn, Alabama (N2 and N5P). Emphasis is on better crop-weather analysis techniques. Also applicable is a proposed World Agricultural Weather Watch (N4P). Two other additional on-going assessment programs are: one that examines productivity modeling (S41), and one that examines the impact of climate on fisheries (N24).

Service-oriented advisory programs in the climate and climate-change problem area include the Agricultural Climatology Program (A2) of the Department of Agriculture; and the Agriculture Weather Support Service (N1) and Environmental Study Service Center (N2), both of NOAA.

Federal Spending In Climate Research and Services During FY 1974 77/

	($ thousands)
Atomic Energy Commission: Research and monitoring of atmospheric trace constituents 78/	20
Department of Agriculture: Water resources studies	450
Services through the Agricultural Extension Service	310
Department of Commerce, National Oceanic and Atmospheric Administration: Research in global monitoring for climate change (GMCC), climate modeling at the NOAA Geophysical Fluid Dynamics Lab, and development of satellite monitoring at the National Environmental Satellite Service	5, 220
Services in long-range forecasting, climatography, and data handling	3, 880
Department of Defense: Research through the Advanced Research Projects Agency (ARPA), specifically in climate modeling	3, 330
Data management and climatological services	4, 670
Department of Transportation: Research in the Climatic Impact Assessment Program (CIAP), designed to determine the possibilities for inadvertent climate modification related to high altitude aircraft	2, 700
National Aeronautics and Space Administration: Research in development of satellite monitoring systems for measuring the Earth's radiation budget	4, 420
National Science Foundation: Support of IDOE, polar climate programs, inadvertent climate modification studies, NCAR climate modeling, and related university grants	9, 000
TOTAL	$34, 000

77/ Source: Executive Secretary, Interdepartmental Committee for Atmospheric Sciences; and NOAA, Office of Environmental Monitoring and Prediction, April 1976. This audit currently being updated by a NOAA/ICAS working group in the process of formulating a National Climate Program Plan. Note: DARPA programs will terminate with the close of FY '76; the Climatic Impact Assessment Program (CIAP) of the Department of Transportation terminated in FY '76; the NSF since this audit instituted a Climate Dynamics Program during FY '76.

78/ Activities of the AEC were transferred to the Energy Research and Development Administration (ERDA) in accordance with the Energy Reorganization Act of 1974 (P.L. 93-438) and Executive Order 11834 of January 19, 1975.

****

CHAPTER IX

MOBILIZING FOR A NATIONAL CLIMATIC RESEARCH PROGRAM:

NEEDS AND DEFICIENCIES

by

John R. Justus
Analyst in Earth Science
Science Policy Research Division

****

MOBILIZING FOR A NATIONAL CLIMATIC RESEARCH PROGRAM: NEEDS AND DEFICIENCIES

Despite everything that science has learned about the broad characteristics of climate and climatic history, relatively little is known of the major processes of climatic change. Lack of knowledge still is a major barrier to accurate forecasting and potential modification of weather and climate. The atmosphere and the ocean make up such a complex and rapidly changing system that even short-range forecasts may often be incorrect. Gathering sufficient information about global climate is of importance if atmospheric scientists are to construct the detailed computerized models capable of rapidly analyzing enormous amounts of data concerning each component of the climatic system, which includes not only the atmosphere but the world ocean, the ice masses, and the exposed land surface.

Observations are essential to the development of an understanding of climatic change. Without them, theories will remain theories and models would be of limited usefulness. Observational records need to be extended in both time and space to facilitate adequate documentation of the climatic events that have occurred in the past and monitoring of the climatically important physical processes occurring now.

Knowledge of the mechanisms of climatic change may be at least as fragmentary as the state of the data. Not only are the basic scientific questions largely unanswered, but in many cases not even enough is known to pose the key questions. What are the most important causes of climatic variation, and which are the most important or most sensitive of the many processes involved in the interaction of the air, sea, ice, and land components of the climatic system? There

is no doubt that the Earth's climates have changed in the past and will likely change in the future. But will it be possible to recognize the first phases of a truly significant climatic change when it does occur?

In a 1975 report, Understanding Climatic Change: A Program for Action, the U. S. Committee for the Global Atmospheric Research Program of the National Research Council enumerated the principal approaches to these problems emphasizing the interdependence of the major components of a climatic research program and posing a number of key questions. The components included:

- Climatic data analysis;

  What has happened in the past?
- Empirical studies;

  How does the system work?
- Monitoring;

  What is going on now?
- Numerical models;

  What is shown by climatic simulations?
- Theoretical studies;

  How much do we really understand?
- Climatic impacts;

  What does it all mean to man?
- Future climates;

  How and when is the climate going to change?

The various components of the climatic research program are to a great extent interdependent: Data are needed to check general circulation models and to calibrate the simpler models; the models are needed to test hypotheses and to project future climates; monitoring

is needed to check the projections; and all are needed to assess the consequences. 79/

The Committee on Atmospheric Sciences, also of the National Research Council, stated in a 1973 report entitled Weather and Climate Modification: Problems and Progress that if society is to deal with long-term problems of inadvertent weather modification and climatic changes caused by man and his activities, then urgent attention and action are required at the earliest possible moment. The Committee outlined several courses of action that should be undertaken, each contributing to a part of the necessary work to be accomplished:

1. A worldwide network of ground-based stations is needed to monitor the properties of the atmosphere with particular attention being given to those gases and aerosols affecting radiation and heat transfer. Precipitation collection should be undertaken for the analysis of atmospheric chemical constituents. Surface monitoring efforts should also be augmented by airborne monitoring of particles and gases in the atmosphere. Table 4 summarizes in detail the variables to be monitored, the method of monitoring, coverage, effort required and frequency required.

2. Since influence on climate caused by human factors is a global matter, internationally cooperative plans should be established that will provide long-term and uniform monitoring data.

3. Continuous monitoring of the Earth by satellites should be developed to measure not only cloud cover and cloud types but also

---

79/ National Research Council. U. S. Committee for the Global Atmospheric Research Program. Understanding Climatic Change: A Program for Action. Washington, National Academy of Sciences, 1975. p. 5, 6.

Table 4: SUMMARY OF CLIMATIC INDEX MONITORING PROGRAM

Variable or Index	Method	Coverage	Effort Required [a]	Frequency Required [b]
Atmospheric indices				
Solar constant	Satellite	Global	N	W
Absorbed radiation, albedo	Satellite	Global	P	W
Latent heating	Satellite	Global	N	W
Surface latent heat flux	Satellite	World ocean	N	W
Surface sensible heat flux	Satellite	Regional	N	W
Cloudiness	Satellite	Global	P	W
Surface wind over ocean	Radar scattering	World ocean	N	W
Oceanic indices				
Sea-surface temperature	Ships, satellites, buoys	World ocean	E	W
Surface-layer heat storage	XBT, AXBT, buoys	Mid-latitude and low-latitude oceans	E, N	W
Heat transport	Moored buoys	Selected sections	N	W
Temperature structure	Ships	Selected sections	E	S
Surface salinity	Ships, buoys	High latitudes	E	W
Sea level	Tide guages	Selected coastal and island sites	E	W
Composition, dissolved gases	Conventional sampling	Selected sections	E	S
Cryospheric indices				
Floating ice extent	Satellite	Polar seas, lakes	E	M
Ice-sheet budget parameters	Satellite	Greenland, Antarctica	N	Y
Mountain glacier extent	Satellite	Selected sites	E	Y
Snow cover	Satellite	Continents	E	M
Surface and hydrologic indices				
River discharge	Flow gauges	Selected sites	E, N	W
Soil moisture	Satellite	Land areas	E	W
Lake levels	Gauges	Selected sites	E	W
Precipitation	Satellite, radar, gauges	Global	E	W
Composition and turbidity indices				
Chemical composition	Sampling	Selected sites	E	S
Aerosols and dust	Satellite	Global	E	W
Anthropogenic indices				
Thermal pollution	Sampling	Continents and coasts	N	W
Air and water pollution	Sampling	Global	E	W
Land use	Satellite	Continents	E	Y

[a] N, completely new monitoring effort required; E, expansion of present monitoring efforts required; P, present (or slightly expanded) monitoring efforts satisfactory but coordination and further analysis required.
[b] W, weekly (or possibly daily in some cases); M, monthly; S, seasonally; Y, yearly (or possibly decadal in some cases).

Source: National Research Council. U.S. Committee for the Global Atmospheric Research Program. Understanding Climatic Change: A Program for Action. Washington, National Academy of Sciences, 1975. p. 78-79.

the thermal characteristics of the atmosphere and the Earth's surface, as well as related variations in the albedo of the Earth. Satellite measurements should be complemented by a program of ground-based remote sensing of the dynamical, chemical, and particulate properties of the atmosphere.

4. Computer capabilities for simulation of climate and climatic changes should be fully utilized. Climatic models eventually may prove to be quite different from the present general circulation models. However, if we are to reach the capability to assess the consequences of further human intervention, climatic model development must be promptly undertaken. 80/

Many of the efforts envisaged are of an obvious international character, and the degree to which they should be regarded as national versus international activities is not of critical importance. The important point is, however, that there are international efforts now underway of direct relevance to the climatic problem.

The World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU) jointly organized a Global Atmospheric Research Program (GARP) in 1967. GARP goals include: providing the improved understanding of the global circulation needed to extend the range and accuracy of weather forecasts; understanding the physical basis of climate and climatic fluctuations; and providing a firm foundation for the World Weather Watch (WWW). 81/ Several

---

80/ National Research Council. Committee on Atmospheric Sciences. Weather and Climate Modification: Problems and Progress, p. 160, 161.

81/ WWW is an operational program of member nations of the WMO for making available the basic meteorological and related environmental information needed by each member nation to supplement and support its meteorological services and research.

GARP regional experiments are planned in order to examine specific processes. The GARP Atlantic Tropical Experiment (GATE) followed the Barbados Oceanographic and Meteorological Experiment (BOMEX, 1969) in a succession of experiments designed to gain increased understanding of the atmosphere and the causes of climatic variation and change. The primary objective of GATE was to learn more about the meteorology of the tropical equatorial belt where vast quantities of heat and moisture, carried upward by organized convective systems, are transported and redistributed to higher latitudes, ultimately affecting global atmospheric circulation patterns. Because the tropics are believed to be a key to these circulation patterns, scientists expect data from GATE to help them better understand the global climate machine. Conducted as scheduled from June 15 to September 30, 1974, GATE had the cooperation of some 72 countries. In addition to BOMEX and GATE, experiments designed to contribute to the understanding of specific oceanic-atmospheric processes in selected regions are: the Air Mass Transformation Experiment (AMTEX), the Monsoon Experiment (MONEX), and the Polar Experiment (POLEX). These regional experiments and the knowledge gleaned from them will culminate in a truly international global observing experiment, the First GARP Global Experiment (FGGE) scheduled for about 1978.

The program goals of GARP intersect with the objectives of other international environmental programs. One such program is the Intergovernmental Oceanographic Commission's Integrated Global Ocean Station System (IGOSS) being developed jointly with the World Meteorological Organization to provide more extensive and timely information for analysis and prediction of the state of the oceans and research purposes. This is accomplished through the development of a

GARP regional experiments are planned in order to examine specific processes. The GARP Atlantic Tropical Experiment (GATE) followed the Barbados Oceanographic and Meteorological Experiment (BOMEX, 1969) in a succession of experiments designed to gain increased understanding of the atmosphere and the causes of climatic variation and change. The primary objective of GATE was to learn more about the meteorology of the tropical equatorial belt where vast quantities of heat and moisture, carried upward by organized convective systems, are transported and redistributed to higher latitudes, ultimately affecting global atmospheric circulation patterns. Because the tropics are believed to be a key to these circulation patterns, scientists expect data from GATE to help them better understand the global climate machine. Conducted as scheduled from June 15 to September 30, 1974, GATE has the cooperation of some 72 countries. In addition to BOMEX and GATE, experiments designed to contribute to the understanding of specific oceanic-atmospheric processes in selected regions are: the Air Mass Transformation Experiment (AMTEX), the Monsoon Experiment (MONEX), and the Polar Experiment (POLEX). These regional experiments and the knowledge gleaned from them will culminate in a truly international global observing experiment, the First GARP Global Experiment (FGGE) scheduled for about 1978.

The program goals of GARP intersect with the objectives of other international environmental programs. One such program is the Intergovernmental Oceanographic Commission's Integrated Global Ocean Station System (IGOSS) being developed jointly with the World Meteorological Organization to provide more extensive and timely information for analysis and prediction of the state of the oceans and research purposes. This is accomplished through the development of a

comprehensive monitoring system for the total physical ocean-atmosphere environment. Another is EARTHWATCH, a major component of the United Nations Environment Program (UNEP) being developed to monitor and assess the state of the oceans, atmosphere, land and human health in order that rational decisions can be made for the management of the environment. EARTHWATCH will also interact with and depend on the monitoring and research capabilities of GARP. A key component of the UNEP/EARTHWATCH global baseline and regional monitoring effort is the Global Environment Monitoring System, which is designed to measure and monitor priority pollutants and related factors of the atmospheric environment, thus permitting quantitative assessment of the global impact of man-made and natural influences on weather and climate.

The Global Observing System provides worldwide meteorological and related environmental observational data needed by the World Weather Watch and GARP. The overall system consists of two subsystems: a space-based satellite subsystem, composed of two types of satellites, those in polar orbit and those in geostationary orbit; and a surface-based subsystem composed of basic synoptic surface and upper air networks, other networks of stations on land and sea, and aircraft meteorological observations.

The United States Committee for the Global Atmospheric Research Program believes that these observational programs planned in support of GARP offer an unparalleled opportunity to observe the global atmosphere, and furthermore that every effort should be made to use these data for climatic purposes as well as for the purposes of weather prediction. The Committee emphasized, however, that the climatic system consists of important nonatmospheric components,

including the world's oceans, ice masses, and land surfaces, together with elements of the biosphere. While it is not necessary to measure all of these components in the same detail with which the atmosphere is observed, their roles in climatic variation should not be overlooked. 82/

The Committee's 1975 report, Understanding Climatic Change: A Program for Action, further stated that:

> the problem of climatic variation differs from that of weather forecastingby the nature of the data sets required. The primary data needs of weather prediction are accurate and dense synoptic observations of the atmosphere's present and future states, while the data needed for studies of climatic variation are longer-term statistics of a much wider variety of variables. When climatic variations over long time scales are considered, these variables must be supplied from fields outside of observational meteorology. Thus, an essential characteristic of climate is its involvement of a wide range of nonatmospheric scientific disciplines, for example, oceanography, glaciology, hydrology, astronomy, geology, and paleontology as well as from the biological and social sciences of ecology, geography, archaeology, history, economics, and sociology.
>
> The types of numerical models needed for climatic research also differ from those of weather prediction. The atmospheric general circulation models do not need a time-dependent ocean for weather-forecasting purposes over periods of a week or two. For climatic change purposes, on the other hand, such numerical models must include the changes of oceanic heat storage. Such a slowly varying feature may be regarded as a boundary or external condition for weather prediction but becomes an internal part of the system for climatic variation. 83/

In view of these characteristics, the Committee suggested that while the GARP concern with climate was a natural one, the problem of climate goes much beyond the present basis and emphasis of GARP. Accordingly, they recommended that the global climate studies that are under way within GARP be viewed as leading to the organization of a

82/ National Research Council. U. S. Committee for the Global Atmospheric Research Program. Understanding Climatic Change: A Program for Action, p. 105, 106.

83/ Ibid., p. 106.

new and long-term international program devoted specifically to the study of climate and climatic variation, an International Climatic Research Program (ICRP).

As viewed by the Committee, the main thrust of the international climatic program would be the collection and analysis of climatic data during a series of International Climatic Decades (ICD) designated for the period 1980-2000. During this period, the cooperation of all nations would be sought to participate in an intensive effort to develop and secure as complete a global climatic data base as possible. The Committee urged the creation of an international cooperative program for the monitoring of selected climatic indices and the extraction of historical and proxy climatic data unique to each nation, which would include, but not be limited to, such indices as glaciers, rain forest precipitation, lake levels, local desert history, tree rings, and soil records. This would take the form of an International Paleoclimatic Data Network (IPDN), as a subprogram of the ICRP.

To promote wider international participation in climatic research, it was recommended that programs and activities be developed to encourage international cooperation in climatic research and to facilitate the participation of developing nations that do not yet have adequate training or research facilities. Internationally supported regional climatic studies describing and modeling local climatic anomalies of special interest were also recommended.

The Committee stressed the importance of international cooperative programs to assess the impacts of presently observed climatic changes on the economies of the world's nations, including the effects on water supply, food production, and energy utilization, as well as analyses of the regional impacts of possible future climates.

A United States Climate Program

Because the impacts of climatic fluctuations are felt both directly and indirectly by all nations, and because the processes that control climate and the systems to monitor them are global in scope, the United States is fostering and financially supporting international efforts in all appropriate forums. 84/ However, this circumstance seems hardly sufficient to account for the paucity of Federal funding of national climatic research in response, not just to the clamor of the "doomsday prophets," but also to a series of highly authoritative and respectible reports -- all of which have reiterated the need for a major increase in climate research activities. No doubt this may in part be ascribed to the Nation's economic difficulties, but another more trenchant cause for the problem arises -- specifically a failure to demonstrate to funders of such research the practical benefits that can result within a time frame of relevance to their mandate.

With a realization that global food and energy supply crises could be sharply intensified by fluctuations of regional climate; and, furthermore, with a realization that longer-term changes in climate -- whether naturally occurring or resulting from man's activities or both -- may be leading to new global climate regimes with widespread impact (either negative or perhaps even positive) on food production, energy consumption, and water resources; an urgency is perceived for a

---

84/ See: U.S. President, 1974 - (Ford). World Weather Program Plan for Fiscal Year 1976; annual report describing current and planned Federal activities that contribute to the World Weather Program. Transmitted in accordance with Senate Concurrent Resolution 67 of the 90th Congress. Washington, For Sale by the Superintendent of Documents, U.S. Govt. Print. Off., 1975. 54 p.

national program that could offer hope of knowing and anticipating the effects of climate fluctuations and changes in this Country and around the world.

In August 1974, the Domestic Council's Environmental Resources Committee, at the request of the Council, formed the Subcommittee on Climate Change to: examine what is known about the causes, extent, and impacts of climate fluctuations and changes; examine the present domestic and international programs that address these issues; and identify and recommend domestic and international program options and cooperative efforts that may help to alleviate adverse impacts of climatic variations.

In its December 1974 report, A United States Climate Program, the Subcommittee on Climate Change found that the current national capability to anticipate and explain either natural fluctuations or man-induced changes of climate falls short of being useful to the planners and policy makers, who must face these problems, and short of the best that science and technology can offer. The Subcommittee concurred that a start should be made on an organized research effort leading to an improved understanding of, and a capability to predict, natural fluctuations and man-induced changes of climate and their consequences. Rapid and significant improvements in the utility of currently available climatic information could also be achieved. 85/

The Subcommittee recommended that a U.S. Climate Program be initiated and organized as a matter of urgency in order to develop a capability for predicting the occurrence and the consequences of

85/ U.S. Domestic Council. Environmental Resources Committee. Subcommittee on Climate Change. A United States Climate Program. [Washington] 1974. p. i, 3.

natural climate fluctuations and inadvertent, man-induced climate changes. To meet these goals of a U. S. Climate Program, a four point program was envisioned which would:

- establish a climatic impact warning system to provide both real-time warnings and assessments of the risks of future climatic impacts;
- improve existing climate prediction, with an emphasis on current monthly and seasonal climate predictions;
- develop mathematical-computer systems for simulation of climate and for prediction of man's effects on climate;
- develop an international global climate monitoring system to support early warning and prediction efforts.

The U. S. Climate Program requires the expertise and facilities of many different Federal agencies and the participation of the non-governmental scientific community. Its international aspects require the participation of other governments and international agencies. Thus, it becomes clear that this program is carried out through a network of institutions. Realizing that this network can only succeed in its objectives if managerial, coordinating, and funding responsibilities are clearly identified and the necessary authorities specified, the Subcommittee recommended the following institutional arrangements:

Federal Institutions. A Federal agency should be given the authority and responsibility for the planning, budget coordination and program monitoring that will be necessary to ensure a coherent national effort. It was suggested that the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce be designated as this coordinating agency by Presidential directive. A mechanism to assist NOAA in its coordinating functions should be established.

Attendantly, the Secretary of Commerce in consultation with all appropriate Government agencies should take steps to establish an Interagency Climate Program Mangement Review Board.

Recognizing the fact that there are existing climate programs within the Departments of Agriculture, Commerce, Defense, Interior, State, and Transportation as well as in the National Science Foundation and the National Aeronautics and Space Administration, the Subcommittee recommended that the expertise of these participating agencies be used to a maximum as a base upon which to build the U.S. Climate Program.

While this approach would make maximum use of ongoing programs, it would require multiple agency funding. This raises the requirement that the Office of Management and Budget review the U.S. Climate Program each year as a coherent, multiple agency effort, to ensure that all parts of the program are moving ahead as planned. The annual review by the Office of Management and Budget should be based upon an annual plan prepared by NOAA with the assistance of all participating agencies.

The National Oceanic and Atmospheric Administration should fund and direct aspects of the U.S. Climate Program effort, including those of an administrative and coordinating nature, which do not clearly fall within the existing responsibilities of the agencies who will participate in the program.

Non-Federal Institutions. The Subcommittee on Climate Change recognized that the U.S. Climate Program cannot reach its stated goal without the active and continuous involvement of the universities, other governmental institutions, and industry. The program envisioned

by the Subcommittee implicitly relies upon this reservoir of capabilities and presumes their direct and indirect contributions. In order to receive the full benefits of advice from the scientific community and the non-Federal sector, the Subcommittee recommended that non-governmental advisory bodies be consulted periodically to review progress and plans concerning the research aspects of the U.S. Climate Program. 86/

Funding Recommendations. The funding in Table 5 would bring about the desired level of effort for a U.S. Climate Program as envisioned by the Subcommittee. Depicted are fiscal year (FY) 1975 base funding, by agency, devoted to the achievement of program objectives, and incremental funding required for FY 76, FY 77, and FY 78 over the previous year's base. The total annual costs of the recommended program were $63.7 million for FY 76; $71.0 million for FY 77; and $80.4 million for FY 78 with the requirement of $39.8 million of new funding in FY 76 and further increases, respectively, of $7.3 million in FY 77, and $9.4 million in FY 78.

86/ Ibid., p. 7-20, 21-23.

TABLE 5

U.S. CLIMATE PROGRAM FUNDING[1]
(In Millions of $)

Objective	Agency	Direct Base FY 75	Incremental Funding FY 76	FY 77	FY 78
Establish a Climate Impact Warning System	DOC/NOAA	3.8	5.9	2.5	0.2
	NSF	0.2	0.3	0.5	0.3
	Total	4.0	6.2	3.0	0.5
Cumulative	Total	4.0	10.2	13.2	13.7
Improve Existing Climate Prediction	DOC/NOAA	0.3	0.7	0.2	0.1
	NSF	1.0	0.3	0.2	0.2
	Total	1.3	1.0	0.4	0.3
Cumulative	Total	1.3	2.3	2.7	3.0
Develop Computer Simulation and Prediction of Climate	NSF	1.9	2.5	1.7	1.3
	DOC/NOAA	2.7	3.1	2.0	1.6
	NASA[2]	1.2	1.0	0.8	0.8
	DOD	1.3	-0.7	-0.6	0
	DOT	0.9	-0.7	0	0
	Total	8.0	5.2	3.9	3.7
Cumulative	Total	8.0	13.2	17.1	20.8
Develop a Global Monitoring System for Climate	DOC/NOAA	2.5	18.9	4.6	3.3
	NASA[2,3]	2.8	4.7	-2.8	+1.1
	NSF	3.3	3.8	-2.0	0.3
	ERDA	0.2	0	0	0
	DOT	1.8	-0.6	0	0
	Total	10.6	26.8	-0.2	4.7
Cumulative	Total	10.6	37.4	37.2	41.9
Program Management	DOC/NOAA	0	0.6	0.2	0.2
TOTAL PROGRAM		23.9	39.8	7.3	9.4
Cumulative Total Program		23.9	63.7	71.0	80.4

1 Entries in the table are preliminary and not cleared by agencies.

2 NASA funding indicated supports a number of disipline areas — e.g., meteorology, earth resources, oceanography — but also has direct application to climate. No attempt has been made to prorate the funds among the disciplines.

3 Major development projects (flight and ground based) do not appear in these numbers, because they are primarily designed to serve other programs. They include among others Nimbus G, SAGE, and SEASAT.

TABLE 6

A Summary of Agency Funding*
(In Millions of $)

	Direct Base	Incremental Funding		
	FY 75	FY 76	FY 77	FY 78
DOD	1.3	-0.7	-0.6	0
DOT	2.7	-1.3	0	0
ERDA	0.2	0	0	0
NASA	4.0	5.7	-2.0	1.9
DOC/NOAA	9.3	29.2	9.5	5.4
NSF	6.4	6.9	0.4	2.1
TOTAL	23.9	39.8	7.3	9.4

* Entries in the table are preliminary and not cleared by agencies.

A P P E N D I X E S

****

Appendix A

Selection of Current Readings

****

APPENDIX A

CONTENTS

OMINOUS CHANGES IN THE WORLD'S WEATHER

Climatologists now blame those recurring droughts and floods on a global cooling trend. It could bring massive tragedies for mankind.

by Tom Alexander

For several years now, odd and unpleasant things have been happening to weather around the world. The droughts south of the Sahara, where unknown thousands of persons have died of famine and its associated diseases and millions more have been kept alive only by emergency food shipments, have been well publicized. It is not so well known that the African drought belt is part of a much larger dry-weather pattern extending all the way through the Middle East to India, South Asia, and North China. Drought has struck Central America as well. While these regions were drying up, places as widely scattered as the midwestern U.S., the Philippines, and Italy were submerged in some of their severest floods in centuries. And while low-temperature records were being broken in some northern regions, Siberia for example, others such as European Russia and the northeastern U.S. were enjoying unprecedentedly warm winters.

Not too long ago, if anyone asked whether something was going wrong with the climate, weather scientists answered with a slightly superior, "No." The eminent British meteorologist Hubert Lamb, who heads Europe's only climatic research organization, at the University of East Anglia, says it has always been assumed that climatic change of any significance was something that belonged to the geological past. "It was denied that there was anything other than random fluctuations from year to year or from one little group of years to another." Climatology, the study of long-term weather conditions, was regarded, says Lamb, as "the dullest branch of meteorology."

Armadillos in retreat

In the last decade, however, a number of scientists from several disciplines have concluded that some fairly drastic climate change *is* going on. Their message is that for nearly half of the current century mankind was apparently blessed with the most benign climate of any period in at least a thousand years. During this kindly era the human population more than doubled. But now there's good reason to believe that the world's climate is reverting rapidly to its less beneficent norm.

Research associate: Beth Bogie

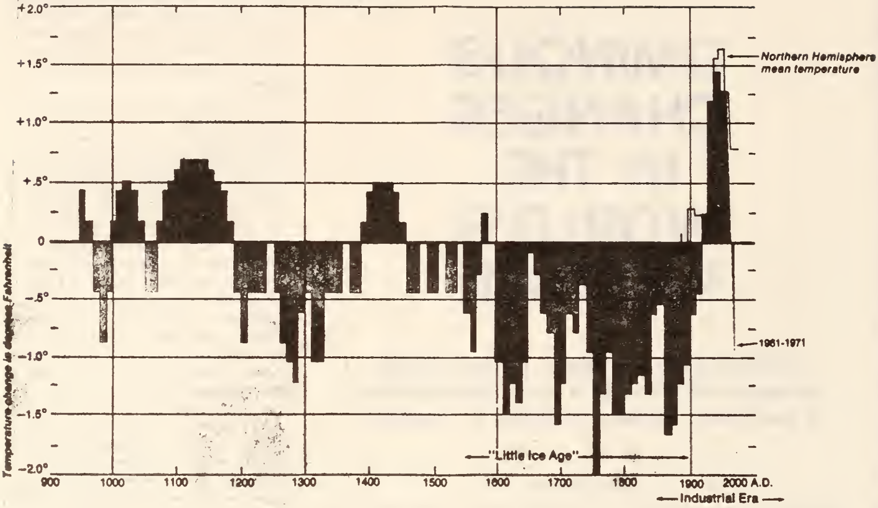
The changes, which are charted on the facing page, began with a pronounced warming trend after about 1890. Mean temperatures peaked in 1945 and have been dropping sharply ever since. The total drop since the Forties—about 2.7° F.—hardly seems dramatic, but the effects have been substantial. Icelandic fishing fleets that learned to range northward during the warm period have now had to return to traditional waters to the south. For the first time in this century, ships making for Iceland's ports have found navigation impeded by drifting ice. Since the late Fifties, Iceland's per-acre yield of hay has dropped 25 percent.

In North America, the armadillo extended its range as far north as Nebraska during the warming trend, and now is beating a retreat southward again. In England, the average growing season is two weeks shorter than it was prior to 1950. As Lamb puts it, "Global temperatures since 1945 constitute, we believe, the longest unbroken trend downward in hundreds of years."

Grandpa wasn't kidding

A fair rule of thumb is that *any* climate change is bad; not only armadillos but man and his institutions are adjusted to precisely the weather that prevails. As for the present cooling trend, a number of leading climatologists have concluded that it is very bad news indeed. They say that it is the root cause of a lot of that unpleasant weather around the world and they warn that it carries the potential for human disasters of unprecedented magnitude. The most telling effect of the falling temperatures is to alter the vast, integrated system of winds that sweep about the planet. And the most grievous result of the new wind pattern has been the blocking of vital monsoon rains upon which large sections of Africa, Asia, and Central America depend. Elsewhere in the world,

A thousand-year history of Iceland's temperature

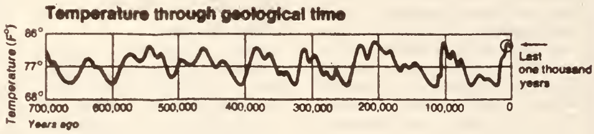


A Fifty-Year Balmy Spell Comes to an End

Mankind obviously has been enjoying a spell of warmth unusual in the time scales of both the historical and the geological past. The thousand-year record for Iceland was reconstructed by meteorologist Pall Bergthorsson, who worked from such evidence as the Viking settlers' surprisingly complete accounts of the duration and extent of sea ice. By comparing these records with recent experience, Bergthorsson could estimate the mean temperature for each decade. Because of Iceland's location and vulnerability to small temperature changes, climatologists regard it as a good indicator of what is happening over the whole Northern Hemisphere. The black line starting in the nineteenth century is the actual measured mean for the Northern Hemisphere and shows reasonably good correspondence. Temperatures began rising sharply after 1890, peaked in the 1940's, and have been dropping ever since. Leading climatologists say that we may be returning to the "little ice age" that gripped the world from the sixteenth to the nineteenth centuries.

Below is a 700,000-year temperature record prepared by marine geologist Cesare Emiliani of the University of Miami. The ratio of the two oxygen isotopes in seashells has been found to vary with water temperature, and this made it possible for Emiliani to calculate ancient water temperatures from fossils in the sediment layers in the Caribbean. The chart shows a regular succession of major ice ages at intervals of about 100,000 years. Within these cycles, spells of relative coolness and warmth alternate at roughly 20,000-year intervals. The calculations indicate that the 6,000 years of civilization have coincided with the warmest temperatures in nearly 100,000 years.

Temperature through geological time



there seems to be a return to the more extreme and variable weather conditions—including floods, droughts, and great winter blizzards—that were typical of the nineteenth century. "When Grandpa said the weather was different in his day, he wasn't kidding," remarks one climatologist.

Long-range climate forecasting is still pretty much beyond the grip of science, but in recent months highly respected climatologists have been risking their reputations to predict that things will get worse. Japan's Meteorological Agency has warned its government to expect long-term increasing coldness in the north and drought in western Japan.

In the U.S., the most outspoken perceiver of climatological danger signals is Reid Bryson, director of the Institute for Environmental Studies at the University of Wisconsin. "There is very important climatic change going on right now," he says. "And it's not merely something of academic interest. It is something that, if it continues, will affect the whole human occupation of the earth—like a billion people starving. The effects are already showing up in rather drastic ways."

"The most abnormal period"

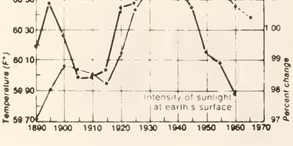
Bryson draws upon a broad variety of research performed by himself and others, but his conclusions are molded by his own unusual combination of interests. Originally, he wanted to become an archaeologist. During World War II, however, he was trained in meteorology by the Army Air Corps and became persuaded that this field might provide a unique perspective into the study of man. After the war, he received the thirtieth Ph.D. degree in meteorology ever handed out in the U.S. and went on to found the meteorology department at the University of Wisconsin, now the largest in the country. He has spent much of his scientific career in remote parts of the world gathering hints as to what past climates were like and what might have caused them to change. At the same time, his archaeological interest has kept him unusually conscious of the effects of climate upon man—and vice versa.

From this long-range perspective,

The Great Global Struggle of the Winds

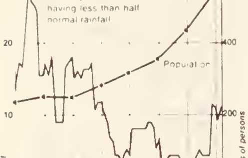
The most dangerous effect of the global cooling trend has been a change in atmospheric circulation and rainfall. The change centers on the behavior of the circumpolar vortex, the great cap of high-altitude winds revolving about the poles from west to east. The broad, brown band across the Northern Hemisphere marks the approximate southern edge of this wind system as it was during summertime in the early Sixties. Its southern edge determines the location of the belt of high pressure regions, indicated here by narrow, clockwise-spiraling red arrows representing winds flowing outward. The highs result from dry winds that descend after traveling at high altitudes from the equator. They create the world's great deserts, determining the northern limit of penetration by rain-bearing summer monsoons (indicated by heavy, northward-trending arrows). The limit is known as the "intertropical convergence zone."

Because of the global cooling trend, the lower edge of the circumpolar vortex has in recent years stayed farther south during the summer, in the position shown by the blue band. It has kept the high-pressure zones farther south too, blocking the monsoons out of regions where they are vital to the survival of hundreds of millions of people. At the same time, the vortex's semistationary wave patterns have altered, affecting rainfall patterns in temperate regions and making the climate more variable. The deeper wave over the U.S., for example, is believed responsible for recent cold winters in the West and mild ones in the East. The West has been getting north winds and the East the return flow. While there is some evidence that the cooling trend has affected wind patterns in the Southern Hemisphere as well, weather statistics are scanty there.



Atmospheric dust is the culprit in the recent cooling trend, according to climatologist Reid Bryson The chart above shows a fairly good correlation between mean Northern Hemisphere temperatures and measurements of the intensity of sunlight striking the earth on cloudless days Bryson argues that the variation in sunlight is caused by the effects of dust on the transparency of the atmosphere. Because of the "greenhouse effect" of carbon dioxide, temperatures did not fall as rapidly after 1930 as would otherwise have been the case Other meteorologists, including Russia's Mikhail Budyko, who made the sunlight measurements, have speculated that the variations may be caused by fluctuations within the sun itself

A grim prospect for India is suggested by the chart below drawn from data compiled by Reid Bryson Droughts in northern India declined in frequency during the period when the world was getting warmer, but have been increasing in recent years Points on the chart indicate the proportion of weather stations whose average rainfall for the previous ten years was less than 50 percent of normal The red line shows India's population growth, which Bryson contends was encouraged by the unusual interlude of favorable climate



Bryson finds it wildly inappropriate that it is the modern era, with its beneficent climate, that meteorologists, by international agreement, define as normal. "It's perfectly obvious," Bryson says, "that this has been the most abnormal period in at least a thousand years." He points, for example, to the fact that from 1918 to 1960 India experienced far fewer droughts than would have been expected from the prior record (see the chart at lower left). The comparative absence of famine in this period, he contends, has played a large role, along with improved medical care, in causing the population of such regions as India to more than double in this century.

Bryson believes that the period from about 1890 to 1945 amounted merely to a brief respite from the "little ice age" that has held the world in its grip ever since the sixteenth century.

The whitening of Greenland

Before the little ice age, grapes were widely cultivated in England, and the French complained of English wine makers dumping their wares in European markets. As early as the tenth century, the Vikings had established prosperous colonies in Greenland, having named the island for its verdant pastures. By the early fifteenth century, however, these colonies were wiped out by cold and hunger and now four-fifths of Greenland lies buried under hundreds of feet of ice cap.

From the evidence found in such things as sea-floor sediments, peat bogs, and tree rings, the earth's long-term climatological history has been as full of rallies and plunges as the stock market (see the chart on page 91). Even the little ice age is really only a minor squiggle in much longer-term oscillations between warm periods and true ice ages. In terms of these cycles, there's fair agreement among researchers that the earth is now heading very slowly into another major ice age such as the one that brought the glaciers deep into North America before it retreated some 10,000 years ago.

One of climatology's more surprising recent conclusions, derived from investigations of sea-floor sediments, is that for at least the past 700,000 years, global mean temperatures have been as high as they are now only about 5 percent of the time. Says Cesare Emiliani, who has been plotting the long-term cycles at the University of Miami, "We used to think intervals as warm as the present lasted 100,000 years or so. Instead, they appear to be short, infrequent episodes." Another surprising finding is that sometimes transitions from one major temperature regime to another have taken place with astounding rapidity, often within a century or so.

What makes the temperature fluctuate at all is a matter of intense debate. Many believe that the long-term cycles have astronomical causes. The earth has a slightly elliptical orbit that brings it closer to the sun at certain times of the year than at others. In addition, the axis upon which the earth spins is tilted. Finally, the earth wobbles slightly upon this axis, like a top. The combination of all these circumstances can, for example, lead to a series of very cool summers during which an unusual proportion of each winter's snow fails to melt in the northern latitudes.

It is known that the world's climate is a delicately balanced system, full of sensitive feedback mechanisms that serve either to amplify or to counter changes that occur. It is also known that the climate depends primarily upon the amount of solar radiation that gets absorbed by the earth and atmosphere. This is determined by the planet's overall "albedo," the measure of its reflectivity. The greater the albedo, the colder the earth. Since white things are highly reflective, clouds are major contributors to the albedo, as are snow and ice.

Volcanoes that dimmed the sun

Clouds can serve to moderate whatever climate trend is under way: if the earth's surface temperature climbs for whatever reason, more water evaporates and may rise to form more cloud cover. This increases the albedo and lowers the rate of heating. Ice and snow, on the other hand, provide positive feedback: if the average year-round temperature decreases, the extent of ice and snow coverage increases and reflects more of

the incoming sunlight back to space. The result is to lower the rate of heating still more, particularly in the regions closest to the poles.

There's yet another contributor to the planet's albedo—airborne particles, particularly the extremely fine dust particles that have been carried too high in the atmosphere to be washed out by precipitation. Many of these particles remain aloft for months or years. It's Reid Bryson's thesis that dust of various kinds initiates short-term cooling trends with characteristic time spans of decades or centuries.

Past cool epochs, he believes, were triggered by increases in volcanic eruptions, which spewed huge quantities of dust into the stratosphere. Historical writings are full of accounts of the dimming of sunlight and the brilliant sunsets that prevailed throughout the world for several years after major eruptions. Scientists who have drilled through many layers of the Greenland and Antarctic ice sheets report evidence of lower temperatures in the same layers in which a lot of volcanic dust is deposited. And most climatologists agree that a diminution of the sunlight as small as 1 percent would suffice to initiate a cool period and perhaps even major glaciation.

During the early parts of the century, when the climate began warming, volcanoes were unusually quiescent. They've been acting up again since 1955, and monitoring stations in places as scattered as the Caucasus Mountains, Mongolia, and Greenland have recorded measurable increases in dust fall, as well as decreases in the transparency of the atmosphere, and in the amount of direct sunlight reaching the earth.

The human impact

Bryson calculates, however, that neither volcanic activity nor the lack of it seems sufficient to account for the temperature ups and downs of this century. He is convinced that man's activities have been playing an increasingly significant part.

In agreement with other climatologists, he believes that a substantial increase in carbon dioxide from the burning of fossil fuels contributed to the earlier warming trend, through what's called the "greenhouse effect." Carbon dioxide happens to be quite transparent to light of short, visible wavelengths, which include most of the energy we receive from the sun. After this light penetrates the atmosphere, however, it is converted into heat by the earth and reradiated at the longer infrared wavelengths. Carbon dioxide molecules are not very transparent to infrared wavelengths, so this energy is trapped and reinforces the solar heating effect.

A bold forecaster, University of Wisconsin climatologist Reid Bryson says that cooling will probably continue and, if it does, mass starvation will result.

Bryson contends that sometime after 1930, the cooling effect of more dust in the atmosphere began to overpower the warming effect of carbon dioxide. Part of the dust blanket, no doubt, is due to industrial pollution. But Bryson suspects that windblown dust from mechanized agricultural operations and overgrazed arid land, plus smoke from the primitive slash-and-burn land-clearing methods widely practiced in the tropics, may have contributed even more. While all the man-made particles together are probably still outweighed by contributions from nature—volcanic dust, salt particles from evaporated ocean spray, and organic compounds emitted by vegetation—the human contribution is the only part over which man has any control.

Whatever its source, dust has a more pronounced cooling effect on the polar regions than on the tropics. For one thing, sunlight reaching the poles must travel obliquely through the dust layers, and therefore more of it is reflected. Also, there seems to be much less dust over the equator than in middle and higher latitudes.

Nature's effort to equalize

What makes this variation important is that the large-scale circulation of the atmosphere is largely induced by the temperature difference between the equator and the poles. The wind system, which is illustrated on pages 92-93, can be viewed as nature's effort to equalize temperatures around the globe.

One mechanism is the heating and ensuing rise of warm, moist air from the equatorial oceans. In rising, the air sheds much of its moisture on equatorial rainy belts and then, like air above a radiator that spreads along the ceiling to the cooler walls, it travels toward either pole. It reaches only about a third of the way to the poles before it descends again to create the high-pressure belts where most of the world's major deserts are found.

Some of the descended air circulates back toward the equator in the form of the trade winds, while the rest continues on toward the poles. As it does so, it still carrie. with it much of the speed induced by the earth's east-to-west spin. At the equator, this amounts to about 1,100 mph, while precisely at the poles, of course, the rotational speed is zero. So as the air moves poleward, it blows more and more strongly from the west—the prevailing westerlies at lower altitudes and the jet streams on high.

Eventually the poleward-trending air runs into a barrier of sorts in the form of great caps of heavy, cold air extending outward from either pole. Together the westerly winds and the polar air mass make up what meteorologists

continued page 142

Weather *continued from page 95*

call the "circumpolar vortex." It resembles a great skirt whirling around the poles. The lower hem of this skirt is full of waves and turbulence, particularly in the Northern Hemisphere, where there are numerous mountain ranges to perturb the flow of the wind.

Waves along the boundary come in several sizes. The very largest—of which there are normally only from two to six stretching end to end around the earth's temperate zones—tend to remain semistationary. Their location is determined partly by terrain and partly by temperature differences between various parts of the earth's surface.

Rain on the plains

The vagaries of the circumpolar vortex account for most of the weather patterns in the temperate zones. The westerly winds, following the wavy profile, serve to bring warm southern air to northern regions or cold northern air southward. The greater the temperature contrast between the equator and the poles, the deeper and more numerous are the waves in the vortex, as though nature were trying harder to equalize the temperatures.

Long-range meteorologist Jerome Namias of the Scripps Institution of Oceanography says that the peculiarly cold winters in the western U.S. and the warmish winters in the East over the last few years are due to a southward projection of one of these waves, which has now situated itself over the central U.S. Cold air flows down its western boundary, and the return flow warms the East.

Such large waves also establish which places get rain and which don't. Several of Bryson's colleagues at Wisconsin, who detect emerging patterns like those that prevailed during the nineteenth century, predict that one consequence will be a return of heavier rainfall in the western plains and Rocky Mountain states. Many of the forty-niners who made the trek to California recounted that a hazard of crossing the plains was losing sight of the main party amid

continued page 146

Weather *continued*

endless seas of head-high grass—growing in regions that are practically desert today. Climate, Bryson speculates, may have played a greater part than hunters in the disappearance of the huge herds of bison.

Snow in August

But the new weather patterns seem likely to do more harm than good, even in North America. Excessive rain on the plains can contribute to flooding as far away as the Mississippi Valley, where rivers got far out of their banks last spring. In Canada last year, a storm in the middle of August dropped eight inches of snow on the western wheat fields. This is reminiscent of midsummer snows that occasionally devastated New England agriculture early in the nineteenth century.

The grain belt in the U.S. Midwest would probably be less affected, but, even so, production might not measure up to past levels. James McQuigg, a government climatologist at the University of Missouri who specializes in the economic implications of weather, has for some years been analyzing the year-by-year yields of various American crops during the past century and relating these to each year's weather. While conventional wisdom has it that the phenomenal yields of the last fifteen years or so are attributable to improved technology and crop strains, McQuigg concludes that at least as much credit should be given to extremely favorable temperatures and rainfall. "The probability of getting another fifteen consecutive years that good is about one in 10,000," says McQuigg, who also happens to subscribe to Bryson's theories about a deteriorating climate.

Elsewhere in the world, the effects of changes in the circumpolar vortex could be massively tragic. Last year, British meteorologist Derek Winstanley analyzed the persistent droughts in Central Africa, the Middle East, and India. Winstanley concluded that instead of withdrawing northward as the Northern Hemisphere warms up each summer, the lower hem of the vortex has stayed

continued page 150

Weather *continued*

unusually far south. In turn, the great desert-forming belts of descending air have been pushed farther south into heavily populated regions. The outward rush of air from these high-pressure zones has prevented the moisture-laden summer monsoon winds from penetrating into grazing lands that are dry the rest of the year. So the blocked monsoons ended up dropping their precious rainfall into the oceans or into regions that already have too much rain anyway.

If deserts move south

Winstanley also noted that some areas to the north, on the Mediterranean coast, had been getting unusually heavy rainfall, while farther north still, in the British Isles, for example, rains had been generally scanty in recent years. He concluded that all these weather peculiarities derived from the same general circumstances: namely, the expanding size and the increasing waviness of the circumpolar vortex. If these weather patterns persist, they will shift entire deserts such as the Sahara southward, and all mankind's efforts to halt such climatological encroachment by, for example, planting windbreaks, or irrigation, will be futile.

By now, many experts agree that the circumpolar vortex is behaving in the peculiar way Winstanley describes. Reid Bryson ties this behavior mostly to the global cooling trend and the widening temperature gap between the poles and the equator. In effect, the circumpolar vortex is acting a little as though it were winter all year round, refusing to contract poleward and smooth itself out.

Even though man's increasing production of carbon dioxide has helped to moderate the cooling trend and should continue to do so, Bryson contends that the greenhouse effect may actually be contributing to the troubles in the monsoon belt. Carbon dioxide in the atmosphere warms the earth's surface more than it does the upper air. The effect of a greater ground-to-air temperature differential is to increase the force of the upward movement of air at the equator and therefore the downward rush of air over the deserts.

Some climatologists remain unconvinced by Bryson's theories about the cause of the present cooling trend and the likelihood of its persistence. One of the most prominent of them is J. Murray Mitchell Jr., of the National Oceanic and Atmospheric Administration, who says, "I'm an agnostic. We observe these trends in the Northern Hemisphere, and we've seen they're real. But we can't find the central tendency of the trends or know how long they will last." Mitchell emphasizes that it's impossible to predict volcanic activity, and that climatic change appears to be a random matter. He suspects, though, that the present cooling trend will reverse itself for natural reasons, aided, perhaps, by the greenhouse effect. This would ease the blockage of the monsoons.

Other doubters include astronomer Walter Orr Roberts and M.I.T. meteorologist Hurd Willett, who suspect that climatic change is influenced by variations in the sun itself. They are among a number of meteorologists who have long puzzled over an apparent—though disputed—relationship between weather patterns and the eleven-year sunspot cycle. So far, though, no one has much in the way of an acceptable theory as to just how sunspots, which seem to cause only very small changes in solar energy, could exert any observable effect upon the climate.

Bad odds for optimists

Others emphasize that climatological theory as a whole is still far too primitive to predict what the future holds. One of these is Stephen Schneider, who is attempting to construct a mathematical model of climatological change at the National Center for Atmospheric Research in Boulder, Colorado. Schneider believes that there's just as much in the way of physical evidence favoring a future warming trend as there is for continued cooling. Nevertheless, Schneider acknowledges that past experience can at least help to educate guesses about what the future holds: "If you were a gambler looking over the

continued page 152

record and saw a temperature peak such as the one we've just been through, you wouldn't gamble that we're going to go back to *that* again. So Bryson has got his fingers on what is potentially a very serious problem."

A surprising number of respected figures in the field are willing to go along with Bryson's grim scenario—or at least regard it as a plausible outcome, based on present knowledge. Britain's Hubert Lamb, together with colleagues, is completing a study of last year's drought conditions in Africa, Trinidad, and the northern part of South America. Like Bryson and Winstanley, Lamb's group is coming to conclude that the droughts are associated with the cooling trend and particularly with the cooling of the Arctic. "Bryson and I have got an almost identical view of this," says Lamb, "but one must remember that there are quite important fluctuations in a rather short time scale going on all the time, superimposed on this long-term trend, so to speak. Probably 1973 was a particularly bad year."

Banking food for emergencies

A fervent convert to Bryson's position is Kenneth Hare, of the University of Toronto, former president of Britain's Royal Meteorological Society, and now director general of research on the environment for the Canadian government. "Bryson is the most important figure in climatology today," Hare declares. "I'm naturally a lot more conservative than he is, but I take what he says very seriously indeed." Hare is interested in persuading governments to establish food banks to meet the climatic emergencies that he thinks may come to pass. "I don't believe the world's present population is sustainable if there were more than three years like 1972 in a row," he says.

No one has much idea as to how long the new climatic regime will last or how far it will proceed. At best, though, there's considerable inertia in the climate-generating system in the form of vast depths of ocean water that, once cooled, would take decades, at least, to warm back up again. Lamb's investigations reveal that past cool periods usually lasted for about a century, the minimum being about forty years.

Bryson believes that monsoons will probably not return regularly to regions such as northern India during the remainder of this century. If he is correct, there would seem to be scant prospect that even the present populations of the monsoon belts can be maintained, even if all the arable land in the rest of the world were placed in full production for this purpose.

Why empires fell

Recently, some archaeologists and historians have been revising old theories about the fall of numerous elaborate and powerful civilizations of the past, such as the Indus, the Hittite, the Mycenaean, and the Mali empire in Africa. There is considerable evidence that they may have been undone not by barbarian invaders but by climatic change. Bryn Mawr archaeologist Rhys Carpenter has tied several of these declines to specific global cool periods, major and minor, that affected the global atmospheric circulation and brought wave upon wave of drought to formerly rich agricultural lands.

Refugees from those collapsing civilizations were often able to migrate to better lands. And Bryson speculates that a new rainfall pattern might actually revive agriculture in some once-flourishing regions such as the northern Sahara and the Iranian plateau where Darius's armies fed. But this will be of little comfort to people afflicted by the southward encroachment of the Sahara. The world is too densely inhabited and politically divided now to accommodate mass migrations.

McQuigg at Missouri and several researchers in a food-climate research project under way at Wisconsin's Institute for Environmental Studies are also concerned about the impact of climate change upon the highly specialized crop strains developed in the vaunted green revolution. They suspect that the price that has been paid for the high productivity may be lack of adaptability. The grains have been optimized for the narrow spectrum of temperature and rainfall that has prevailed in recent decades. There's reason to assume, say these researchers, that even though the older strains yield less under optimum conditions, they are more tolerant and likely to yield more under the multiple stresses of climatic change.

Climatologists worry, too, that powerful nations may try to overrule nature through ill-considered engineering projects. In the U.S.S.R., for example, a third of the grain crop comes from the drought-prone virgin lands of Siberia, and there has been talk of diverting some of the great Siberian rivers into vast irrigation projects. These rivers empty into the Arctic Ocean, where the light, fresh water spreads out atop the salt water and permits the arctic seas to freeze over. According to some experiments by a Russian scientist, O.A. Drozdov, and by British meteorologist R.L. Newson, who constructed a mathematical model of winds in the Northern Hemisphere, the paradoxical consequence of preventing the freezing of the Arctic Ocean is likely to be that winters would become colder and drier over many continental areas in middle latitudes. Even some prominent Soviet meteorologists have spoken out against the proposal. But if disastrous, prolonged droughts were to overtake the Siberian wheatlands, Soviet authorities might conclude that there is little to lose in going ahead with the projects.

Plenty of margin for error

From the anthill perspective of a human lifetime, it is easy to perceive the sand-grain texture of weather but hard to comprehend the rolling topography of climate. Perhaps the most crucial insight to be gained from what the climatologists are learning is not some exact forecast of future climate, but rather that climate is, for calculational purposes, not a constant factor. Rather, it appears to be a wildly fluctuating variable—and a more important problem than others that we know a lot more about. In writing the equations for mankind's survival, we'd better allow plenty of margin for error. END

8 March 1974, Volume 183, Number 4128 **SCIENCE**

Atmospheric Effects of Pollutants

Pollutants which affect clouds are most likely to produce modifications in weather and climate.

P. V. Hobbs, H. Harrison, E. Robinson

In this article we shall consider some of the present and potential future influences of pollution upon the atmosphere, particularly upon the earth's temperatures, clouds, and precipitation. Our concern is with local, regional, and global effects. Included will be a discussion of atmospheric processes that may be affected by pollutants with subsequent impacts on weather and climate along with suggested criteria by which chemicals may be classified according to their effects upon atmospheric processes. We shall also discuss control criteria and monitoring and present summarizing conclusions and recommendations for attitudes toward and questions to be asked regarding possible future air pollutants as they may affect weather and climate.

Atmospheric Dispersion Cycle of Pollutants

The dispersion cycle of a pollutant through the atmosphere depends on the nature of the source, its dilution and dispersion by atmospheric motions, and the removal or scavenging of the pollutant by atmospheric and surface processes. In the evaluation of a new material as a potential source of air pollution one should consider the material at the various stages in its manufacture and disposal. The material may initially reach the atmosphere during production, when, because of a lack of adequate emission control, a significant amount of it may be vented into the atmosphere. The production phase may also be a source of significant by-products which may be important environmental pollutants. In fact, by-product emissions constitute a large fraction of current industrial air pollution problems [for example, sulfur dioxide (SO_2) from smelters or aerosol particles from pulp and paper mills]. A material may also become an air pollutant as a result of its use (for example, solvents or additives in fuel). Usage sources may also be divided on the basis of whether or not combustion is involved, because combustion provides a mechanism for chemical change. The last stage of the usage cycle in which a potential for air pollution is present is in final disposal. Incineration is probably of most concern, but the volatilization of certain materials can also produce air pollutants.

For meteorological purposes, sources should also be classified according to their geometry. An isolated source, such as an industrial stack, is a "point source" and may cause relatively high concentrations of pollutant emissions in local areas downwind from the source. Turbulence in the atmosphere disperses a point source emission both laterally and vertically relative to the average wind, and this causes a relatively rapid dilution of the emission with distance downwind. Another type of source geometry is the "area source" which can be considered to be made up of a large number of small sources distributed more or less uniformly over a large area. Vehicle exhausts or home heating emissions are typical examples of sources that may be considered as components of an area source. Because of the size of an area source, dispersion in a crosswind direction is generally ineffective in diluting the effluent cloud and thus the reduction in concentration downwind must be accomplished by vertical mixing processes. Decisions on whether a given source should be classed as a large point source or a small area source should be made on the basis of whether or not crosswind dispersion is an effective factor in diluting the plume.

Atmospheric diffusion models may be applied to estimate the downwind concentration field of a pollutant (*1*). In areas close to a point source the height of the emission plays a role in the concentration pattern. At distances represented by significant travel times the same diffusion model may be used for both point and area sources, and the long-range wind trajectory becomes the controlling factor in estimating exposure levels. Through the successive application of modeling schemes and with the appropriate climatological data, estimates of global concentration fields can be developed. The simpler modeling schemes can be modified to include various atmospheric processes that tend to scavenge the materials from the atmosphere (*2*).

Temperatures in cities are commonly 2° to 3°C and occasionally as much as 10°C higher than those in neighboring rural areas (*3*). Although this effect, which is referred to as the urban "heat island," is not due principally to chemical emissions, we mention it here because it can play a role in the dispersion of pollutants in cities. The urban heat island is produced primarily by the large areas of concrete and asphalt in cities, which absorb and store heat better than vegetation or soil and which

Dr. Hobbs is professor of atmospheric sciences and director of the Cloud Physics Research Group, University of Washington, Seattle 98195. Dr Harrison is associate professor of atmospheric sciences, University of Washington. Dr Robinson is professor of civil engineering in the Air Pollution Research Unit, Washington State University, Pullman 99163.

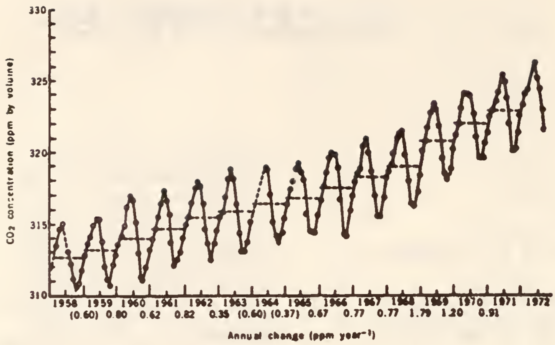


Fig. 1. Mean monthly CO_2 concentrations at Mauna Loa, Hawaii. Horizontal dashed lines indicate average yearly values. Annual changes in parentheses are based on an incomplete record. [Data from Keeling *et al.* (*14*)]

impede transpiration cooling. This effect is compounded by the enormous quantities of heat injected into the air in cities from combustion processes and air-conditioners.

Cities also affect winds by virtue of channeling by streets and the increased "roughness" of the surface topography (*3*). On the average, the winds measured in the downtown area are about 10 percent less than at an airport on the outskirts of a city. However, in light winds (less than about 15 kilometers per hour) the reduction can be as high as 40 percent. Since light winds often accompany synoptic situations conducive to air pollution, reductions in wind speeds caused by buildings in cities can be especially harmful.

Once pollutants are emitted to the atmosphere, transformations and scavenging processes begin to affect them and to act in concert with dispersion factors to increase dilution. These transformation or scavenging processes include both chemical reactions and direct removal mechanisms (*4*).

Precipitation provides the major mechanism by which pollutant materials are removed from the atmosphere. Although gaseous materials may be dissolved in cloud droplets and raindrops, aerosol particles are especially susceptible to precipitation scavenging mechanisms. Small particles can be incorporated into cloud droplets and ultimately into rain if they act as condensation or freezing nuclei. At later stages in the growth processes, particles may be brought into contact with cloud droplets or ice crystals by Brownian motion and thermophoretic and diffusiophoretic effects. If the pollution and precipitation particles are in the proper size range, pollutants may also be captured by precipitation particles as they fall to the ground. Studies of nuclear fallout have shown that precipitation scavenging processes account for about 80 to 90 percent of the atmospheric aerosol removal in regions with moderate rainfall (*4*).

Aerosol Dynamics

Some of the earth's aerosol burden is injected into the air directly (for example, by forest fires, volcanoes, and wind-scoured dust). In addition, however, many complicated processes can generate aerosol gas-to-particle conversions, and the particles can then grow by surface chemistry and physical accretion. Photochemical reactions of gaseous species, especially of the nitrogen oxides, promote oxidative attack upon naturally occurring forest terpenes and waste industrial organic molecules to produce the hygroscopic and polymeric species of smog (*5*). Sulfur dioxide from smelting wastes and fuel combustion oxidizes (in large part heterogeneously but also with the aid of nitrogen oxides) to form sulfur trioxide (SO_3), which hydrolyzes to sulfuric acid (H_2SO_4) mists and ammonium sulfate aerosols. The number density and surface density of the resulting aerosol populations increase markedly at the small end of their size spectra, that is, at radii much less than 0.1 micrometer, which is about the threshold for appreciable interaction of the aerosol particles with light (*6*). Consequently, most of the primary gas-to-particle conversions are also concentrated among the smallest particles. Particles with radii in excess of 1 μm begin to settle out by gravitational sedimentation and, with increasing efficiency, to be washed out by clouds and rain. Intermediate populations are maintained in a quasi steady state by coagulation kinetics.

Particles grow and shrink in response to local humidities, and multiplication processes and chemical reactions may occur in evaporating clouds (*7*). Surface-active chemicals, such as fatty acids and alcohols, alter coagulation kinetics and may "stabilize" the large particles by impeding their growth.

The complexity of processes affecting aerosol kinetics and the resulting populations of particle sizes and types enhance the possibilities for minor atmospheric constituents to amplify effects. For example, aerosols may influence the vertical temperature structure of the atmosphere, which in turn influences mixing and dispersion and the buildup of aerosols.

Cloud and Precipitation Processes

Perhaps the most sensitive atmospheric processes which can be affected by air pollutants are those involved in the development of clouds and precipitation. The structure of clouds with temperatures below 0°C (that is, cold clouds) can be modified, and under certain conditions precipitation from them altered, by particles which are termed ice nuclei (*8*). The concentrations of natural ice nuclei in the air appear to be very low (about 1 per liter, therefore only about 1 in 10^8 airborne particles are ice nuclei). Consequently, even very few particles which are effective as ice nuclei at temperatures above about −15°C have the potential for modifying the structure of clouds and the development of precipitation. If the concentration of the anthropogenic ice nuclei is about 1 per liter, the result may be an enhancement of precipitation; however, if the concentration is greatly in excess of 1 per liter, the result will be a tendency to "overseed" cold clouds and reduce precipitation. Certain steel mills have been identified as sources of ice nuclei. Also of concern is the possibility that emissions from automobiles may combine

with trace chemicals in the atmosphere to produce ice nuclei.

Precipitation from clouds that have temperatures above 0°C (that is, warm clouds) may be modified by particles which serve as cloud condensation nuclei (CCN). Efficient CCN are hygroscopic particles with sizes in excess of a few tenths of a micrometer. A source that produces comparatively low concentrations of very efficient CCN will tend to increase precipitation from warm clouds, whereas one that produces large concentrations of somewhat less efficient CCN might decrease precipitation. Modifications in the structure of clouds and precipitation have been observed many miles downwind of fires (*9*) and pulp and paper mills (*10*), both of which emit CCN into the air.

Apart from effects on precipitation processes, inadvertent modification of the microstructure and distribution of clouds will affect radiative properties. Such changes could have profound effects on atmospheric temperature distributions and global climate (*11*).

Radiation Balance

Many molecules absorb strongly in limited parts of the spectrum, particularly in the infrared region; for example, water vapor (H_2O), carbon dioxide (CO_2), and ozone (O_3) each significantly affect the heat transfer of outgoing thermal radiation from the earth's surface (*12*). The infrared radiation is a minor part of the incoming solar power, however, which peaks at wavelengths near 0.5 μm. Around this wavelength only two atmospheric molecules normally occur in concentrations sufficient for their molecular absorptions to significantly affect the atmospheric heating rate, namely, O_3 and nitrogen dioxide (NO_2).

The O_3 absorbs strongly in the ultraviolet, with a maximum cross section of 10^{-21} square meter at 0.25 μm. At longer wavelengths absorption by O_3 is weaker, and near the earth's surface the normal background concentrations of O_3 produce average heating rates less than 10^{-3} °C per day; in dense urban smog, O_3 concentrations occasionally approach 1 part per million (ppm), with the result that direct heating rates may approach 0.1°C per day. Even the larger of these rates is negligible by comparison with advective heat transfer upward from the hot surface of the earth. Therefore, O_3 is not a significant direct agent for energy input to the lower atmosphere. However, O_3 is intimately associated with aerosol formation in photochemical smogs and may, therefore, indirectly affect the radiation balance.

The NO_2 absorbs strongly in the visible, with a richly structured spectrum of mean cross section 2×10^{-23} square meter between 0.30 and 0.55 μm. Integrated over the solar spectrum, the mean mixing fraction of NO_2 (that is, the number of moles of NO_2 divided by the total number of moles in the air) in the remote troposphere is 3×10^{-9}, and this mixing fraction produces a heating rate of 0.06°C per 12-hour day at the earth's surface. Mixing fractions of NO_2 greater than 10^{-6} have been observed in Los Angeles, and NO_2 with mixing fractions greater than 0.5×10^{-6} and 0.25×10^{-6} occurs there for short time periods with an average expectancy of 3 and 29 days per year, respectively. The greater of these values results in heating rates of 1°C per hour, a very significant contribution (*13*).

In addition to direct heating by molecular absorption, the radiation balance of the atmosphere is affected by aerosol absorption and scattering. Heating rates are especially sensitive to the imaginary part of an aerosol's index of refraction and to the particle size distribution. In the troposphere, remote from large cities and industries, an aerosol burden of about 10^{-8} kilogram per cubic meter of air produces a heating rate corresponding to 0.5°C per 12-hour day (*14*). In urban areas, on the other hand, the heating rate may exceed 1°C per hour, although this neglects multiple scattering. Such a heating rate will profoundly influence the vertical temperature distributions and stabilities above smoggy cities.

In the troposphere, the main mechanism by which a parcel of air cools is by adiabatic expansion during lifting. The predominant mode by which a parcel loses energy is by infrared radiation in the numerous molecular bands of H_2O vapor and CO_2, and by graybody thermal emission from water clouds. Atmospheric constituents with mixing fractions less than 10^{-6} are unlikely to contribute significantly to cooling the air by direct molecular emissions, and even in dense aerosols near cities cooling by graybody radiation can be neglected. Thus, any trace chemical introduced into the atmosphere is unlikely to affect the heating or cooling of the air through direct molecular contributions. However, since aerosols and NO_2 are significant contributors to the heating of the air and since these substances and O_3 interact chemically, any trace chemical which interacts with these constituents has the potential for altering the radiation balance of the earth.

Of great interest and importance to the problem of predicting the effects on atmospheric motions is the observation that, for aerosol spatial distributions which are initially more or less uniform below a critical altitude (as is frequently the case below inversions), heat deposition by aerosol absorption may be concentrated just below that critical altitude with the result that the inversion may be intensified. The converse may also occur when an initial vertical distribution of aerosol burden diminishes exponentially with height, as is frequently the case in unstable air. Incoming radiation may then penetrate the upper and more tenuous aerosols without much heat deposition and instead heat the air at lower altitudes. In this case, the added heating rate at low altitudes may enhance vertical mixing so as to reduce low-level pollution, which then in turn reduces the radiation heat input. Thus, radiation heating by aerosols may operate either to intensify periods of pollution or to speed their dispersal, depending upon the vertical distribution of the aerosols (*13*).

Global Effects

Like the weather, the climate of the earth fluctuates with time but on a longer time scale. Prior to the industrial revolution, changes in climate were almost certainly unrelated to human activity. However, in recent years the question has arisen whether the activities of man might be changing world climate (*8*, *11*).

The atmospheric constituent most often mentioned in this regard is CO_2. The concentration of CO_2 in the air has increased by about 10 percent since the beginning of the Industrial revolution (Fig. 1). This increase is attributed to the consumption of fossil fuels. Simple theoretical models predict that increases in the concentration of CO_2 in the air should result in increases in temperature at ground level as a result of the "greenhouse" effect. Climatological data indicate that the earth's average annual surface temperature did, in fact, increase by about 0.6°C from 1880 to 1940. Since 1940, however, this temperature has been decreasing and is now about 0.3°C lower than in 1940.

Table 1. Estimated particle production in units of 10^6 metric tons per year due to natural phenomena in all countries. [From Peterson and Junge (*18*)]

Source	Particle diameter	
	> 5 μm	< 5 μm
Direct particle production		
Sea salt	500	500
Windblown dust	250	250
Forest fires	30	5
Meteoric debris	10	0
Volcanoes (highly variable)	?	25
Total	790+	780
Particles formed from gases		
Sulfates	85	335
Hydrocarbons	0	75
Nitrates	15	60
Total	100	470

Table 2. Estimated particle production in units of 10^6 metric tons per year due to human activities in all countries. [From Peterson and Junge (*18*)]

Source	1968		2000, < 5 μm
	> 5 μm	< 5 μm	
Direct particle production			
Transportation	0.4	1.8	
Stationary sources (fuel combustion)	33.8	9.6	
Industrial processes	44.0	12.4	
Solid waste disposal	2.0	0.4	
Miscellaneous	23.4	5.4	
Total	103.6	29.6	100
Particles formed from gases			
Converted sulfates	20	200	450
Converted nitrates	5	35	80
Converted hydrocarbons	0	15	50
Total	25	250	580

The changes in temperature in recent years raise the question of possible climatic effects attributable to increased particulate loading. There are some indications that there is an upward trend in the concentrations of particles in the air in the Northern Hemisphere and also at some locations in the Southern Hemisphere which are close to large cities or industrial areas. Estimates of the contributions to particles in the atmosphere due to natural and anthropogenic sources in 1968 and the year 2000 are given in Tables 1 and 2.

The meteorological effects of airborne particles depend on their optical and chemical characteristics, as well as on their sizes. Most important are the optical absorption and scattering properties of particles, about which very little is known. At the present time, it is not possible to predict with certainty even the sign of the ground-level temperature change that would accompany an increase in the concentration of atmospheric particles. Increases in particulate loading could increase the amount of solar energy reflected back into space, so that the atmosphere would be cooled (*15*). This might be the reason for the observed decreasing temperatures in recent years. However, if the particles had an absorption-to-backscattering ratio greater than a critical value, the lower atmosphere would be warmed by an increase in particulate loading. Moreover, the sign of the effect depends on the distribution of the particles between and above cloud layers. The weight of arguments at this time probably favors cooling rather than warming as a direct effect of increased particulate loading. It is our opinion, however, that coupled effects between particles and clouds are likely to outweigh direct albedo effects from the particles themselves.

The earth's stratosphere, which is situated between 10 and 50 kilometers above the surface of the earth, is particularly sensitive to pollutants because the residence time of gases and submicrometer sized particles is 1 to 3 years (by comparison, the residence time in the troposphere is 1 to 2 weeks). Photochemical processes occur in the stratosphere, especially O_3-forming reactions, and the dominant heating results from the absorption of solar energy by O_3. Moreover, O_3 absorbs solar radiation at wavelengths shorter than about 0.3 μm and thereby provides a protective shield for protoplasm in the troposphere. These considerations have stimulated concern over possible modifications in stratospheric chemistry that might be caused by supersonic aircraft (*8*, *11*). In particular, it appears that nitrogen oxides released in the stratosphere by such aircraft could lead to a significant reduction in the O_3 content if the mixing ratio of the natural nitrogen oxides in the stratosphere is significantly less than 10^{-8} (*16*). Unfortunately, good measurements of the concentrations of nitrogen oxides in the stratosphere are not yet available. The destruction of atmospheric O_3 through "wet photolysis" might also be important (*17*).

Criteria for the Classification of Potential Air Pollutants

In order for a chemical to affect the atmosphere significantly, it must have a physical state compatible with residence in the atmosphere. In principle, any chemical with a finite vapor pressure can become airborne and exist in the atmosphere at concentrations up to an equilibrium value. For example, a chemical compound with a vapor pressure of only 10^{-6} torr (760 torr = 1 atmosphere) can reach its equilibrium concentration of approximately 1 part per billion (ppb) in the air. Similarly, a chemical with a vapor pressure higher than the ambient pressure boils in the atmosphere and may be present in the atmosphere at any mixing fraction.

For species that are molecularly dispersed, the requirement for appreciable vapor pressure immediately sets upper limits upon molecular weights and dipole moments. For nonpolar molecules (for example, alkanes) vapor pressures at 10°C correspond approximately to mixing fractions of 1 ppm of $H_2(CH_2)_{16}$ and 1 ppb of $H_2(CH_2)_{22}$, which have molecular weights of 226 and 310, respectively. For increasingly polar molecules the lower the molecular weight, the less may be the volatility. Thus, nitrobenzene ($C_6H_5NO_2$) has a mixing fraction at room temperature near 10 ppm, despite the fact that its molecular weight is only 123. Therefore, for chemical species with molecular weights substantially higher than 200 to 300, molecular residence in the atmosphere is incompatible with appreciable mixing fractions. Nevertheless, many of these heavy species can and do significantly affect the atmosphere, but they exist as aerosols rather than as dispersed molecules.

Molecular dipole moments not only affect vapor pressures but also act to enhance solubility in polar fluids, such as water. Similarly, strongly ionic crystals dissolve more readily than covalent or metallic substances. Consequently, polar and ionic species which may enter the atmosphere are preferentially absorbed, dissolved, and concentrated in aqueous clouds. This process facilitates both heterogeneous and aqueous chemistry, which may transform the chemical nature of the original tracer species, and precipitation washout, which may remove these species from the atmosphere entirely.

We have noted that one of the most profound potential effects of extraneous material added to the atmosphere is its possible action as ice nuclei or CCN. The effectiveness of any such agent is related largely to its physical properties, for example, a crystal structure resembling that of ice in the case of ice nuclei and high solubility in the case of CCN. Therefore, these physical properties are signals that may be used to warn of the need for cautionary action.

Among many others, the following kinds of molecules are likely in various ways to interact strongly with photochemical oxidation sequences in the air: (i) photoactive molecules which may form O, OH, H, or halogen atoms in ultraviolet or visible radiation; (ii) free-radical scavenging molecules (these first two kinds of molecules will be especially active if any mechanism exists for a regenerating chain); (iii) molecules with double bonds, –C=C–, especially conjugated double bonds, –C=C–C=C–; (iv) molecules with aromatic and heterocyclic rings, especially adjacent to vinyls, nitrates, sulfates, and amines; (v) molecules that form long-lived triplet states by absorption near 3000 to 4000 angstroms (substituted naphthalenes, anthracenes, and similar species); and (vi) molecules with strained rings (that is, three-, four-, or seven-membered rings).

Control Criteria

The most elementary precautionary criterion of possible disturbance to the atmosphere of a chemical discharge is that of amount. For each possible chemical constituent, a concentration exists below which the effect of a chemical on the atmosphere will either not be measurable or will be of less significance than natural atmospheric constituents. However, our experience with the difficulties associated with defining any acceptably "negligible" background of radioactive wastes must be taken as a warning that similar difficulties are likely to arise in efforts to determine future control concentrations for many other chemical discharges into the atmosphere. Nevertheless, we can suggest certain concentrations of chemical contamination below which it is increasingly improbable that "significant" atmospheric effects can be expected. We do this by looking at present minor atmospheric species and noticing the concentrations at which we begin to call them to account in explaining atmospheric phenomena.

Table 3. Approximate minimum concentration thresholds for atmospheric effects due to minor constituents.

Species	Effect	Threshold	
		Volume per unit volume of air	Kilograms per cubic kilometer of air
Ice nuclei	Cloud structure and precipitation	10^{-18}	10^{-6}
CCN	Cloud structure and precipitation	10^{-15}	10^{-4}
Aerosols	Visibility and heating rates	10^{-13}	10^{0}
HCl, H_2SO_4	pH of rain	10^{-11}	10^{-6}
Aerosols	pH of rain	10^{-10}	10^{0}
NH_3	pH of rain	10^{-10}	10^{-1}
SO_2	pH of rain	10^{-9}	10^{1}
NO_2	Visibility and heating rates	10^{-7}	10^{3}
O_3	Heating rates	10^{-6}	10^{3}

Table 3 illustrates some of these species and their associated thresholds for affecting particular processes. The direct influences of certain trace gases upon state variables, such as temperature and wind velocity, can be expected at concentrations as low as 10^{-2} kilogram per cubic kilometer of air. Owing to the great variety and complexity of measurable effects in the atmosphere, we judge it likely that most chemicals will measurably affect one process or another when their concentrations approach or exceed 10^3 per cubic kilometer of air (or mixing fractions near 1 ppm). We judge it unlikely that any added chemicals will "appreciably" affect atmospheric processes at concentrations near to or below 1 gram per cubic kilometer of air (or 10^{-8} ppb), except those which act as ice nuclei or CCN and modify the structure of clouds.

Perhaps next in order of elementary criteria to assist one in judging possible mischief to the atmosphere induced by added chemicals is the question of the rate of discharge. Since the concentration of a tracer chemical on any scale, from microclimate (tens of meters or less) up to global systems ($\simeq 10^4$ kilometers), results from the time-dependent interplay of sources, transport, and sinks, the rates of each of these processes must be considered in estimating both the concentrations and the spatial distributions which may be attained by atmospheric chemicals. Upper limits in acceptable concentrations imply upper limits in acceptable input rates.

Since the transport of chemicals in the atmosphere and the sinks for the chemicals are not constant, an acceptable source rate may be difficult to specify. As an example of what is probably an excessive rate, we are familiar with a single source of SO_2 of 5 kilograms per second from a copper smelter which has the effect of reducing the mean pH of rainfall, measured at 70 kilometers downwind, one pH unit below its normally CO_2-buffered value of 5.6. This example illustrates a condition in which the sources and sinks are rather large, yet the concentrations of ambient SO_2 and sulfate aerosols remain fairly low (5 to 20 ppb) by comparison with other localities which enjoy comparable input but less active transport and washout. For this circumstance a control limit on the input flux of chemicals to the atmosphere would probably be more sensible than a limit on ambient concentrations. The determinations of which of these alternate control criteria will best suit any particular chemical depends principally upon the nature of the sink.

We turn now to several specific suggestions on control criteria.

1) We believe that the influences of chemical wastes on weather and climate are likely to be greatly amplified if they affect clouds. The presence or absence of clouds and their nature can have dramatic effects, as can small changes in their frequency or placement. Therefore, changes in clouds produced by aerosols generate enormous relative differences per unit of aerosol mass. Consequently, control attention should be directed especially to a chemical's prospective effects on cloud modification and aerosol dynamics.

2) Regenerating chains of chemical interactions, for example, those involving OH and the oxides of nitrogen, are especially sensitive to modification by additional chemicals which may compete for the chain-carrying radicals. We particularly emphasize the importance of OH and the need to develop and deploy analytical techniques to

Table 4. Some questions and comments on atmospheric pollutants.

Question	Comments
1. What atmospheric process is the discharge likely to affect?	Controls should be based on known or postulated effects of the pollutants (see Table 3).
2. Is the discharge large or small relative to the concentration of the same or other agents in the atmosphere which act similarly?	A discharge must cause an appreciable change in the concentration of the same or similar agents in order to affect an atmospheric process.
3. Are all the constituents of the effluent known?	Trace substances might have more impact on the atmosphere than the primary constituents.
4. Will any of the chemicals in the discharge react with atmospheric constituents?	Beware of regenerating chemical chains, especially those known to involve OH and nitric oxide (NO). Small influences on these two species may have large secondary effects (for example, photochemical reactions leading to smog formation).
5. Can chemicals in the discharge interact in the atmosphere to amplify their effects?	If so, beware! [For example, the reaction between SO_2 and ammonia (NH_3) in the gaseous phase is slow, but in the presence of cloud droplets it is accelerated enormously to produce sulfates.]
6. Is the discharge concentrated (a point source) or diffuse (an area source)?	The first may stimulate more complaints, but the latter more damage.
7. What concentrations are to be expected downwind from sources of pollutants?	Simple model calculations can be used to estimate these concentrations. (The results are not always reliable.)
8. Is the weather stagnant or dispersive?	Controlled emissions are generally best vented in dispersive conditions. However, in some cases discharges in dispersive conditions might produce more total damage by being distributed over a wider area.
9. What are the lifetimes and sinks of the pollutants?	Rapid sinks depress concentrations, but the throughput may remain high and the deposition concentrated.
10. Are the pollutants water-soluble or hygroscopic?	If so, they will concentrate in clouds, will be potentially active in modifying warm clouds, and will experience relatively short residence times in the atmosphere with possibly large local deposition.
11. Are the pollutants surface-active?	Surface-active molecules may coat cloud droplets and affect cloud and aerosol evaporation and coagulation.
12. Do the solid pollutants have crystal structures and dimensions similar to those of ice (that is, hexagonal) and are they insoluble?	If so, beware! They may nucleate ice in cold clouds and affect precipitation processes, even at very low concentrations.
13. Do the chemicals interact with visible light?	If so, they may contribute to atmospheric heating.
If so, (i) Do they photodissociate? (ii) Do they form reactive fragments such as free radicals and metastable atoms? (iii) Do they sensitize other chemicals?	Affirmative answers to these questions imply activity in photochemical processes affecting smog.
14. Do the chemicals interact with infrared radiation?	If so, they will affect radiation transfer, especially if they absorb between the strong lines of H_2O and CO_2. Absorption at these wavelengths will cause warming near the earth's surface but cooling in the stratosphere.
15. Most critical of all, do the pollutants affect aerosols which play a role in cloud processes?	If so, the structure and distribution of clouds may be affected by the pollutants, thereby causing changes in precipitation and optical scattering. Research priority should be given to this area.

measure its role in photochemical smogs.

3) We believe that present control criteria for many constituents based on ambient concentrations might profitably be reexamined to determine whether they might better be based upon area flux levels, or throughput. Variable emission licensing, adjusted to the local dispersive capacity of the air, might be explored. However, care must be taken that acute local problems are not converted into chronic regional or global problems.

4) In conventional monitoring for toxic materials, the risk function is usually assumed to be an increasing function of concentration multiplied by the exposure time. With monitoring for meteorological disturbances, similar risk functions may not be appropriate. Thus, risks may often maximize during periods which do not coincide with exposure levels (for example, clouds might be particularly susceptible to modification during periods of high humidity and moderate supercooling). In this case, a monitoring program geared to peak concentration episodes may be seriously misleading. In general, each postulated contaminant must be considered in the light of a likely contaminating mechanism or impact, and control schedules and risk functions defined accordingly.

5) Listed in Table 4 are some pertinent questions and comments on atmospheric pollutants.

Summary

We have argued that aerosols are probably the principal agents by which pollutants may affect weather and climate. They are most likely to act by influencing the structure and distribution of clouds. On the local scale, the effects of pollutants on some aspects of weather are unmistakable. The effects of man-made pollutants on global climate are a matter of debate, but they may already be significant.

References and Notes

1. See, for example, D. B. Turner, "Workbook of atmospheric dispersion estimates" [*U.S. Public Health Serv. Publ. 999-AP-26* (1969)].
2. L. Machta, O. Ferber, J. Heffter, unpublished report of the Air Resources Laboratories, National Oceanic and Atmospheric Administration, Silver Spring, Maryland 20910 (June 1973).
3. J. T. Peterson, *The Climate of Cities: A Survey of Recent Literature* (National Air Pollution Control Administration, U.S. Government Printing Office, Washington, D.C., 1969).
4. See, for example, *Precipitation Scavenging (1970): Proceedings of a Symposium Held at*

Richland, Washington, 2-4 June 1970 (available as CONF-700601 from the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22151).
5. P. A. Leighton, *Photochemistry of Air Pollution* (Academic Press, New York, 1961); H. Levy, *Planet. Space Sci.* **20**, 919 (1972).
6. C. E. Junge, *Air Chemistry and Radioactivity* (Academic Press, New York, 1963); K. J. Whitby, R. B. Husan, B. Y. H. Lin, *J. Colloid Interface Sci.* **39**, 136 (1972).
7. W. D. Scott and P. V. Hobbs, *J. Atmos. Sci.* **24**, 54 (1967); P. V. Hobbs, *Q. J. R. Meteorol. Soc.* **97**, 263 (1971).
8. Committee on Atmospheric Sciences, "Weather and climate modification: Problems and prospects" [*Natl. Acad. Sci.–Natl. Res. Counc. Publ. 1350* (1966)].
9. J. Warner, *J. Appl. Meteorol.* **7**, 247 (1968).
10. P. V. Hobbs, L. F. Radke, S. B. Shumway, *J. Atmos. Sci.* **27**, 81 (1970); R. C. Eagan, P. V. Hobbs, L. F. Radke, in preparation.
11. C. L. Wilson and W. H. Mathews, Eds., *Inadvertent Climate Modification* (MIT Press, Cambridge, Massachusetts, 1971).
12. R. M. Goody, *Atmospheric Radiation* (Oxford Univ. Press, Oxford, England, 1964).
13. P. D. Try, thesis, University of Washington (1972).
14. C. D. Keeling, A. E. Bainbridge, C. A. Ekdahl, P. Guenther, J. F. S. Chin, *Tellus*, in press.
15. S. I. Rasool and S. H. Schneider, *Science* **173**, 138 (1971).
16. H. Johnston, *ibid.*, p. 517.
17. W. B. DeMore, *ibid.* **180**, 735 (1973).
18. J. T. Peterson and C. E. Junge, in *Man's Impact on the Climate*, W. H. Mathews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Massachusetts, 1971).
19. This article is based on a more lengthy report prepared for the Working Conference on Principles of Protocol for Evaluating Chemicals in the Environment, organized by the Environmental Studies Board of the National Academy of Sciences at the request of the Environmental Protection Agency. We thank Drs. N. Nelson (chairman of the conference), H. Niki and L. Machta (members of the panel on the atmosphere), and the staff members of the Environmental Studies Board for their help in this study. Contribution No. 293 from the Atmospheric Sciences Department, University of Washington.

Selenium Biochemistry

Proteins containing selenium are essential components of certain bacterial and mammalian enzyme systems.

Thressa C. Stadtman

The element selenium was discovered by Berzelius in 1817 and the first organic compound containing selenium, ethylselenol, was prepared in 1847 (*1*). However, for many years few organic selenium compounds were known and, for the most part, these were considered mere chemical curiosities. Eventually, in the 1930's, selenium was identified as a potent toxic substance for cattle and other livestock, and this focused attention on the biochemical properties of selenium compounds. In 1957 selenium was identified as the essential component of a dietary factor that protected rats from severe necrotic degeneration of the liver (*2*). This finding soon led to the recognition by animal nutritionists that several important livestock diseases are actually selenium deficiency syndromes (*3, 4*). Nevertheless, even today the toxicity of selenium and selenium-containing compounds is more generally appreciated than is the essential nature of this micronutrient. It is becoming increasingly evident that animals, bacteria, and possibly higher plants all require trace amounts of selenium, and that when available in the proper amounts the selenium is incorporated in a highly specific fashion into certain functional proteins of the cell. When organisms receive more than micromolar concentrations of selenium, those enzyme systems that cannot distinguish it from its close chemical relative, sulfur (*5*), begin to substitute the selenium indiscriminately for sulfur in many cellular constituents. Because of the greater reactivity and lower stability of selenium compounds compared to the corresponding sulfur compounds, the cell may encounter metabolic problems which eventually can lead to death of the organism. In the present article an attempt is made (i) to discuss briefly those enzymic processes which do not distinguish selenium from sulfur and therefore may be important in selenium toxicity, and (ii) to summarize the current information concerning specific enzymic reactions in which selenium participates as an essential enzyme component.

Although selenium is present in detectable amounts in all soils, it is not usually present in toxic amounts except in semiarid regions in soils derived from cretaceous shales (*6, 7*). In humid climates, or under conditions of irrigation, most of the selenium is leached from soils of this type.

There is a group of plants known as selenium indicator plants that grow in semiarid regions in soils containing large amounts of selenium (*7*). A few of these plants are normally limited in distribution to such areas and, when cultured in the laboratory in solution or moist sand, they exhibit markedly improved growth in response to the addition of selenium (*8*). Selenium indicator plants that have been studied in some detail (*7*) are *Astragalus pectinatus* (narrow-leaved vetch), *A. bisulcatus* (two-grooved poison vetch), and *Stanleya pinnata* (prince's plume). Taxonomic descriptions of these and related species (*9*) usually mention the unpleasant odor of the plants. The bad odor is due to the presence in their tissues of large amounts of various selenium-containing organic compounds which are far more malodorous than their sulfur-containing analogs. In fact the amounts of organoselenium compounds in these plants are often sufficient to cause acute selenium poisoning of grazing animals. Death of the animal may occur within a few hours after ingestion of the toxic plants.

Types of Organoselenium Compounds in Green Plants

Accumulation of the selenium analogs of methionine, *S*-methylcysteine, gamma-glutamylcysteine, and cystathionine appears to account, at least partially, for the high selenium content of some species of selenium indicator plants of the genus *Astragalus*. From specimens of *A. pectinatus* which contained 1500 to 2000 parts per million (ppm) of selenium (1.5 to 2 grams per kilogram of tissue, dry weight) Horn and Jones in 1941 (*10*) isolated a crystalline material that, on the basis of

The author is a biochemist at the National Heart and Lung Institute, National Institutes of Health, Bethesda, Maryland 20014.

17 May 19/4, Volume 184, Number 4138 SCIENCE

A Perspective on Climatic Change

Climate responds rapidly and significantly to small changes of the independent variables.

Reid A. Bryson

In recent years, with the heightened concern about the impact of human activities on the environment and the more immediate concern about the impact of the environment on world food supplies, there has been an upsurge of interest in climatic change at all scales, from local to global. Discussions of climatic change in the general press and professional journals have ranged from completely theoretical to completely descriptive, and from detailed analysis of certain aspects of the problem to general speculation. However, there has been a dearth of discussion of climatic change from an historical perspective and minimal attention to certain important questions, such as: (i) How large must a climatic change be to be important? (ii) How fast can the climate change? (iii) What are the causal parameters, and why do they change? (iv) How sensitive is the climate to small changes in the causal parameters? This article is an attempt to provide an element of perspective on these questions.

How Big Is an Important Change?

Climatic variations range in size from those which mark the onset or end of a glacial epoch down to those which are questionably detectable by the present meteorological observing network. Clearly, variations that bring on ice ages are important. An ice sheet 4000 kilometers wide and 3 kilometers high, reaching from the Arctic to Ohio and from the Rockies to the Atlantic, certainly represents a significant modification of the North American environment. A concomitant worldwide reduction of sea level of 100 to 150 meters is also significant if one looks at a bathymetric chart. But how much change of climate is necessary to initiate or terminate such conditions? There are a number of estimates based on field data to answer this question (*1*).

Oxygen isotope analyses of deep sea cores in the tropics suggest glacial to postglacial changes of temperature of the order of a few degrees Celsius (*2*). Similar analyses of Greenland ice cores suggest temperature differences at high latitude of about 10°C (*3*), and analyses of pollens from Minnesota give a July mean temperature difference of 3° to 4°C (*4*), as shown in Fig. 1. Most careful analyses suggest a mean global surface temperature difference from full glacial to the present of 4° to 6°C, but with smaller and larger changes in specific areas. Most of the changes deduced from the geologic record, for specific places, fall within the range of individual monthly anomalies for the historical record.

Figure 1 gives not only the magnitude of the temperature change between glacial and postglacial, but an indication of the rapidity with which the climate can change to extreme conditions. The time resolution of most records of the Pleistocene-Holocene break is two to five centuries, but the few records which have finer resolution suggest that most of that dramatic climatic change occurred in a century or two at the most. Indicators such as biotic assemblages and areal extent of continental glaciers have time constants that tend to mask the rapidity of the changes (*5*).

On the scale of Fig. 1, it is clear that the character of the past ten millennia (the Holocene) is quite different from that of the preceding millennia (the Pleistocene) in terms of temperature, and that the mean temperature fluctuations within the Holocene are an order of magnitude smaller than the differences between epochs. One should not assume, however, that the fluctuations of climate during the Holocene were unimportant. The records of summer temperatures reflect radiation conditions dominantly. Other climatic parameters show more differentiation of the Holocene into distinctive episodes.

Consider, for example, the length of the growing season, precipitation during the growing season, annual hours of sunshine, and annual snowfall that parallel the July mean temperature for a location near Minneapolis, Minnesota, represented in Fig. 1 (Fig. 2). These plots are for a particular location, but, considering the integrity of the hemispheric circulation pattern, the postglacial climatic changes indicated here must have been associated with changes over large parts of the world. Clearly, the Holocene has not been a time of unchanging climate, even though the changes were smaller than those which terminated the Pleistocene. The period around 8000 years ago in southeastern Minnesota was only slightly warmer in July, but it was cloudier, drier in summer, less snowy in winter, and had a somewhat longer growing season than at present. In fact, if these reconstructions are correct, the climate was rather like that of Huron, South Dakota, at present. Certainly, in

The author is director of the Institute for Environmental Studies at the University of Wisconsin, Madison 53706, where he is also professor of meteorology and of geography. This article is based on a lecture given at the AAAS meeting in Washington, D.C., on 28 December 1972.

terms of agriculture, this represents a significant difference.

The last 2000 years is not only a period for which we have a great deal of historical information, but it is also a distinct climatic period within the Holocene. However, the time resolution of the data for Figs. 1 and 2 is too coarse for us to explore the question of climatic changes over shorter historical periods and their significance. There is a suggestion of such changes in those figures but too much uncertainty as to timing. In order to get more resolution we may turn to the work of Lamb (*6*) and Bergthorsson (*7*).

Bergthorsson has reconstructed the decadal mean annual temperature for Iceland over the past 1000 years from the historic records of the duration and extent of sea ice on its shores. By calibrating the ice record against the observed climatic data for the past century and a half, he was able to derive a regression equation that makes possible a rather credible decadal temperature plot for the past millennium (Fig. 3).

Figure 3 puts the present and the climatic "normal" period 1931 to 1960 into perspective. The normal period is normal only by definition. There appears to be nothing like it in the past 1000 years.

Figure 3 also raises two pertinent questions: (i) How important are the mean temperature variations shown? (After all, the whole range is less than 2°C.) (ii) How representative is Icelandic temperature of climate other than that of Iceland? (It's a very small country.)

The significance of small mean temperature changes in Iceland is rather easy to demonstrate, thanks to the excellent documentation summarized by Thorarinsson (*8*) and others. Famines are noteworthy events in a subsistence economy, and if a chronicler describes the death of animals and people in winter and failure of the few crops and pastures in summer because of the cold, there is no a priori reason to doubt him.

According to Thoroddsen (*9*), there were 12 famine years between A.D. 975 and 1500, and 37 between A.D. 1500 and 1804. Of the first group of famine years, five were in the cold period between A.D. 1250 and 1390, and of the second group, 34 were between A.D. 1600 and 1804. The famines are clearly associated with the cold periods. This sensitivity of food production to small changes of climate may be illustrated by considering the nature of the agriculture in Iceland and the proportional effect of small mean temperature changes, as shown in Fig. 4.

The mainstay of Icelandic agriculture is grass and the flocks raised on it. In a climate of ample moisture the forage yield is approximately proportional to the number of growing degree-days above a base of 5°C. Figure 4 shows schematically that a decrease of 1°C in the mean annual temperature of Akureyri, Iceland, would reduce the length of the growing season by about 2 weeks, but would reduce the number of growing degree-days by 27 percent. A reduction of mean annual temperature by 2.4°C would reduce the number of growing degree-days by 54 percent and the growing season by 40 days (25 percent). This would be disastrous to a subsistence economy.

In the late 1950's, hay yields in Iceland averaged 4.33 metric tons per hectare with 2.83 kilograms of nitrogen fertilizer per hectare and a mean warm-half-year temperature of 7.65°C. In 1966 and 1967, the yields averaged only 3.22 metric tons per hectare with 4.83 kg of fertilizer, but with a mean temperature of 6.83°C. The climatic reduction of yield overshadowed the expected technological increase (*10*).

This discussion highlights the significance of small temperature changes in cold-limited, marginal northern agriculture, but does not show that climatic differences, such as those between the past century and the present, are important in a broader context. Along with changes of temperature, which are associated with changes of atmospheric circulation, there are also changes of precipitation. Wahl and Lawson (*11*) have documented the changes of seasonal temperature and precipitation from the period 1850 to 1870 to the modern "normal" period.

Most interesting is the change in the western half of the United States. In the earlier period the high plains and Rockies were up to 20 percent wetter for the whole year and 20 to 30 percent wetter in summer. Consider the high plains, which are currently semiarid range land, in terms of carrying capacity, and the vast bison herds of the last century. Assuming that the carrying capacity of the range for bison is proportional to the carrying capacity for cattle, figures given in the *Yearbook of Agriculture* (*12*) suggest that the bison herds would have diminished by 50 to 75 percent as the precipitation diminished in the late 19th century, even without overhunting.

At the present time of world food grain shortage, a return to the higher rainfall and range carrying capacity of the mid-1800's would be most significant, and yet such changes seem to be small compared to the intermillennial changes of the Holocene. A climatic change does not have to be large in absolute numbers to be important.

There is another way in which small climatic changes are important, and this is related to the physiology of trees and probably most perennials.

During one growing season a tree normally stores photosynthates in excess of that year's growth needs. This provides a reserve which is drawn on the following year and makes it possible for the tree to survive a single severe year. Pine trees also retain their needles for a number of years. These integrative mechanisms mean that the variance spectrum of tree response to climate should show suppressed response to high-frequency climatic variations, but accumulated response to small systematic changes in climate, and such spectra do (*13*). Thus, trees

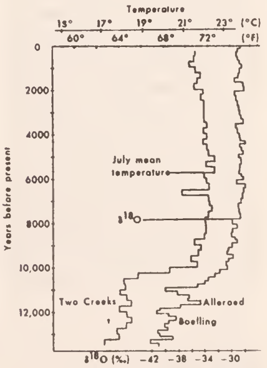


Fig. 1. July mean temperatures at Kirchner Marsh, Dakota County, Minnesota, compared with the oxygen isotope variation in Greenland over the past 13,000 years. The temperatures are from pollen data; the isotope variation is expressed as the per mil enrichment in ^{18}O, or $\delta^{18}O$, and should be proportional to the snow season mean temperature. Two Creeks, Alleroed, and Boelling denote late glacial intervals. Pollen data are from Wright *et al.* (*42*), analyzed by the method of Webb and Bryson (*4*), and isotope data are from Dansgaard *et al.* (*3*).

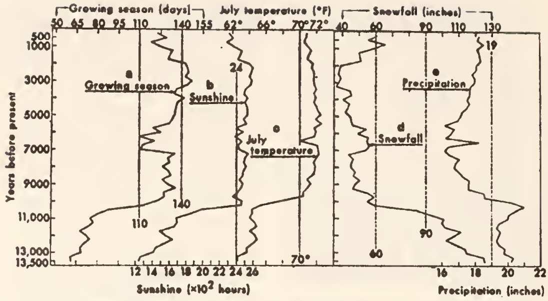


Fig. 2. Thirteen-thousand-year record of (a) length of the growing season, (b) hours of bright sunshine annually, (c) mean July temperature, (d) annual snowfall, and (e) precipitation during the growing season at Kirchner Marsh, Minnesota. The climatic data are derived from pollen data by canonical transfer functions.

can somewhat ignore large seasonal anomalies but integrate the effect of small systematic changes into the biomass of the forest. It is not realistic to say that, because trees survive the large interannual variations, climatic mean changes are unimportant.

Glaciers provide a clear-cut example of the significance of small systematic changes in climate. If ablation over the year is equal to or potentially slightly greater than the snowfall, there is no glacier. But if accumulation is greater than ablation by even a tiny amount, the glacier will inexorably grow. In the Canadian Arctic, on the Keewatin ice divide north of Baker Lake, snowdrifts last until late summer and the snows begin in September. August is cool and often cloudy. A slightly cooler summer that would reduce ablation slightly, or somewhat heavier winter snows—just enough to make the snowdrifts last a month longer, would let the September snows begin to accumulate on the residual of the previous year. Continued, this would inevitably result in a glacier. The region is marginally interglacial at present.

Reviewing Figs. 1 and 2, and dozens of similar diagrams, one finds that the past analog of the present climate is to be found in the transition from Pleistocene to Holocene; that is, the present climate is marginally interglacial.

According to Mitchell's work (*14*), the present episode of warmer temperature in the Northern Hemisphere began about 1920. It appears to be terminating at present (*15, 16*). Before 1920, stations in northwestern India experienced years with less than half of normal rainfall with a probability of .116 or a "return period" of around 8.6 years. From 1920 through 1960 the probability of such a dry year was .071 for a return period of about 14 years. During the 1930's, the warmest decade of this century in terms of mean temperature in the Northern Hemisphere, the probability was .055 or about once in 18 years. If the climate returns to that typical of the period before 1920, will a half-again-as-probable recurrence of drought be significant in that hungry land?

How Big Are the Causes of Climatic Change?

Considering the small absolute magnitude of significant climatic change, one might conclude prematurely that the climate is rather insensitive to changes in causal factors, or that there is some stabilizing influence, such as the oceans, which reduces the impact of changes in the causal factors. If this were the case, we could simply monitor those factors and anticipate when the changes were becoming big enough to be of concern. Let us consider whether this is the case.

As an extreme instance, assume that the entire Northern Hemisphere is covered by water and that the thermally active layer of this sea is 100 m deep. How much heat must be stored in this layer of water to produce a temperature rise of 0.5°C per 20 years? This figure is picked to match the increase of the mean surface air temperature in the Northern Hemisphere observed between 1920 and 1940. Simple arithmetic gives a figure of about 0.7 calorie per day per square centimeter of surface. Certainly, this is not currently measurable at any one point, and it is not likely that a rise in mean sea temperature of 0.1°C in 4 years would be readily monitored. Making the case more realistic by introducing continents of lower heat capacity reduces the heat storage required to simulate the observed change.

Reitan (*17*) estimates that the changes of solar radiation required to produce the observed temperature changes over the past century are of the order of 2 cal cm^{-2} day^{-1}. In order to monitor changes of 50 percent in this number, which might be produced by fluctuations in the solar constant, the solar constant would have to be measured with an accuracy of 1 part in 700. Judging from the variety of published values, one would conclude that the solar constant is not known to that accuracy, even though each published value may be assigned higher accuracy.

Assuming that the solar input of heat to the earth and back radiation from the earth were equal in 1920 and again in 1940, we may calculate how much

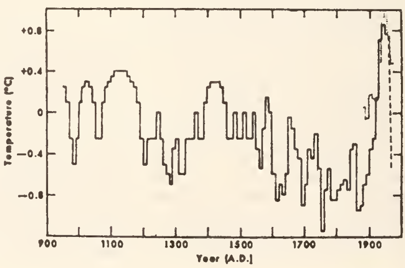


Fig. 3. Mean annual temperature in Iceland over the past millennium [data from Bergthorsson (7)]. The dashed line indicates the rate of temperature decline in the period 1961 to 1971, and the dotted line shows the variation of mean temperature in the Northern Hemisphere plotted to the same scale.

the albedo of the earth-atmosphere system would have to have diminished to account for the mean temperature rise of 0.5°C. A decrease from 35 to 34 percent would be more than adequate, yet we cannot measure the overall albedo with sufficient accuracy to know whether such changes have occurred or are occurring. To know whether the observed temperature change at the earth's surface was the result of changes in the greenhouse effect would require knowing the difference between the upward radiation from the surface of the earth and the upward radiation from the top of the atmosphere to an accuracy of about 1.6 percent, or about 0.004 cal cm^{-2} min^{-1}. This is probably beyond our present capability of measurement, but perhaps within the range of calculation as a relative change, if we assume that the parameters needed for calculation are known with sufficient accuracy.

The point of all this discussion is to emphasize the small magnitude of the variations in climatic causal factors needed to make significant, though small, climatic changes.

Of course, it may be argued that the global mean temperature is not really very important compared to changes in circulation pattern that might affect rainfall patterns.

Some light may be thrown on this question by considering a criterion derived by Smagorinsky (*18*). The defining equation is:

$$\tan \phi_c = -(H/R)\left(\frac{\partial\theta}{\partial z}\Big/\frac{\partial\theta}{\partial y}\right) \quad (1)$$

where ϕ_c is the latitude at which wave number one of the zonal flow becomes dynamically unstable (which in turn approximates, in practice, the latitude of the transition from Rossby regime to Hadley regime); H is a scale height, roughly the height of the 500-millibar level of the atmosphere; R is the radius of the earth; $\partial\theta/\partial z$ is the vertical lapse rate of potential temperature; and $\partial\theta/\partial y$ is the north-south gradient of potential temperature.

Empirically, ϕ_c is a good approximation to the subtropical anticyclone latitude at the surface as well as the latitude of the Rossby-Hadley transition aloft. Since the latitude of the subtropical anticyclones is critical to the great subtropical desert regions, the monsoon regions, and the equatorward portions of the Mediterranean climates, ϕ_c is an important circulation parameter.

The greenhouse effect of water vapor

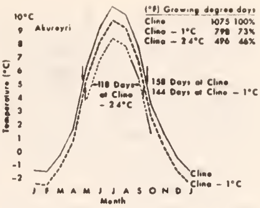


Fig. 4. Effect of reduction of the annual mean temperature on the length of the growing season and the number of Fahrenheit growing degree-days. The figures apply to Akureyri, Iceland. *Clino* means climatic normal, here the normal annual mean temperature. The figures at the upper right show that at 1°C below *clino*, for example, there are 798 growing degree-days, or 73 percent of the normal number.

and carbon dioxide affects the surface temperature and upward radiation from the earth's surface but at equilibrium with the solar input cannot affect the effective radiation out of the top of the atmosphere. Defining the magnitude of the greenhouse effect as the difference between upward infrared radiation from the earth's surface and upward infrared radiation from the top of the atmosphere gives a number of the order of 0.024 cal cm^{-2} min^{-1}. Thus, a 1 percent change in the greenhouse effect would change the surface temperature about 0.3°C and the vertical lapse rate about 0.8 percent.

Logarithmic differentiation of Eq. 1 shows that a 1 percent change in either the vertical lapse rate or the horizontal temperature gradient changes the tangent of ϕ_c by 1 percent. For summer subtropical anticyclones, this is about 0.2° of latitude.

Now if we plot the latitude of the northern boundary of monsoon rains in West Africa [which is at the intertropical discontinuity (ITD) between moist monsoon air and dry desert air] against the latitude of the subtropical anticyclones, we find that there is about a three-to-one amplification, so that moving the subtropical anticyclone 0.2° farther south moves the ITD 0.6° southward (*19*). Since Ilesanmi (*20*) has shown that the annual rainfall gradient south of the ITD is about 180 mm per degree of latitude, it would appear that a 1 percent change in the greenhouse effect would move the ITD southward by 0.6° and reduce the West African monsoon rainfall by over 100 mm.

By similar reasoning, we can examine the effect of a change of 0.4 percent in the solar radiation intensity, which was suggested by Reitan (*17*) as adequate to explain the rise of mean hemispheric temperature (0.5°C) from 1920 to 1940. This change was mostly in the higher latitudes, with essentially no change in the tropics. Assuming that there was a 1.0°C rise at 60°N and none at 20°N gives a decrease in the north-south gradient of about 0.24°C per 1000 km, for a change of about 2.4 percent in the mean. In turn, a 2.4 percent change in gradient would mean a 2.4 percent change in tan ϕ_c, or a change in the latitude of the anticyclones of about half a degree and a change of the West African rainfall of 270 mm/year.

Before about 1945 these two effects should have been opposed, but since then they would be additive in reducing sub-Saharan West African rainfall.

If we estimate the warming of the earth's surface due to increased carbon dioxide as 0.1°C between 1957 and 1970, and the increase of the north-south temperature gradient as 0.05°C per 1000 km during the same time, the figures above would suggest a decrease of precipitation of 86 mm annually in the Sahel of West Africa. According to Winstanley (*21*), the decrease averaged for five Sahelian stations was 96 mm between 1957 and 1970. This is a disastrous decline in an arid region, but with miniscule causes if the reasoning above is correct. It suggests that our climatic pattern is fragile rather than robust.

What Changes the Climate?

Practically every elementary textbook of meteorology or climatology contains a description of the atmosphere as a heat engine driven by the sun. A primary or general circulation results from the distribution of heating and cooling, and this, interacting with the terrain (in the broadest sense) and generating large-scale waves and eddies, produces the climatic pattern of the world. The dynamic internal mechanism and details are the essence of meteorology, but we shall focus here on the heat engine controls extrinsic to these internal mechanisms of the atmosphere itself. The extrinsic variables are (i) the intensity of sunlight reaching the earth; (ii) the transmittance of the atmosphere as modified by processes not internal to the atmosphere; (iii) the albedo of

the earth-atmosphere system or the earth's surface, again as modified by noninternal processes; and (iv) the greenhouse control of infrared fluxes from the earth, as modified by gases and particulates not depending directly on atmospheric processes.

Intensity of sunlight—the solar constant. The evidence is weak that the intensity of the sunlight leaving the sun is variable on the scale of years to thousands of years. There may be changes of solar output on this scale, and indeed there are measured changes in some wavelengths, but the total energy that ultimately drives the atmosphere does not seem to be variable within the limits of observational accuracy. There is now an opportunity to establish the fact of the matter from space platforms, but past measurements —even from mountain observatories— are not unequivocal. Each earth-based observation must be corrected for large atmospheric effects, and thus the source of the variance is difficult to determine.

Whether or not there are short-term variations in solar output, there are calculable variations of solar input to the top of the atmosphere arising from the varying distance from the sun to the earth, and changes in seasonal and latitudinal distribution of the input depending on the variation in inclination of the earth's axis to the plane of the ecliptic and the axis of the earth's orbit. These variations were studied extensively by Milankovich (*22*) and more recently by Broecker (*23*) and Kutzbach *et al.* (*24*), among others. Such variations are of great interest in the study of recurrent ice ages, but the time scale of the cycles involved is of the order of 10^4 to 10^5 years, and they contribute little to our understanding of decadal to millennial changes.

There is a modifiable heat input, however, that simulates, to a certain extent, variations in solar input; that is, "waste heat." The term itself is rather anthropocentric, however, for essentially all energy used by man is ultimately degraded to heat, which is added to the atmosphere. The local effects of this waste heat on city climates, for example, is widely known and has been extensively discussed [for example, see (*25*)]. Less is known about global climatic effects of waste heat (*26*), but it is estimated as 3.8×10^{-5} times the average solar input to the atmosphere-earth system. However, it is mostly released as sensible heat and is about 5.8×10^{-4} times the natural sensible heat flux at the earth's surface, and is released almost entirely over the continental areas. For midlatitude regions of the continents, this figure should probably be multiplied by a factor of 6 to 10. This is still a very small fraction of the heat from natural sources, but secondary effects of this energy use have a larger impact, as will be indicated below.

Transmittance. Since the climate is primarily determined by processes near the earth's surface, the solar energy arriving at the top of the atmosphere is really not as important as that reaching the lower atmosphere. If the physical properties of the atmosphere and the earth were invariant, then about the only cause of climatic variation would be variations in the input from the sun at the top of the atmosphere. However, the transmittance of the atmosphere varies with time, and this variation modulates the receipt of solar energy in the lower atmosphere and at the surface.

If changes of water vapor and cloud are regarded as internal to the climate and part of the climatic response rather than a direct cause, the major variation of transmittance due to external causes is the result of addition of particulate material to the atmosphere.

There has been a great deal of discussion of the relative importance of various sources of particulate material in the atmosphere, both primary particles and those derived from gaseous or liquid precursors. It is hard to see how the particulate turbidity of the atmosphere would vary on a time scale of decades to millennia without climatic change being the cause of the variation, if the sole source of the particulates were natural atmospheric processes operating at the surface of the land or sea, such as deflation of soil material from deserts, evaporation of sea spray, or emission of terpenes from forests.

I assume in the following discussion that there is a level of natural turbidity normal to each climatic state, and that variations from this level are due to external sources such as volcanoes, direct man-made sources such as fossil fuel fires and machines, and human modification of natural sources such as increased soil disturbance, increased forest fires, and slash-and-burn agriculture. For example, Rex and Goldberg (*27*) have shown that there has been much eolian transport of dust throughout the Pleistocene and Holocene, but there have been no adequate studies of the increase in the atmospheric loading of soil material resulting from human disturbance of the surface. There are indications that it is of considerable magnitude (*16*).

Historically, by far the greatest extrinsic source of particulates has been volcanic activity. Volcanic activity is variable in the right frequency range to match climatic change, the magnitude of the injections of volcanic dust is right, and significant changes of atmospheric transmittance have been measured following eruptions. The evidence of Hamilton and Seliga (*28*) is quite convincing. They have shown that the temperatures over the Greenland and Antarctic ice sheets have been inversely proportional to the amount of volcanic dust falling on those ice sheets over the past hundred millennia or so. Bryson (*16*) and Reitan (*17*) have shown that in the past century a major control of the mean temperature in the Northern Hemisphere has been volcanic dust augmented by a human contribution.

A particular feature of volcanic activity is that it is sporadic, occurring in pulses, although the frequency and intensity of these pulses vary greatly (*29*). If the colder periods of recent earth history have been due to pulsed volcanic injections that reduce atmospheric transmittance, then these colder periods should have more temperature variance than the warm periods of volcanic quiescence. This is evident in Fig. 3.

Direct measurement of the solar radiation normally incident at the ground under a cloudless sky (*30*) shows a variation in transmittance during the past century, with the highest values in the warm period of the 1920's and 1930's, when volcanic activity was at a minimum. However, both the mean temperatures and the measured radiation intensity in the Northern Hemisphere began to decrease before the resumption of volcanic activity in the 1950's and 1960's. This suggests another source of particulates, which should have become significant by 1940.

If the industrialization and mechanization of the world are a source of particulate material, then there should have been a nearly exponential increase in the atmospheric loading of the by-products of this trend in the middle third of this century. The lead fall on the Greenland ice cap shows this effect (*31*) (see Fig. 5). The most rapid increase began about 1940. A

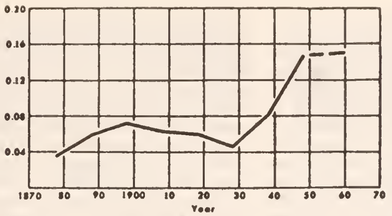


Fig. 5. Variation of anthropogenic lead dust fall at Camp Century, Greenland, from about 1880 to 1960, showing the rapid recent increase in man-made particulates in the atmosphere. Lead is measured as parts per billion (ppb). [After Murozumi *et al.* (*31*)]

similar rapid increase of dust fall on the Caucasian snowfields began about 1930 to 1940, indicating at least a rapid increase in soil deflation in eastern Europe or the Near East, probably due to increased mechanization of agriculture (*32*). The population of the world has doubled, with especially rapid growth in the subtropics, since 1940. In the drier monsoon lands this has led to overuse of the land and extreme dust loading of the atmosphere (*16*), and, in the wetter regions, an increased slash-and-burn rotation rate with increased production of smoke.

Again assuming that the climatic complex of patterns, and its internal oscillations and variations, changes in response to extrinsic variables, then the major control of secular changes of atmospheric transmittance should be injection of particles of volcanic origin and of direct and indirect human origin. Robinson and Robbins (*33*) estimate the extrinsic particulate inputs into the atmosphere annually as 4×10^{6} metric tons of fine volcanic dust and 296×10^{6} metric tons from human pollutant emissions. To these figures may be added my own estimates, based on field observation and measurement, of $(40 \text{ to } 60) \times 10^{6}$ metric tons from smoke from slash-and-burn agriculture and $(100 \text{ to } 250) \times 10^{6}$ metric tons from deflation of soil disturbed by agriculture and construction.

Of course, the actual atmospheric loading of particles and its variation with time is the critical parameter in climatic change. Peterson and Junge (*34*) quote an estimated 4×10^{6} metric tons of volcanic "dust" particles in the troposphere and an equal amount, averaged over the past 120 years, in the stratosphere. Since volcanic eruptions are sporadic, the amount of volcanic dust in suspension must vary from nearly zero during the volcanically quiet period between 1920 and 1955 to very large quantities during the years immediately following the eruptions of volcanoes like Tambora (1815), Krakatoa (1883), or Agung (1963). Such volcanoes can eject as much as 100×10^{6} metric tons of fine ash in a very short time. This variable input produces a variable transmittance of the atmosphere, which produces climatic variation.

Human inputs of particulates into the atmosphere are not sporadic—nearly everyone on the earth works at it nearly every day—and the number of individual sources is so myriad that the day-to-day fluctuations are averaged out. It is a variable input, however, for the number of people keeps growing, as do the extent of mechanization and industrialization and the extent and intensity of agriculture. Pollutant emission tends to be proportional to energy use and economic level (*35*), and both of these parameters are growing rapidly.

An important question is how much of the man-generated particulate material remains in the atmosphere at any given time. Estimates range from 10^{-3} (*36*) to 4×10^{-2} (*26*, p. 201). The former appears far too small, for it requires that the atmosphere be completely scavenged of particulates every 8 or 9 hours on the average. A figure of 2×10^{-2} to 4×10^{-2} is more reasonable. This would yield a particulate loading of the atmosphere due to human activities of roughly $(8 \text{ to } 24) \times 10^{6}$ metric tons; that is, an amount comparable to that produced by moderate volcanic activity. According to Barrett (*37*), an increase of 2×10^{6} metric tons in atmospheric loading is capable of reducing world mean temperatures by 0.4°C. Thus, both men and volcanoes appear adequate to account for the hemispheric cooling since 1940.

According to Machta (*38*), most of the recent increase of turbidity has been at middle to high latitudes. This, plus the greater path length of sunlight through the atmosphere at higher latitudes, should have produced selective cooling of these latitudes, and that is what has been observed (*26*, p. 44).

The major effect of particles in the atmosphere (turbidity) on transmittance is through the backscatter of solar radiation. This affects the albedo of the earth (*39*). There are other factors also which may modify the albedo.

Albedo. Much has been made of the effect that variable cloudiness would have on the climate of the earth (*40*). However, cloudiness is part of the climate and responds to climatic change in a feedback loop. It is not an extrinsic factor, except perhaps for the condensation trail.

Other than variations in cloudiness and turbidity, two factors may modify the albedo: snow cover variations and changes in the surface characteristics of the continents. Snow cover, like cloudiness, is a response to climate and is part of the climate. Man, as an extrinsic factor, can change the albedo of the earth's surface by changing the nature of the surface from natural cover to crops and cities, and so forth. However, a rough calculation suggests that this effect is of minor significance. About .05 of the overall albedo of the earth is contributed by the surface, of which about 30 percent is land. Of the land, about 12 percent is agricultural or urban. A reasonable change of albedo due to changed land use is 15 percent, and a generous estimate of the rate of change of albedo with changing land use is 5 percent per decade. This gives $.05 \times .30 \times .12 \times .15 \times .05$, or 1.35×10^{-5} per decade, or a little over a thousandth of a percent per decade as the albedo change. According to Manabe and Wetherald (*41*), this would produce a mean surface temperature change of about 0.001°C per decade. It does not appear to be comparable to other extrinsic climate-changing factors.

Greenhouse effect. The solar energy which is not reflected from the earth-atmosphere system (65 percent) is absorbed at the earth's surface (47 percent) or in the atmosphere (18 percent). This absorbed portion must be reradiated if the global climate is to remain constant. Since the infrared reradiation to space is dependent on the effective temperature of the earth-atmosphere system, if the solar energy arriving at the top of the atmosphere and the overall albedo remain constant, then the effective radiating temperature of the system must remain constant also. This does not mean a constant surface climate of the earth, however.

A change in the composition of the atmosphere may change the distribution of temperature within the atmosphere (*41*).

The constituent gases of the atmosphere that are important variables are water vapor and carbon dioxide. They both have an important role in modifying the vertical distribution of temperature in the atmosphere by controlling the flux of infrared radiation. It is this control which is called the greenhouse effect. However, the water vapor content of the atmosphere responds to the climate (with feedback, of course), and Manabe and Wetherald (*41*) imply this in the assumption of constant relative humidity. Carbon dioxide, on the other hand, is an extrinsic variable, generally regarded as responding not to climate but to consumption of fossil fuels (*38*). If this is indeed the major source of carbon dioxide variation, then it must be a cause of climatic change of rather recent origin in the perspective of climatic history.

The concentration of carbon dioxide in the atmosphere is currently about 320 parts per million (ppm) and is increasing about 1 ppm annually (*38*). The evidence suggests that this rate will also increase, and is greater now than a decade ago, and the estimated effect of this is that the global mean surface temperature will rise roughly 0.01°C per ppm carbon dioxide increase (*41*). In the last century the carbon dioxide content of the atmosphere changed from about 292 to about 320 ppm. If this were the only cause of climatic change, the mean global surface temperature should have risen steadily and smoothly, at an increasing rate, by about 0.25°C. It has not, and in fact has decreased by about that amount since 1940. There clearly are other factors of greater magnitude that dominate climatic change in terms of mean global surface temperature.

Probably more important is the role of carbon dioxide variation in changing the static stability of the atmosphere. Since the effect of changing carbon dioxide becomes nil at an altitude of about 12 km, a change of 0.01°C/ppm at the surface will change the lapse rate about $0.001°C\ km^{-1}\ ppm^{-1}$. As pointed out in a preceding section, the latitude of the subtropical anticyclones depends in part on the vertical stability. So do the vertical motions of the Hadley circulation. These minute changes appear to be capable of producing very important shifts in the distribution of rainfall.

Summary

Throughout the preceding discussion certain assumptions have been made, and certain others were implicit. It has been assumed that variations of the gross energy flow controls extrinsic to the atmosphere are adequate to explain climatic variations without seeking some "trigger" mechanism of small size, such as a burst of solar particles which modifies the high atmosphere and, in turn, the low-level climate. This does not imply that there is no short-term atmospheric effect, but that there is simply no climatic effect of significance compared to those which relate to the all-important solar energy which drives the atmosphere.

Also implicit is the assumption that climate is thermodynamically forced and that the overall hydrodynamic pattern of waves, eddies, momentum fluxes, and the like is an internal response to this forcing.

Another implicit assumption has been that there is only one climatic pattern that is appropriate to each configuration of the extrinsic control variables, at equilibrium. In the perspective of climatic history as we know it at present, there appears to be no need to adduce alternate quasi-stable patterns as responses to a given set of inputs.

At the beginning of this article I posed certain questions about the size of important climatic changes and the magnitude of changes in the causal parameters needed to produce these changes. I showed that numerically small changes in climatic variables may produce significant environment changes and that rather small changes in the extrinsic control variables are adequate to explain these responses. A significant feature of recent paleoclimatic research is that significant climatic pattern changes are surprisingly small—explanation of past environments does not require drastic modification of the general circulation.

I also suggested that several of the extrinsic control variables may be significantly modified by human activity. These include the turbidity of the atmosphere and its carbon dioxide content.

The data presented in several of the figures show that climate can change very rapidly. While some causal parameters, such as earth-sun geometry, change slowly, others, such as volcano-induced turbidity, may change rapidly and sporadically. Apparently the only controls of the speed of climatic change are the time constant of the active layer at the surface of the earth and the time constant of glaciers. Ice age climates may end (and probably start) in a century or two, although glacial and oceanic response and a new equilibrium may take millennia. Holocene climatic changes, smaller in magnitude, may be accomplished in decades. The overriding present question, of course, is how the present climatic change will develop. In perspective, such changes do not appear to be random fluctuations from some long-term "normal."

References and Notes

1. No effort will be made to be bibliographically complete in this article; that is, to hide the author's bias.
2. C. Emiliani, *Science* 168, 822 (1970).
3. W. Dansgaard, S. J. Johnsen, J. Møller, *ibid.* 166, 377 (1969).
4. T. Webb III and R. A. Bryson, *Quat. Res. (N.Y.)* 2, 70 (1972).
5. R. A. Bryson, D. A. Baerreis, W. M. Wendland, in *Pleistocene and Recent Environments of the Central Great Plains*, W. A. Dort, Jr., and J. K. Jones, Jr., Eds. (Univ. Press of Kansas, Lawrence, 1970), pp. 53–76.
6. H. H. Lamb, in *World Survey of Climatology*, H. Flohn, Ed. (Elsevier, Amsterdam, Netherlands, 1969), vol. 2, pp. 173–250.
7. P. Bergthorsson, paper presented at the National Center for Atmospheric Research–Air Force Cambridge Research Laboratories Conference on the Climate of the 11th and 16th Centuries, Aspen, Colorado, 16 to 24 June 1962.
8. S. Thorarinsson, *Miscellaneous Publication No. 14* (Department of Geology and Geography, Museum of Natural History, Reykjavik, Iceland, 1956).
9. B. Thoroddsen, *Climate of Iceland in 1000 Years* (Copenhagen, Denmark, 1916-1917), cited by Bergthorsson (*7*).
10. These temperatures are averages from two stations in northwest Iceland for April to September. The amounts of fertilizer were estimated by dividing the total nitrogen fertilizer added by the total area of pasture.
11. E. W. Wahl and T. L. Lawson, *Mon. Weather Rev.* 98, 259 (1970).
12. U.S. Department of Agriculture, *1941 Yearbook of Agriculture, Climate and Man* (Government Printing Office, Washington, D.C., 1941).
13. R. A. Bryson and J. A. Dutton, *Ann. N.Y. Acad. Sci.* 95, 580 (1961).
14. J. M. Mitchell, Jr., *ibid.*, p. 235; in *Global Effects of Environmental Pollution*, S. F. Singer, Ed. (Springer-Verlag, New York, 1970), pp. 139–155.
15. H. H. Lamb, *Geogr. J.* 132, 183 (1966).
16. R. A. Bryson, in *The Environmental Future*, N. Polunin, Ed. (Macmillan, New York, 1971), pp. 133–154.
17. C. H. Reitan, thesis, University of Wisconsin (1971).
18. J. Smagorinsky, *Mon. Weather Rev.* 91, 99 (1963).
19. R. A. Bryson, *Ecologist* 3, 366 (1973).
20. O. O. Ileoanmi, *J. Appl. Meteorol.* 10, 882 (1971).
21. D. Winstanley, *Nature (Lond.)* 243, 464 (1973).
22. M. Milankovich, in *Handbuch der Klimatologie* (Borntraeger, Berlin, 1930), vol. 1, part A.
23. W. S. Broecker, *Meteorol. Monogr.* 8 (No. 30), 139 (1965).
24. J. E. Kutzbach, R. A. Bryson, W. C. Shen, *ibid.*, p. 134.
25. H. E. Landsberg, *Science* 170, 1265 (1970).
26. SMIC (Study of Man's Impact on Climate) report, *Inadvertent Climate Modification* (MIT Press, Cambridge, Mass., 1971).
27. R. W. Rex and E. D. Goldberg, *Tellus* 10, 153 (1958).
28. W. L. Hamilton and T. A. Seliga, *Nature (Lond.)* 235, 320 (1972).

29. H. H. Lamb, *Philos. Trans. R. Soc. Lond. Ser. A* **266**, 425 (1970).
30. M. I. Budyko, *Tellus* **21**, 611 (1969).
31. M. Murozumi, T. J. Chow, C. Patterson, *Geochim. Cosmochim. Acta* **33**, 1247 (1969).
32. F. F. Davitaya, *Ann. Assoc. Am. Geogr.* **59**, 552 (1969).
33. E. Robinson and R. E. Robbins, *SRI Project SCC-8507 Final Report* (Stanford Research Institute, Menlo Park, Calif., 1971).
34. J. T. Peterson and C. E. Junge, in *Man's Impact on the Climate*, W. H. Matthews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971).
35. R. A. Bryson and J. E. Ross, *Working Paper No. 3* (revised) (Institute for Environmental Studies, University of Wisconsin, Madison, 1973).
36. Committee on Atmospheric Sciences, *Weather and Climate Modification: Problems and Progress* (National Academy of Sciences–National Research Council, Washington, D.C., 1973).
37. E. W. Barrett, *Sol. Energy* **13**, 323 (1971).
38. L. Machta, *Bull. Am. Meteorol. Soc.* **53**, 402 (1972).
39. A. Angstrom, *Tellus* **14**, 435 (1962).
40. S. Schneider, *J. Atmos. Sci.* **29**, 1413 (1972).
41. S. Manabe and R. T. Wetherald, *ibid.* **24**, 241 (1967).
42. H. E. Wright, T. C. Winter, H. L. Patten, *Geol. Soc. Am. Bull.* **74**, 1371 (1963).

43. This article is based in part on research supported by NSF grant GA 10651X.

Biosynthesis of Natural Products

Problems of substrate nonpermeability and location of isotopic label are described.

A. Ian Scott

Natural products, for many years the touchstones of structural and synthetic organic chemists, continue to be discovered from various sources; and 1000 structures are added annually to a storehouse of some 12,000 described molecules whose molecular weights are between 20 and 2000. These compounds are usually referred to as "secondary" metabolites because their biochemical function in the host organism is in most cases obscure. Yet in the few cell-free systems that have been developed to study the biosynthesis of natural products, the enzymology appears to follow the operation of mechanisms identical or closely allied to "primary" metabolism. In view of the considerable practical difficulties in the preparation of the enzymes of secondary metabolism, knowledge of this field has mainly been derived from the results of administration of ^{14}C-, ^{2}H-, and ^{3}H-labeled substrates to the intact plant or organism, with subsequent appropriate degradative techniques to locate the label, and, more recently, from the use of isotope ratio techniques to ensure nonrandomization. Although great progress in experimental techniques has been made, it seems to be an intrinsic property of many higher plant systems that specific incorporations of between 0.01 and 0.1 percent represent an average level of success. The purpose of this article is to suggest that several techniques can be used to improve a given situation which at first sight might be indicative of negative incorporation of a suspected precursor. In addition, in systems where incorporation of 5 percent or more can be achieved (usually in fungi or bacteria) the use of ^{13}C as biosynthetic label offers unique advantages and can be combined very successfully with the results of other kinds of radioactive labeling experiments.

The author is professor of organic chemistry, Sterling Chemistry Laboratory, Yale University, New Haven, Connecticut 06520.

Identification of Intermediates by Short-Term Incubation in Vinca rosea

Of the plants in which indole alkaloids occur, perhaps none holds more interest for the chemist or the biochemist than *Vinca rosea* in that the periwinkle produces a profuse array of indole alkaloids including some 100 representatives of all the important structural classes (*1–3*). It is also an ideal plant with which to begin cell-free studies, for the viable seeds are readily available, easy to cultivate, and the seedlings possess a remarkable capacity for synthesizing alkaloids with a vigor that is perhaps matched only by the chemotaxonomists who have bestowed such complex names on these compounds.

Earlier biosynthetic studies (*2*) with *V. rosea* utilized either intact shoots or seeds. After some experimentation it was decided to use young seedlings (9 to 17 days from germination) grown from a mixed strain (Burpee) at 33°C in an environmental chamber with full light. Intact seedlings were removed and placed in groups of four (the average weight was 16 milligrams) in ¼-dram vials (1 dram = 1.8 grams). The seedlings remained healthy and continued to develop root growth for about 9 to 10 days in water at 33°C. The range of alkaloids present in the 9-day seedlings approximated to that of mature *V. rosea*, and the more predominant compounds were easily detectable by thin-layer chromatography (TLC) (*4*). These were vindoline (**13**), coronaridine (**12**), catharanthine (**11**), akuammicine (**5**), and vinervine (**6**) (see chart 1). One of the main difficulties in carrying out cell-free studies with *V. rosea* is the absence (or virtual absence) in the mature plant of many alkaloids which correspond to the intermediates of the various pathways. In practical terms this will probably require preparative scale cell-free incubations to isolate and characterize these dynamic compounds. However, with the use of short-term incubation techniques with the above seedlings, some progress can be made toward the solution of this problem.

The main events of indole alkaloid biosynthesis based on earlier incorporation data (*2*) are summarized in chart 1. Here the structures marked with an asterisk (*) correspond to alkaloids identified below. The remaining alkaloids have already been described from mature plants and germinating seeds of *V. rosea* (*2*).

Incorporation of tryptophan into the alkaloids takes place in two distinct phases. For the first 2 hours of incubation it is linear (Fig. 1), but after this interval a rapid increase in the rate of incorporation is observed. Between 12 and 48 hours, a maximum of 3 percent is reached and this level is maintained during the full time of the experiment

IFIAS THE INTERNATIONAL FEDERATION OF INSTITUTES FOR ADVANCED STUDY

STATEMENT OF IFIAS ON CLIMATE CHANGE AND WORLD FOOD PRODUCTION

ADOPTED BY IFIAS
BOARD OF TRUSTEES
3 OCTOBER 1974
BOULDER, COLORADO, USA

SUMMARY

A particular world climatic pattern, generally thought of as normal, has prevailed during the lives of most people now on the earth. During this time the population of the world has more than doubled; the resource demands of affluence have increased; the easily arable land has been occupied; and the barriers to migration have increased.

The studies of many scholars of climatic change attest that during the last few years the climatic pattern has been altering. It is agreed among experts that there is no reason to believe that the climate will soon return to the pattern of the recent past. If it does not, our current food production systems may not easily be able to adjust. It is also quite possible that the climate will become more variable than in recent decades.

We believe that this climatic change poses a threat to the people of the world. The direction of the change is such that if it persists, as it well may, we must expect almost certain crop failures within the decade. This, coinciding with a period of almost non-existent grain reserves, can be ignored only at the risk of great suffering and mass starvation.

We urge the nations, individually and collectively, to plan and act to establish the technical, social, and political means to meet this challenge to peace and well-being. We feel that the need is great and the time is short.

* * * * *

THE NOBEL HOUSE STUREGATAN 14 · BOX 5344 S-102 46 STOCKHOLM SWEDEN · CABLE: TRANSNATIONAL · TEL: 63 13 15

TEXT OF FULL STATEMENT

Signs that the climate is now changing are many. Most important, perhaps, has been the steady cooling of average surface temperatures during the past 30 years. The total magnitude seems small -- a drop of only about 0.3^{o} C in the earth's annual average since the 1940's. Even that slight cooling, however, has trimmed about a week or ten days from the growing season in middle latitudes where most food is grown. More serious, there is some reason to believe that a cooler climate may also be a more variable climate. More variable climates are decidedly possible. We may well be faced with more extremes than we have become accustomed to. There are indeed indications that a pattern of extremes has been developing since about 1960, marked, for instance, in the tragically prolonged drought in the Sahel region of Africa; in the repeated droughts in India unprecedented in their frequency and impact in this century; in the hot, dry summer of 1972 in the Soviet wheat fields; in the "unusual" spells of weather including droughts and floods, both of which were suffered for instance in parts of Africa, Australia, and Latin America.

We must anticipate that such deviations or "anomalies" will recur. At this moment the world is unprepared to cope with them. Grain reserves which used to be abundant in some regions are no longer sufficient to serve as insurance against disaster and by some estimates have dropped to such low levels that they can supply the world needs for less than one month at present consumption rates. At the same time wasteful and excessive consumption by the affluent, along with increasing numbers of mouths to feed, strains the capacity of farmers to deliver enough food even from the best of harvests. It becomes ever more difficult, expensive and risky to open up new arable land, and at least as difficult to limit the use of marginal lands highly vulnerable to erosion and worsening of climate.

In short, the current food-production system now has little flexibility with which to meet emergencies. What we have hitherto regarded as occasional emergencies, moreover, can no longer rationally be so regarded.

The nature of climate change is such that even the most optimistic experts assign a substantial probability of major crop failures within a decade. If national and international policies do not take such failures into account, they may result in mass deaths by starvation and perhaps in anarchy and violence that could exact a still more terrible toll. It would be irresponsible in these circumstances to continue passively in our present condition of helplessness: without food reserves or alternative technologies to produce food, and without adequate means to redistribute food from the more favored nations or more favored groups within nations to the less favored in time of urgent need.

The most obvious and immediately practicable steps to reduce that helplessness are to encourage the production and storage of food in excess of current consumption. This should be the policy not only of the bread-basket nations but so far as possible of those most vulnerable themselves to climatic catastrophes. At best even modest reserves will need some years of good growing weather to accumulate. For the longer run there must be intensified research into the causes of climatic change. We cannot safely assume that what we now face is a temporary aberration in a normally benign climate. It is at least as probable that the climate of our immediate future will be "worse" than the present one as it is that we will see a return to the "better" conditions of the immediate past. For these same reasons we must carry out intensified research on promising new sources of food, such as conversion of cellulose and marine farming, for instance.

New, or at least newly urgent, ethical problems loom in perhaps unavoidable decisions to allocate food supplies that are grossly inadequate to keep everyone alive. Age-old problems of social justice inherent in the current distribution of wealth among economic classes will at the very least be sharpened. These furthermore may now have practical as well as ethical significance; one way to find reserves could be to eliminate wasteful and physiologically excessive consumption among the affluent of the world; another might be to improve food-handling processes to plug the holes through which so much grain now goes to waste; finally further reform is still needed in the land-holding systems of some of the poorest countries that too often have discouraged farmers from increasing production.

In view of the importance of climate to all mankind, we urge the dedication of the climatic system to peaceful purposes. In recent years, there have been efforts to try to develop techniques to change weather and climate conditions. We need to take the necessary measures to ensure that such techniques, if developed, are not used for hostile purposes. Moreover with the present lack of flexibility any change of climate, natural or induced by man deliberately or inadvertently, is very likely to involve stress and suffering in various regions of the earth before the human economy becomes adjusted to the new conditions.

In issuing this statement, we are aware of differences among experts as to the cause-and-effect relationships of observed climatic facts, and consequently as to the most likely prognoses. Professionally the differences are important, but they do not -- and should not be allowed to -- obscure the larger consensus that the observed changes are neither trivial nor can they be assumed to be ephemeral. Extreme variations in climate inevitably entail disasters where people are locked into expectations that the climate will not materially change. Moreover the facts on which we have grounded this statement are only those which are generally agreed.

We conclude by urging that while scientists continue to seek more perfect understanding leading, among other things, to an improved ability to predict climate, those directly charged with making policy in national capitals and in international organizations do not wait but begin to act now. Among research needs we note that insufficient effort has so far been made to improve our knowledge of the past record of climate by collaboration of meteorological, archaeological and historical research, and further that transdisciplinary research on the implications of climatic change needs to be encouraged. The evidence is imperfect but nonetheless convincing that the climate of coming decades may intensify food problems that will soon dwarf most -- perhaps all -- others.

* * * * *

Please address any comments or queries to either or both of the two following persons:

Dr. Sam Nilsson, Executive Secretary, IFIAS
(at address on letterhead)

Dr. Walter Orr Roberts, Climate Project Leader,
Aspen Institute for Humanistic Studies
P. O. Box 3000, Boulder, CO 80303, USA

BACKGROUND NOTE REGARDING IFIAS CLIMATE AND FOOD STATEMENT

The above statement originated at the IFIAS "Workshop on the Impact of Climate Change on the Quality and Character of Human Life", hosted by Prof. H. Flohn, Director of the Meteorological Institute of the University of Bonn, FRG, 6-10 May 1974. The Workshop's primary product was the design of three "commissioned studies" related to assessment of the social, economic and ethical implications of the problems highlighted by the statement. These studies will be carried out by IFIAS in the coming years.

The Workshop was attended by 21 participants, including climatologists, geographers, agricultural economists, lawyers, oceanographers, and political scientists from Canada, Great Britain, India, Israel, Japan, Kenya, Sweden, USA, West Germany, and Yugoslavia, as well as representatives from the League of Red Cross Societies and the World Council of Churches.

The Workshop statement was widely distributed in June. The Program Chairman of IFIAS solicited queries and comments, and a large number were received. Some of these suggested improvements or changes in the statement. At the request of the IFIAS Trustees the Program Chairman compiled the present version of the statement, which incorporates a number of the suggestions. The statement was then adopted by the IFIAS Board of Trustees at its meetings in Aspen and Boulder, Colorado, on 30 September - 3 October 1974.

The IFIAS membership includes the following Institutes:

Aspen Institute for Humanistic Studies	USA
Athens Center of Ekistics	Greece
Center for Theoretical Studies University of Miami	USA
El Colegio de Mexico	Mexico
Department of Cell Research and Genetics Medical Nobel Institute Karolinska Institutet	Sweden
The Graduate Institute of International Studies	Switzerland
Instituto de Biofísica	Brazil
International Centre for Theoretical Physics	Italy

The International Centre of Insect Physiology and Ecology	Kenya
The International Rice Research Institute	Philippines
The Japan Economic Research Center	Japan
Johnson Research Foundation University of Pennsylvania	USA
Mathematics Institute University of Warwick	England
Niels Bohr Institute of Physics	Denmark
Institut Pasteur	France
Tata Institute of Fundamental Research	India
University Corporation for Atmospheric Research	USA
The Walter and Eliza Hall Institute of Medical Research	Australia
The Weizmann Institute of Science	Israel
Woods Hole Oceanographic Institution	USA

76-572 O - 76 - 14

unsettled and variable climate— uncertain food supply!

Dr. Wayne L. Decker, *University of Missouri-Columbia*

THE ATMOSPHERE is both a natural resource and a mechanism for transport. As a resource, it provides a reservoir for oxygen, carbon dioxide, and gaseous water, a life support to biological systems. The motion or circulation of air provides the mechanisms for the cycling and transportation of water vapor and other gases.

Man uses the atmosphere as a sewer, dumping more than a quarter of billion metric tons of material into the atmosphere each year. This foreign material combines with two billion metric tons of natural particulate matter. Thus it can influence the energy balance of the earth-atmosphere system and the chemistry of atmospheric condensation and precipitation processes.

Impact on food production

The impact of climate on food production, can best be assessed by considering the basic processes through which growth occurs. The cycles of carbon and other essential elements begin with their uptake by plants from the soil or atmosphere. Through plant metabolism and growth processes, the basic biological material is formed. Of course, a portion of the plant material is consumed by animals, and all must ultimately be returned to the natural reservoir.

The atmosphere provides oxygen for all respiration processes, as well as carbon dioxide for photosynthesis by plants. For a better understanding of the physical processes by which the CO_2 is transferred from the atmosphere to plants, the reader should review the recent paper by Lemon *et al.* (1).

Plant growth is driven by the energy from the environment at a rate dictated by the most limiting essential ingredient for growth. The climatic contribution to the abundance and reliability of yields of stover and grain is derived primarily from air temperature, solar energy, and water supply. Of these, the greatest limitation for growth is the availability of water.

One need only to recall the geographic distribution of the world's agriculture and the major variation of yields in the grain-producing regions to understand the importance of moisture supply.

The weather of one year may vary greatly

from that of the previous year. A dry year may follow a wet one, or a cold year precede a warm year etc., but the trends in climate are not likely to change drastically from year to year.

There is considerable stability induced by the heat storage of the oceans and the energy required to change the size of the polar ice packs. Yet comparatively large changes in temperature and precipitation have been noted for the time scale of a century, with smaller changes for one or two decades.

The earth's ice pack

It is known that large changes in climate have occurred throughout the earth's history. Over the past billion years there have been at least four and perhaps five major glacial epochs. During these periods, ice spread southward over a large portion of the land masses of the northern hemisphere.

The vital point to recognize is that, historically, climates have changed drastically and rapidly. One does not need a computer to project changes in the climate in future centuries.

Apparently about 30% of the land area of the earth has been covered with ice at some time. When these invasions of ice into the midlatitudes occurred, the air temperature in the northern hemisphere averaged some 6 C (11 F) cooler than at present. It has been suggested that, when compared to present temperatures, the cooling was greatest in the midlatitudes.

There were mild epochs between each of the glacial periods. During these "optimum" periods the temperatures were warmer than at present, with the mild conditions extending into the polar latitudes. In fact, these warm conditions dominate in the geological time scale. Thus the mild interglacial periods should be considered the "norm" for the geologic climates.

The last glacial maximum occurred some 30,000 years ago. Since then the climate of the earth has pulsated between the climate characteristic of the glacial epoch and that of the nonglacial periods.

In general, throughout this period, the earth's climate has remained closer to that of the glacial epoch than to that of the geological "norm." For a complete survey of climate through geologic time the reader is referred to the book by the British climatologist C. E. P. Brooks, "Climate through the Ages" (2) which has recently been republished in the U.S.

The schematic drawing shows the climatic trends since the last glacial maximum. Prior to 5000 BC there was an apparent gradual northward retreat of the glaciers. But about 5000 BC, the climate changed abruptly toward one similar to the interglacial periods of geologic time. Vegetation requiring warm temperatures grew in the northern parts of Europe, Asia and North America. About 1000 BC the climate again sharply changed to resemble a glacial type pattern. Professor H. C. Willett (3) of M.I.T. writing in 1949 said of this period:

> During the sub-Atlantic period which lasted with variations, but in general colder and wetter (more stormy) than the climate of the present, until approximately 350 A.D., glaciers advanced and numerous new glaciers were formed in many parts of the world. In both Asia and North America non-outlet lakes reached the highest levels that have been attained since the retreat of the last ice sheet.

When this cold period ended, a climatic optimum was re-established. The warmer period continued until about 1000 AD when the cooler and stormier period of the most recent millennium began.

Although interesting, it is difficult to attach great economic significance to the fact that the climates have drastically changed in the last billion years. It is similarly impossible to extend prognostic inferences from the historic fact that dramatic shifts in the climate have occurred in the past 7,000 years.

The vital point to recognize is that, historically, climates have changed drastically and rapidly (say, over a century). One does not require a computer to project changes in the climate in future centuries.

During the past 200 years, when measurements by instruments have been possible, there have been small but important changes in the climate of the earth. The period from 1600 until 1800 was comparatively mild while the nineteenth century was cold. Just prior to 1900 a warming trend began which lasted until the early 1940s.

Since 1940 all indices of temperature reflect a cooling trend. The warming from the 1880s until 1940 was about 0.6 C. (1.1 F.) while the cooling since 1940 has been about 0.35 C.

The cooling trend has been documented by observed expansion of glaciers, increase in Arctic ice pack, and decline in measured temperatures. The greatest cooling has occurred in the arctic and subarctic regions.

A lesson to be learned from the preceding discussion is that the "climate" is not constant. Variations in the climate have occurred on all time scales from the geologic scene to the recent historical periods. Even in the late twentieth century a detectible trend in climate is raising two questions:

- Can the change in climate for the next decade(s) or century be predicted?
- What effect will these changes have on man?

The causes of climatic change

The description and causes of climatic change have been a topic for serious study for many years. In the early fifties, famed astrophysicist, Harlow Shapley, edited a volume (4) summarizing the causal relationship

for climatic change as viewed at that time. Throughout the volume there appeared to be a conscious effort by the contributors to use the same mechanisms for explaining both the short-term and long-term variations in climate.

In spite of the flurry of recent articles and reviews on the subject, there have not been any really new theories for climatic change suggested since this volume was prepared. In broad and general terms, climatic change is induced by two types of mechanisms:

- Mechanisms which change the amount of solar energy reaching the outer boundary of the atmosphere.
- Mechanisms which alter the amount of energy absorbed by the earth-atmosphere system.

Both mechanisms for climatic change recognize that climate is the result of the amount and distribution of energy in the continent-ocean-atmosphere system.

Mechanism of solar energy variations

The mechanisms which induce variations in the quantity of solar energy reaching the top of the atmosphere are variations in the solar output, irregularities in the distance of the earth from the sun because of the eccentricities in the earth's orbit, and variations in the obliquity of the earth's axis.

The sun is quite a reliable source of energy. Although the solar constant has been reported at different quantities from time to time, these variations were primarily because of inaccuracies in calculation or imprecisions in measurement. [The solar constant is the amount of energy reaching a plane perpendicular to the sun's rays at the top of the atmosphere. It is equal to approximately 2 calories/cm^2/min (1396 watts/m^2).] The actual variations in solar output are too small for conventional means of measurement.

Sunspots are visible symptoms of variations in the properties of the sun's surface. It has long been supposed that the number of active sunspots might be related to climatic anomalies. The fact that the number of sunspots tends to follow a cyclic pattern with an 11-year maximum and a major maximum every 22 years provided a means for explaining periodic variation in the climate of one or two decades in length. Actually, there appears to be small physical basis for the correlation between sunspot numbers and climatic change.

A second mechanism for change in solar energy involves the variations in the distance of the earth to the sun and the slope of the terrestrial axis relative to the plane of the earth's orbit. These factors induce predictable systematic changes in solar intensity at the top of the atmosphere for different latitudes.

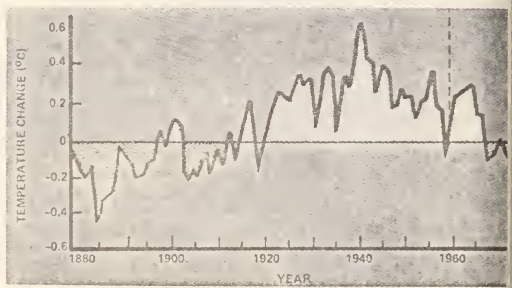
Mitchell (5) has examined the trends in solar energy induced by these irregularities. He concludes that the analogy between recent variations (say the last 10,000 years) and trends in solar radiation occurring during previous geological periods are not clear enough to provide a basis for prediction into the next millennium.

Mechanism for energy balance changes

The earth and its atmosphere continually exchange energy through fluxes in sensible heat, latent heat, and radiation. In a simplified model of the system, the cloud-free atmosphere allows the sun's energy to pass without absorbing great quantities of this radiation. That is, the atmosphere is transparent to much of the solar radiation.

From 80% to 90% of the solar radiation reaching the earth's surface is absorbed.

The earth's surface radiates, nearly as a black body, an amount of energy in proportion to the fourth power of its absolute temperature. All earth radiation is at wave lengths in the infrared. Several of the atmospheric gases have absorption bands in wave lengths radiated by the earth (ozone, CO_2 and H_2O). Therefore, much of the infrared radiation from the earth is absorbed by the atmosphere.

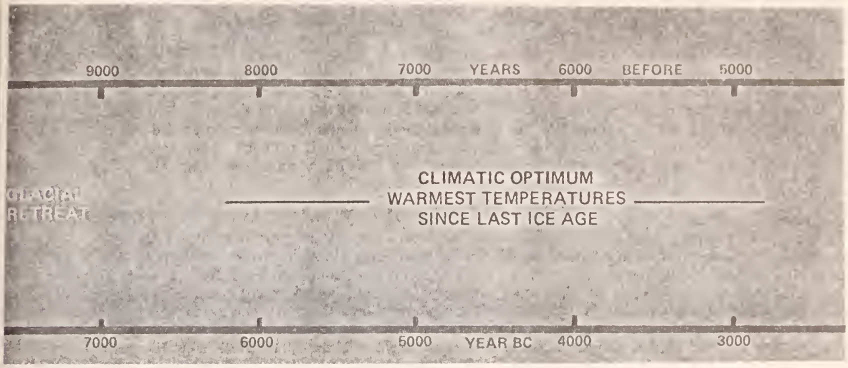


Recorded changes of annual mean temperature for the northern hemisphere by Budyko and by Asakura.

This differential absorption produces the well known "greenhouse effect." That is, the atmosphere is transparent to solar radiation, but absorbs and is warmed by the radiation from the terrestrial surface.

Aerosols and clouds alter the energy balance between the earth and the atmosphere. Clouds and aerosols in the atmosphere reflect and/or scatter a greater amount of the solar radiation away from the earth atmosphere system than would be lost from a clear atmosphere.

If these conditions act alone, the decline in energy resulting from increases in turbidity will ultimately reduce the temperature of the earth and atmosphere. This mechanism provides a reasonable basis for assessing declining temperatures of the earth to pollution. Contaminants reaching the stratosphere from



volcanic activity would remain for long periods of time and induce a similar effect.

When fossil fuels are burned, carbon dioxide is released into the atmosphere. This release increases the content of CO_2 in the atmosphere with the passage of time. There is observational evidence that the CO_2 content of the atmosphere has increased by 3% since 1958 and indirect evidence that the CO_2 content is currently 10% higher than in 1800. Since CO_2 is a good absorber of infrared (10 μm) radiation from the earth, increasing the atmospheric CO_2 will result in higher equilibrium temperatures.

Even without examining the flow equations, one can sense that changes in temperature must lead to alterations in the intensity and direction of atmospheric and oceanic circulation.

The atmosphere and the earth have at least two effects working to change the overall temperature. One effect, increasing particle concentration, tends to induce cooling; the second, increasing CO_2, provides a mechanism for warming. A recent article by Mitchell (6) presents a more-complete discussion of this.

Man's land-use pattern may also intensify a changing climate on a local or regional basis. Overgrazing by livestock will change the character of the earth's surface. The resulting dust from the barren land will increase the turbidity of the lower atmosphere and reduce the vertical currents in the atmosphere through greater atmospheric stability.

This condition will lead to less cloudiness and an increase in the aridity. Bryson and Baerreis (7) have suggested that the Thar Desert of Northwest India and Pakistan was induced by the "dust pall" resulting from overgrazing by the nomadic tribes of the area. This situation apparently has occurred recently to some degree in central Africa. Overcropping in semi-arid regions could have a similar effect.

The consequences of climatic change

In a recent article in *Science*, Bryson (8) effectively argues that the universal acceptance of "the mechansm" for climatic change by scientists is not necessary to make initial assessment of the consequences. It is clear that a major shift has occurred over the past 35 years. Because of the inertia of the energy systems, it is not likely that recent trends will be reversed in the next few years.

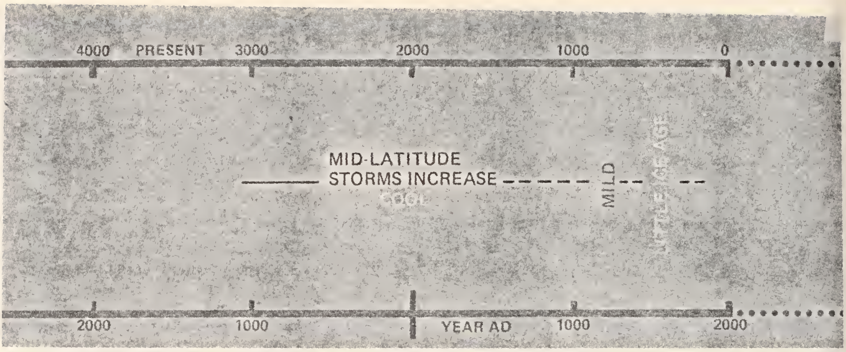
The primary consequence of temperature change is its effect on the global circulation systems. The earth's surface receives varying quantities of energy in different locations (latitudes). In general, the sub-tropics and tropics receive greater quantities of solar energy than the polar regions.

In response to temperature gradients, the energy is redistributed by the atmospheric and oceanic circulation. Even without examining the resulting flow equations, one can sense that changes in temperature must lead to alterations in the intensity and direction of atmospheric and oceanic circulation.

One of the recognized circulatory changes associated with cooling of the polar areas of the earth is a shift toward the equator of the subtropical arid regions. Even the novice student of climate knows that the extensive hot desert regions of the world are found between 20° and 30° latitude (Australian, Sahara, and Arabian deserts and Asia minor and the southwestern North America).

Between these deserts and the humid tropics is an area that receives adequate to abunrant rainfall in summer while turning dry in winter. As the polar regions cool there is a tendency for the subtropical desert to be extended into the transition zone between the desert and the tropics. That is, the summer rainfall in these regions becomes less abundant and less reliable. This shift appears to have occurred in the area south of the Sahara desert in Africa (often called the Sahel area of Africa). The same shift also appears to have caused the recent failures of the southeast Asia monsoon.

An important consequence of climatic change is its effect on food production and



Climatic change *since the last Ice Age. Smaller pulsations in the climate are superimposed on each characterization.*

the nutrition of the world. Obviously, a cooler climate will have an effect on the length of the growing season, adaptability of varieties, and rate of photosynthesis. But the greatest effect will be on the water balance of crops.

We recently observed (9) that in the midwestern U.S., the July and August rainfall provided the dominant climatic effects on production. Adequate rainfall during these periods will assure high yields of both corn and soybeans throughout the region, and for wheat in the northern winter-wheat and in the spring-wheat regions of the Great Plains.

The effect of cooler weather

Cooler weather in the midlatitudes will reduce the water demand by crops and meadows. This removal of stress should improve yields by providing for active photosynthesis, growth, or grain development during the warm summer periods.

Recently, John Benci, a graduate student in the department of atmospheric science of the University of Missouri-Columbia, applied a relationship developed by Dr. E. C. Runge of the UMC agronomy department to corn production in the Midwest. He found that a decrease of summer temperatures in Missouri would increase the average corn yields. In fact, a change in climate which caused the summer temperatures to fall 1 C and rainfall to become less by 10% would increase corn yields by about 20%.

If the cooler average climate induces drought in the subtropical areas, declines in productivity can be expected in these regions. In the subtropics the potential for evaporation is always high. It is particularly great during the rain-free periods of the summer. A change in the subtropical climate which decreases the rainfall but increases evaporative demand will be disastrous.

To further intensify the problem, some of these areas, such as the Asian subcontinent, have large and growing populations. The competition for food in these regions of high population is likely to be intensified by the climatic change of the past 30 years. Even in Africa and South America, where the density of population is currently much smaller than in Asia, a drier summer period will induce stress and even starvation.

Forecasts of climatic trends

For governments to plan singly or collectively for the future, a forecast of the climate is needed. Will the temperature of the earth continue to cool? Is the cooling of the past 30 years only a brief interlude to the trend for warmer conditions which has occurred since 1890? Will the temperatures of the current decade stabilize, remaining essentially as they are now?

In short, what will be the trend in climate in the 1980s or the 1990s or the twenty-first century? If such forecasts were possible, proven mathematical models of the relationships between weather and crop yield could be used to forecast food supply for the expanding population.

To forecast climatic change intelligently, a mathematical model based on cause-and-effect physical relationships is required. This model must solve the atmospheric motion equations based on what is known about the changes in solar energy, the aerosol content of the atmosphere, the increase in CO_2 in the atmosphere, and changes in land management. These causative factors and their interactions would be used as information to computers for the solution of the atmospheric equations of motion.

Recently, the National Center for Atmospheric Research in Boulder, Colo., in an assessment of methods for modeling climatic change said:

> Ideally, models used in climatic forecasting should represent in progressive time steps the state of the atmosphere, oceans, and land surfaces—their temperature, pressure and wind

A climate chang in the Midwest which caused summer temperatures to fall 1 C and rainfall to decline 10% would increase corn yields by about 20%.

fields; their chemical composition; and the energy exchange taking place. The finer the grid resolution, the greater the ability of a model to reproduce directly the atmospheric patterns that lead to energy transport. But each time the resolution of the model is increased by a factor of two, computer time increases by a factor of 16.

Even if the computer system were available, other difficulties would prevent the immediate modeling of the atmosphere to simulate climatic change.

Bryson (8) has effectively argued that the changes in the solar constant, terrestrial reflectivity, and atmospheric transmittance necessary to induce climate change are too small to detect with today's technology. It is not possible at this time to solve the equations of motions of the atmosphere and oceans to simulate changes in circulation from expected changes in solar radiation, increases in aerosols (i.e., atmospheric turbidity), increases in CO_2, and volcanic activity.

In an attempt to overcome the inability of the science of meteorology to utilize atmospheric models for forecasting climate change, many climatologists have resorted to statistical techniques. Each group of experts uses the same basic historical data as a basis for its statistical analysis. Yet the projections often differ.

One group argues that the turbidity of the atmosphere from man's activity and from volcanic erruptions is not likely to decrease. Thus, the earth should continue to cool, providing an increased stress on both the high-latitude and tropical food production. The consequence is an urgent need to increase productivity in the middle latitudes, control populations throughout the world, and establish an international food reserve.

Other climatologists feel that the present cooling trend is not likely to continue. In a recent monograph in which the role of pollution in climate change was discussed, Mitchell (6) states:

> In summary, I suggest that, according to the best information now available, probably not more than one third of the planetary temperature disturbance of the past century is attributable to variations of atmospheric CO_2. Other mechanisms are evidently required to account for part of the warming observed between 1880 and 1940, as well as for the cooling observed since 1940 which has occurred in spite of further warming contributions by CO_2 in that period.
>
> The temperature contribution of CO_2 changes anticipated in the future, neglecting all other mechanisms of climatic change, will consist of a further warming (above present-day temperature levels) of order 0.1 C (0.2 F) by 1980, 0.3 C (0.5 F) by 1990, and 0.6 C (1.0 F) by 2000 A.D. It is therefore likely that, if other causative factors in climatic change do not also become more important in the future than in the past, carbon dioxide will win out by the end of this century as the dominant factor in determining the future course of planetary temperature.

If one accepts this possibility of temperature-reversal, the climate should become less stressed in the coming decades.

Climatic forecasts for the next one or two decades, to which most scientists can subscribe, are not possible at this time. This much can be said: A return of average earth temperatures to the 1940 level within a year or a few years is unlikely. The stressed climate will continue over the short range.

During this same time the population will continue to increase. The chance of severe food shortages, particularly in the tropical regions, is great. Are we prepared to accept the political, economic, and ethical consequence of the climatic stress on food production?

Recently a group of physical and social scientists met in Bonn, Germany, to discuss the impact of climate change on man. This workshop, which was sponsored by the International Federation of Institutes for Advanced Study, concluded in part:

> The studies of many scholars of climatic change attest that a new climatic pattern is now emerging. There is a growing consensus that the change will persist for several decades, and that the current food production systems of man cannot easily adjust. It is also expected that the climate will become more variable than in recent decades.
>
> We believe that this climatic change poses a threat to the people of the world. The direction of the climatic change indicates major crop failures almost certainly within the decade. This, coinciding with a period of almost non-existent grain reserves, can be ignored only at the risk of great suffering and mass starvation. ■

THE AUTHOR

Dr. Wayne L. Decker is Chairman, Department of Atmospheric Science, University of Missouri, Columbia, Mo. He has been a meteorologist with the U.S. Navy and with the U.S. Weather Bureau. Prof. Decker holds a PhD in soil physics and agricultural climatology from Iowa State College.

References

1. Lemon, E., Stewart, D. W., and Shawcraft, R. W., Science, 174, 1971, p. 371.
2. Brooks, C. E. P., "Climates through the Ages," Dover Publications, New York, 1970.
3. Willett, H. C., Jour. Meteor., 6, 1949, p. 34.
4. Shapley, H., ed., "Climatic Change: Evidence, Causes and Effects," Harvard Univ. Press, Cambridge, 1953.
5. Mitchell, J. Jr., Quanternary Res., 2, 1972, p. 437.
6. Mitchell, J., "Global Effects of Environmental Pollution," D. Reidel Publ. Co., Dardrecht, Holland (in press).
7. Bryson, R. A., and Baerreir, D. A., Bull. Am Meteor. Soc., 48, 1967, p. 136.
8. Bryson, R. A., Science, 184, 1974, p. 753.
9. Decker, W. L., 1974, Unpublished remarks, AAAS Symposium, San Francisco, 1974.

Contribution from the Missouri Agricultural Experiment Station, Journal Series No. 7084

CRS-206

A United States Climate Program

Domestic Council
Environmental Resources Committee
Subcommittee on Climate Change

December 1974

Subcommittee on Climate Change
Environmental Resources Committee
Domestic Council

Member	Title and Agency
Dr. Robert M. White, Chairman	Administrator, National Oceanic and Atmospheric Administration Department of Commerce
Dr. Thomas O. Jones	Acting Assistant Director for National and International Programs National Science Foundation
Dr. John E. Naugle	Deputy Associate Administrator National Aeronautics and Space Administration
Dr. Alan Grobecker	Program Manager for CIAP Department of Transportation
Mr. Donald Waldon	Deputy Assistant Secretary for Land and Water Resources Department of Interior
Dr. Harry C. Trelogan	Administrator, Statistical Reporting Service Department of Agriculture
Mr. Christian A. Herter, Jr.	Deputy Assistant Secretary for Environmental and Population Affairs Department of State
Mr. Steven Jellinek	Staff Director Council on Environmental Quality
Mr. Carl Hystad Observer	Chief, Commerce Branch Office of Management and Budget
Mr. Norman E. Ross, Jr. Observer	Assistant Director Domestic Council

SUMMARY

The food and energy crisis is being sharply intensified throughout the world by the natural fluctuations of regional climate. Longer-term changes in climate, whether naturally occurring or resulting from man's activities or both, may be leading to new global climate regimes with widespread effects on food production, energy consumption, and water resources. These circumstances have created an urgent need for a program that can offer hope of knowing and anticipating the effects of climate fluctuations and changes here and around the world. A U.S. Climate Program is proposed which will enable the U.S. Government to meet this need.

A four point program is envisioned which will:

- Establish a climatic impact warning system to provide both real-time warnings and assessments of the risks of future climate impacts.
- Improve current monthly and seasonal climate predictions.
- Develop mathematical-computer systems for prediction of climate and for simulation of man's effects on climate.
- Develop a global climate monitoring system to support early warning and prediction efforts.

The recommended U.S. Climate Program will require $39.8M of new funding in FY 76, with further increases of $7.3M in FY 77 and $9.4M in FY 78.

Because the impacts of climate fluctuations are felt directly or indirectly by all nations, and because the processes that control climate and the systems to monitor them are global in scope, international efforts will be needed. The United States should foster them in all appropriate forums.

PLEASE TREAT THE INFORMATION IN THIS DOCUMENT AS PRIVILEGED UNTIL A PUBLIC ANNOUNCEMENT IS MADE.

SUMMARY

The food and energy crisis is being sharply intensified throughout the world by the natural fluctuations of regional climate. Longer-term changes in climate, whether naturally occurring or resulting from man's activities or both, may be leading to new global climate regimes with widespread effects on food production, energy consumption, and water resources. These circumstances have created an urgent need for a program that can offer hope of knowing and anticipating the effects of climate fluctuations and changes here and around the world. A U.S. Climate Program is proposed which will enable the U.S. Government to meet this need.

A four point program is envisioned which will:

- Establish a climatic impact warning system to provide both real-time warnings and assessments of the risks of future climate impacts.
- Improve current monthly and seasonal climate predictions.
- Develop mathematical-computer systems for prediction of climate and for simulation of man's effects on climate.
- Develop a global climate monitoring system to support early warning and prediction efforts.

The recommended U.S. Climate Program will require \$39.8M of new funding in FY 76, with further increases of \$7.3M in FY 77 and \$9.4M in FY 78.

Because the impacts of climate fluctuations are felt directly or indirectly by all nations, and because the processes that control climate and the systems to monitor them are global in scope, international efforts will be needed. The United States should foster them in all appropriate forums.

PLEASE TREAT THE INFORMATION IN THIS DOCUMENT AS PRIVILEGED UNTIL A PUBLIC ANNOUNCEMENT IS MADE.

TABLE OF CONTENTS

PREFACE

The Domestic Council's Environmental Resources Committee, at the request of the Council, formed the Subcommittee on Climate Change in August, 1974, to: examine what is known about the causes, extent, and impacts of climate fluctuations and changes; examine the present domestic and international programs that address these issues; and identify and recommend domestic and international program options and cooperative efforts that may help to alleviate adverse impacts of climatic variations.

The Subcommittee is composed of representatives drawn from the Departments of Agriculture, Commerce, Interior, State, and Transportation; the Council on Environmental Quality; the National Aeronautics and Space Administration; the National Science Foundation; and the Office of Management and Budget. The Subcommittee sought the advice of the Department of Defense but did not consider military security aspects. Several interagency working groups were formed by the Subcommittee to address specific questions such as Federal program options and the role of weather modification as a response to drought. The counsel of invited scientists was sought through informal discussions with the Subcommittee.

In preparing its report, the Subcommittee has drawn substantially upon the documentation from several major efforts: The proposed Climate Plan, being prepared by the Federal Council on Science and

Technology's Interdepartmental Committee for Atmospheric Sciences; the National Academy of Sciences' Understanding Climatic Change - A Program for Action, prepared by the U.S. Committee for the Global Atmospheric Research Program (GARP); The Role of the Oceans in Predicting Climate, prepared by the National Academy of Sciences' Ocean Science Committee; and (through oral briefings by participants in the drafting conference at Stockholm) The Physical Basis of Climate and Climate Modeling, from the Joint Organizing Committee, World Meteorological Organization/ International Council of Scientific Unions.

The Subcommittee also has benefited from having available many national studies, reports, and documents containing recommendations for research that would lead toward understanding climate and possible man-made influences on climate. These references include the First Annual Report of the Council on Environmental Quality (1970), The Study of Critical Environmental Problems (1970), the Report of the Study of Man's Impact on Climate (1971), the National Academy of Sciences/Committee on Atmospheric Sciences Report: Weather and Climate Modification, Problems and Progress (1973), the Third Annual Report of the National Advisory Committee on Oceans and Atmosphere (1974), and the draft of the Department of Transportation's Climatic Impact Assessment Program Report: The Natural and Radiatively Perturbed Troposphere (to be published in 1975).

These are many pertinent fundamental studies necessary to provide the broad base of knowledge for understanding climate which are not

addressed in our report. Our focus has been on fluctuations of climate of a seasonal or interannual nature and changes caused by man's activities. We have considered the possible role of intentional weather modification in mitigating impacts of climate fluctuations and feel that this issue would be best addressed separately. While the Subcommittee concluded that research in rain augmentation to alleviate drought should be accelerated, we decided to consider this as part of a general review of the Federal role in weather modification. A report on this aspect of the charge to the Subcommittee will be transmitted later.

Agency funding reported herein for FY 76 and beyond is for planning purposes only, subject to further evaluation.

1. THE NEED FOR A CLIMATE PROGRAM

These are some recently recorded facts about climate fluctuations.

- A killing winter freeze followed by a severe summer heat wave and drought produced a 12 percent shortfall in Russian grain production in 1972. The Soviet decision to offset the losses by purchase abroad reduced world grain reserves and helped drive up food prices.

- Collapse of the Peruvian anchovy harvest in late 1972 and early 1973, related to fluctuations in the Pacific ocean currents and atmospheric circulation, impacted world supplies of fertilizer, the soybean market, and prices of all other protein feedstocks.

- The anomalously low precipitation in the U.S. Pacific northwest during the winter of 1972-73 depleted reservoir storage by an amount equivalent to more than 7 percent of the electric energy requirements for the region.

- A three-week siege of hot, dry weather in the midwest in the summer of 1974, following rain-delayed spring planting, greatly reduced U.S. corn and soybean production at a time of mounting world demand for it.

- Inadequate monsoon rains in some parts of southeast Asia and India in 1974, and floods in other parts, are causing famine and suffering there.

- The Sahel area south of the Sahara Desert has suffered 5 years of drought, causing famine and death for unknown thousands and the migration of millions.

- Mean temperatures in the higher latitudes of the Northern Hemisphere have dropped significantly since the 1940's. Below normal temperatures for as long as 19 consecutive months have recently been recorded in certain portions of the Arctic. This is the longest such period in the last 100 years. As a result of the high-latitude cooling the growing season in Great Britain has shortened by two weeks since 1950, reducing food production and use of certain plant varieties. Nobody knows whether such a trend will continue.

- The sensitive ozone layer of the stratosphere, according to recent studies, is subject to depletion by man-made chemicals such as freon and oxides of nitrogen. The increased ultraviolet radiation passing through this weakened shield could have serious impacts on human health.

Climatic fluctuations are not always bad.

- Consistently favorable growing conditions in the U.S corn and wheat belts from the late 1950's until this year helped the U.S. maintain its strong position in world food production.
- The mild winter of 1973-74 in the U.S. and Western Europe helped conservation measures to avert catastrophic oil shortages during the Arab oil embargo.

It is clear that climate fluctuations are resulting in major economic, social and political consequences. Our vulnerability has increased: as the world's population and the affluence of part of it have grown, grain reserves have shrunk to the point where they cannot offset the more serious production shortfalls that can be expected due to the ordinary vagaries of climate. The same factors are pressing on other resources, such as water and energy, whose availability and utilization are closely related to climate. Such pressures have thus rapidly amplified the previously experienced impacts of natural climate fluctuations to critical levels.

These concerns are compounded by mounting evidence that man's industrial and agricultural activities may cause changes in climate inadvertently. Some pollutants, or sufficiently large amounts of heat, when released into the atmosphere, may affect regional or global temperature and rainfall patterns. Intensive land clearing, slash burning,

76-572 O - 76 - 15

or over-grazing also may have adverse effects. Man-induced climatic changes, whose consequences for human health, agricultural productivity, and the economic and political stability of nations may not become evident for a decade or longer, are in urgent need of delineation so that action can be taken to arrest them or ameliorate their consequences. It is equally important to learn which fears of inadvertently shifted climate are unfounded, so that industrial and agricultural growth will not be unnecessarily restrained.

The Subcommittee finds that our present ability to anticipate and explain either natural fluctuations or man-induced changes of climate falls short of being useful to the planners and policy makers who must face these problems, and short of what science and technology can make possible. There is general agreement among those who have examined the problems, and we concur, that a start can and should be made now on an organized research effort to improve our understanding and prediction* of the natural fluctuations and man-induced changes of climate and their consequences. Furthermore, rapid and significant improvements in the utility of presently available climatic information can also be achieved.

---

* A definition: climate prediction begins where day-to-day weather prediction must leave off - at about two weeks in theory, but only five days in actual current practice. It addresses the statistics of weather in time units of at least two weeks, and at ranges of weeks, months, years, or longer.

The Subcommittee recommends that a U.S. Climate Program be organized as a matter of urgency to develop a capability for anticipating the occurrence and the consequences of natural climate fluctuations and inadvertent, man-made climate changes.

While benefits would derive from a foreknowledge of climate fluctuations on any time scale, the greatest responsiveness of government occurs in the range of a year or so. Hence, predictions and assessments of impacts, to be most useful for decision-making, should aim primarily at the natural year-to-year fluctuations of climate and the cumulative climatic impact of man's activities.

Climate is essentially a single global entity, whose fluctuations rarely occur wholly within one country, or even one continent. And while there are a number of United Nations programs relating to climate, there is no comprehensive and consistent international program directed at the problems due to climate fluctuations or changes, such as that called for by the Secretary of State at the United Nations Natural Resources Conference. (See Appendix 1).

The urgent climate problems of the world therefore present a challenge to the United States to seek in many international forums the kind of collaboration required to mount a program having global scope. Because neither the United States nor any single nation has the resources or capabilities to address the full spectrum of necessary efforts alone, we should now offer to lead in giving substance and focus to a world climate program complementing all national programs.

II. THE UTILITY OF CLIMATE INFORMATION

The most critical climate-related problems are now all too familiar. World shortages in basic food and feed grains cause drastic and erratic shifts in food prices, domestic and foreign demand, food reserves, balance of payments, trade and aid. Energy shortages generate analogous shifts. Because food and energy are at the heart of individual and national survival, it becomes imperative to act to moderate these instabilities.

If the risks of various climatic impacts could be calculated earlier or with greater accuracy, or climatic events anticipated more precisely, the utility of this information in planning, policy formulation, and decision-making would be strikingly enhanced. Even modest gains would assist in:

- More efficient management and planning of domestic and international food supplies and natural resource utilization. A reduction in uncertainties about expected agricultural production allows the maintaining of lower average reserve levels. Storage costs are so high that a reduction in reserve requirements of one percent of U.S. production would result in savings of over $120 million per annum.

- Establishment of agricultural export and food assistance policies which reflect the probabilities of various levels of crop yields.

- Improved predictions of expected energy demands. These would influence allocations of limited crude oil supplies and refinery capacities among competing uses: the manufacture of liquified natural gas, fuel oils, gasoline, jet fuels, fertilizers, and other petro-chemical feedstocks. Improved scheduling of fuel deliveries to regions expected to encounter abnormally severe winters would also follow.

- Advance preparations for reallocation of water during droughts, and for disaster relief in response to flood or drought.

Early understanding of the climatic consequences of man's activities would permit:

- Readjustment of national and world-wide industrial, commercial, and land management practices to arrest undesirable climate changes.

- Initiation of necessary R&D programs--as for example in agriculture--to devise long-term responses to irreversible climate changes.

- Improved long-term investment decisions in water resources and energy.

III. THE GOAL OF THE U.S. CLIMATE PROGRAM

The goal of the U.S. Climate Program is to help the nation respond more effectively to climate-induced problems by enabling its government to be aware of or anticipate climate fluctuations and their domestic and international impacts.

IV. WHAT THE U.S. CLIMATE PROGRAM WILL DO

To meet the Goal of the U.S. Climate Program, we propose four objectives whose elements have been chosen from a study of several technical options.* The Program will:

A. Establish a Climatic Impact Warning System

The present Federal effort does not acquire, process, interpret, or deliver timely climatic impact warnings to decision makers. Earlier warning is possible. If we organize our data better, make wider use of computer and satellite technology, and enlist the cooperation of other nations, "real-time" analyses of climatic fluctuations and their associated impacts are possible. FY 75 funding of $4.0M does provide a large data archiving facility and limited climatic impact analyses.

This impact warning system requires:

- Placing present climatic analysis capabilities on a real-time basis.

  Data from world sources should be assembled as rapidly as possible for comprehensive analysis of climatic fluctuation patterns and their possible causes. We need to establish some specialized data processing facilities and improve arrangements for exchange of data among climatic data centers around the world.

---

* We provide here and in the section on management and funding estimated costs of the actions we propose.

Actions and Milestones:

- *Establish a Climate Diagnostics Center in 1976*
- *Develop new linkages between data centers through 1978*
- *Improve arrangements for exchange of data between World Data Centers*
- *Develop by 1978 a comprehensive climatological data index and referral service*
- *Assemble data sets for research and prediction applications*
- *Maintain a synopsis of climatic factors, beginning in 1976*
- *Maintain current awareness of climate fluctuations, beginning in 1976*
- *Provide climate warnings and information to Federal officials.*

Additional Funding*

FY 76	FY 77	FY 78
$2.7M	$2.1M	$ 0

- A program of climatic risk assessment.

No systematic effort brings data on climate, crop yields, and energy consumption together in a form that enables decision makers to examine the worldwide probabilities of varying degrees of climatic impact on food and energy. A program of climatic risk assessment would expand climatic data search, acquisition, analysis, and processing capabilities, and accelerate evaluations of the impacts of climate fluctuations. For policy and management decisions, it would prepare climatic risk statements on the likelihood of individual or simultaneous crop failures, energy shortages, or other climate-related problems occurring on the world scene in the coming few years.

---

* Increments above previous year's base.

A cooperative effort of the National Aeronautics and Space Administration, the Department of Agriculture, and the National Oceanic and Atmospheric Administration, related to but included only partially within the U.S. Climate Program, has begun to examine the possibilities of obtaining frequently updated global assessments of world grain crops by satellite in order to give early warning of potential shortfalls in production. A meteorological satellite system, elaborated upon later in this report under monitoring, will also be essential in obtaining such assessments.

Actions and Milestones:

- *Experiment in 1976 to develop climate/wheat yield assessment models for North America*
- *Establish a climatic data analysis program in 1976*
- *Undertake a comprehensive data search, beginning in 1976*
- *Extend studies of climate fluctuation impacts to other crops and to fisheries, energy demand and distribution, and water resources, in 1977*
- *Combine climatic probabilities and impact analyses to produce risk statements*
- *Extend risk studies in 1977 to simultaneous events in two or more areas.*

Additional Funding

FY 76	FY 77	FY 78
$3.5M	$0.9M	$0.5M

- Establishment of an international early warning system for climatic impacts.

The World Food Conference has adopted a resolution supported by the United States calling for the development of a better basis for

early warning of crop failures. (See Appendix 2). The resolution asks the World Meteorological Organization and the Food and Agricultural Organization to assess weather conditions worldwide and establish weather-crop relationships. Early attention should be given to implementing this resolution and to expanding upon it to include climatic impact on water and energy resources. The timing is right for a coordinated set of international initiatives to complement national efforts. During 1975 the World Meteorological Organization will hold its quadrennial Congress and the Food and Agricultural Organization will also meet. U.S. Delegations to these meetings should press for the international early warning system. As the international program becomes more clearly identified, the Department of State should develop a proposal for increased budget contributions to the appropriate international agencies to help implement it.

B. Improve Existing Climate Prediction

Forecasts of average temperature for the immediately forthcoming month or season are now being made just accurately enough to be of some use to governmental, business, and agricultural interests, but forecasts of rain amounts fall short of this level of accuracy. Valid forecasts of temperature and rainfall fluctuations for more than a season ahead have not been demonstrated. Since limited but significant improvements in these capabilities appear possible, the Subcommittee recommends additional effort, above the FY 75 funding of $1.3M, focused on:

- Analyses of climatic factors and application of statistical methods of prediction

A systematic examination through case studies of the effects of variations of snow and ice cover, solar radiation, and oceanic heat storage should provide a fruitful source of ideas for researchers developing statistical or theoretical methods of predicting the fluctuations of climate. The climatic records assembled for risk assessment studies will contain much of the necessary data for the statistical studies.

Actions and Milestones:

- *Perform case studies and statistical studies of atmospheric response to external influences: the oceans, snow and ice cover, the sun*
- *Develop monthly and seasonal prediction by multivariate statistical analysis*
- *Develop interannual prediction by time series analysis.*

Additional Funding		
FY 76	FY 77	FY 78
$1.0M	$0.4M	$0.3M

C. Develop Computer Simulation and Prediction of Climate

The simulation and forecasting of climatic variations by computer solution of the governing laws of physics offer the only approach that lends itself to answering the full range of climate-related questions to which the government must ultimately respond. There is no other way to assess the consequences of inadvertent climate modification, nor to determine whether the climate is in

theory predictable to the extent required, nor to examine and design the system of environmental monitoring that will be required as the basis for climate prediction.

The Subcommittee, impressed by the rationality of this approach, strongly urges that an intensified effort be made now to explore it, with the full realization that the task is arduous and costly, and that a long-term commitment will be necessary. FY 75 funding of about $8.0M provides a base.

Additional computer capacity must be made available for this effort. Beyond the machines already in place and under procurement by the various institutions active in this research, capability equivalent to the most powerful (50 to 100 million instructions per-second) machine now on the market will be required. A plan should be developed to explore the best way to provide this capability.

The intensified effort in mathematical computer simulation should include the following elements:

- Application of existing mathematical models to experimental monthly forecasts.

Reasonably accurate simulations of typical seasonal distributions of wind, temperature and precipitation have been produced by mathematical models of the atmosphere. It is time now to begin testing the ability of these models to predict monthly climate fluctuation patterns using real atmospheric and oceanic observations. This

intensive research effort would aim at providing a first demonstration of climatic predictability and of the key role of the oceans for it. If the testing is successful, even to a limited degree, the techniques could readily be adapted for operational monthly forecasting.

Actions and Milestones:

- *Organize two independent model application research efforts in 1976*
- *Study model statistics using real data in 1976*
- *Assist in design of ocean monitoring requirements in 1976*
- *Begin monthly forecast tests in 1977*
- *Produce eight test forecasts annually per group by 1978*

Additional Funding

FY 76	FY 77	FY 78
$3.0M	$1.4M	$0.9M

- Development of coupled oceanic/atmospheric models.

Physical reasoning points to the need for a truly coupled oceanic/atmospheric model in order to predict climate a season or more in advance. Fluctuations of climate are thought to result largely from forcing by time-varying heat sources such as the oceans. The changing character of anomalies in sea surface temperature must be provided by a predictive model for the upper layers of the ocean. This modeling work should influence the design of efforts to monitor ocean conditions (see page 16) and draw, in turn, on the results of that monitoring.

Actions and Milestones:

- *Accelerate ocean modeling efforts in 1976*
- *Make experimental 30-day temperature predictions for oceans in 1977*
- *Begin intensive oceanic/atmospheric coupled model experiments by 1978*

Additional Funding

FY 76	FY 77	FY 78
$1.3M	$1.1M	$1.7M

- Determination of the limits of climatic predictability.

The most fundamental question facing any effort to predict climate is that of the limits of the system's predictability. New insight about the limits of day-to-day weather prediction has been obtained from mathematical modeling efforts. Clearly a similar assault on the climatic fluctuation problem is needed. Our climate prediction goals cannot be mirages.

Actions and Milestones:

- *Undertake new analytical and computational approaches to climate predictability*
- *Analyze statistically the output of general circulation models*

Additional Funding

FY 76	FY 77	FY 78
$0.7M	$0.6M	$0.2M

- Simulation of man's effects on climate and determination of possible consequences.

The fragility of the climate system is unknown. There is evidence of weak physical links, such as the ozone layer of the stratosphere, that may be adversely susceptible to man's interference.

There is also evidence that human activities may produce slow changes by adding particles, gases, or ordinary heat to the air. Simulation of these effects now becomes urgent if we are to understand the possible range of consequences.

Actions and Milestones:

- *Intensify application of global atmospheric models to the problems of inadvertent climate change by 1977*
- *Develop improved statistical dynamical models by 1978*

Additional Funding		
FY 76	FY 77	FY 78
\$0.2M	\$0.8M	\$0.9M

D. Develop a Global Monitoring System for Climate.

To predict climate, it is first necessary to monitor the global environmental conditions that tell us the state of the climate and how it is changing, and also to monitor those conditions that control its evolution. An extensive world-wide monitoring system for many important environmental conditions now exists. However, this system will require substantial bolstering to monitor the global climate. The Subcommittee believes that the present system does, nevertheless, provide a sound base (supported by the U.S. for about \$10.6M in FY 75) on which to build U.S. participation in the international climate monitoring effort from which the U.S. and many other nations

will benefit. The Subcommittee's review has shown that the principal efforts now required are in monitoring oceanic conditions, atmospheric trace gases, and solar radiation and other components of the earth's heat budget. The priority environmental monitoring efforts are:

- International ocean monitoring

The present monitoring of the ocean, still in embryo, does not orovide the data needed for the U.S. Climate Program. It gives too few kinds of observations at too few places. The lack of data in turn inhibits climate research and the development and testing of climate prediction methods.

The minimum requirement for going beyond the simplest tests of climatic prediction (p.12) is a system to monitor the heat stored in the sub-surface layers of the oceans (presently not measurable from satellites), its transport by currents from tropical to higher latitudes, and its release to the atmosphere. A global system based upon ocean data buoys, island observatories, ships of opportunity, and satellites should be phased into operation to meet these requirements for data to support the U.S. Climate Program and international climate programs.

The Subcommittee proposes that the United States seek a target date for the implementation of a broad-scale international ocean monitoring program which would allow full advantage to be gained from the first global experiment of the Global Atmospheric Research Program,

presently scheduled for 1978-79. This program should be coordinated with the Integrated Global Ocean Station System (IGOSS) being developed by the Intergovernmental Oceanographic Commission and the World Meteorological Organization. Proposed contributions by the U.S. to such international efforts follow.

Actions and Milestones:

- *Develop a detailed ocean monitoring system design in 1976 to meet U.S. requirements, while simultaneously exploring the development of an international cooperative ocean monitoring program*
- *Spur development of ocean remote sensing and profiling techniques, beginning in 1976*
- *Explore the use of merchant vessels (e.g., implementing the Phantom weather station concept) in expanding oceanic and atmospheric observations over the open seas, beginning in 1976*
- *Augment or establish ten island stations for ocean/atmosphere climate observations, beginning in 1976*
- *Operate a complete North Pacific ocean monitoring program by 1978*
- *Implement ocean monitoring support for the Global Atmospheric Research Program's global scale experiment in 1978*

Additional Funding*

FY 76	FY 77	FY 78
$13.9M	$0.3M	$1.5M

• An earth-orbiting satellite program for climate.

The uniquely global character of the information from earth satellites offers the possibility of a technological solution to a wide range of climate monitoring problems. Work underway at NASA

---

* Based on preliminary studies prepared for the NAS report "The Role of the Oceans in Predicting Climate." Tentative, pending completion of the ocean monitoring system design.

and other agencies clearly demonstrates the value of satellites for monitoring the heat budget of the planet, the extent and distribution of snow and ice cover, the distribution of key pollutants, crop conditions, ocean surface conditions, and many other climate-related variables.

Actions and Milestones:

- *Analyze historical satellite data on sea-surface radiance temperature and global ozone in 1976 and 1977*
- *Expand the capability to monitor such climatic indices as snow extent, sea ice, sea level, and cloud cover, beginning in 1976*
- *Develop a satellite climatic data bank and expand climate-related data analyses*
- *Develop satellite systems, including necessary "ground truth" support for stratospheric monitoring, beginning in 1976*
- *Add all-weather sea-radiance temperature measurements in 1978*
- *Develop, fabricate, and fly spacecraft radiometers for solar-earth radiation monitoring; development begins in 1976 leading to a flight of prototype sensors in 1979*
- *Establish a long-term earth energy budget monitoring program following successful tests of the prototype systems, possibly beginning in 1978*

Additional Funding*

FY 76	FY 77	FY 78
$6.9M	$-1.0M	$2.7M

- A global pollutant monitoring program for climate.

Does man's input of carbon dioxide, particulate matter, freon, and oxides of nitrogen into the atmosphere affect the climate? The possibilities are serious, but the case is unproven. Only a monitoring

* Major development projects (flight and ground based) do not appear in these numbers because they are primarily designed to serve other programs. They include Nimbus G, SAGE, and SEASAT. See also Footnote 2 on page 28.

76-752 O - 76 - 16

system can tell us how much contaminant is there and at what rate it is changing; only with these data can mathematical climate simulations tell us the possible consequences.

Actions and Milestones:

- *Conduct stratospheric monitoring and research to examine the possible impact of man-made pollutants on ozone, beginning in 1976*
- *Expand the existing solar radiation network in 1976*
- *Upgrade the existing network of climatic baseline observatories in 1976*
- *Establish West Coast and Bermuda climatic baseline observatories in 1976 and 1977*
- *Expand analyses of the climatic baseline data related to man's inadvertent modification of climate, beginning in 1976*
- *Continue activities initiated under the Department of Transportation's Climate Impact Assessment Program, and increase the monitoring of, and research on, atmospheric trace gas and aerosol constituents having a potential for climatic impact, beginning in 1976*

Additional Funding		
FY 76	FY 77	FY 78
$6.0M	$0.5M	$0.5M

- Accelerated development of the climate-related environmental monitoring systems of the United Nations Agencies.

A full-scale assault on the problems of climate will require the monitoring of many different aspects of the environment. The Global Environmental Monitoring System (GEMS) of the United Nations Environment Program (UNEP), now in its formative stages, provides a framework within which existing and planned monitoring capabilities of both governments and specialized agencies of the United Nations can be coordinated and stimulated to provide the data required for an

international climate monitoring effort. A major emphasis in the GEMS program will be to increase capabilities of the developing countries to participate in a global monitoring network. Approximately $500K of UNEP funds for FY 75 are being devoted to this. Other U.N. agencies have similar and in some cases larger efforts. The U.S. should press for UNEP and other U.N. agencies to accelerate their efforts to fill gaps in the total monitoring system. Those elements of the monitoring system of greatest importance to understanding and predicting climate should be given support by the U.S. delegation to the forthcoming meetings of all the U.N. agencies. The proposed U.S. efforts in monitoring would contribute to international programs as they are developed.

V. PROGRAM MANAGEMENT AND FUNDING

The U.S. Climate Program will require the expertise and facilities of many different Federal agencies and the participation of the non-governmental scientific community. Its international aspects will require the participation of other governments and international agencies. It is clear that this program can only be carried out through a network of institutions. The network, however, can only succeed in its objectives if managerial, coordinating, and funding responsibilities are clearly identified and the necessary authorities specified. The Subcommittee recommends the following institutional arrangements:

Federal Institutions

- A Federal agency should be given the authority and responsibility for the planning, budget coordination and program monitoring that will be necessary to ensure a coherent national effort. The Department of Commerce/NOAA should be designated as this coordinating agency by Presidential directive. No new legislative authority is required.

- A mechanism to assist the National Oceanic and Atmospheric Administration in its coordinating functions should be established. The Secretary of Commerce in consultation with all appropriate government agencies should take steps to establish an Interagency Climate Program Management Review Board.

• There are existing climate programs within the Departments of Agriculture, Commerce, Defense, Interior, State, and Transportation as well as in the National Science Foundation and the National Aeronautics and Space Administration. The expertise of these participating agencies should be used to a maximum as a base upon which to build the U.S. Climate Program. For example, the National Aeronautics and Space Administration will be expected to lead in the development of space technology related to climate. This approach will make maximum use of ongoing programs, but will require multiple agency funding.

• The Office of Management and Budget should review the U.S. Climate Program each year as a coherent, multiple agency effort, to ensure that all parts of the program are moving ahead as planned. The annual review by the Office of Management and Budget should be based upon an annual plan prepared by NOAA with the assistance of all participating agencies.

• The National Oceanic and Atmospheric Administration should fund and direct aspects of the U.S. Climate Program effort, including those of an administrative and coordinating nature, which do not clearly fall within the existing responsibilities of the agencies who will participate in the program.

Non-Federal Institutions

The U.S. Climate Program cannot reach its stated goal without the active and continuous involvement of the Universities, other non-governmental institutions, and industry. The Program described in this report has implicitly relied upon this reservoir of capabilities and presumes their direct and indirect contributions. Approximately 55 percent of the funding requirements for FY 76 stated below is to be devoted to the non-Federal sector. The remaining funds would support Federal in-house research and service efforts. We look to the National Science Foundation to carry a large share of the responsibility for support of academic research in this area.

In order to receive the full benefits of advice from the scientific community, the Subcommittee recommends that:

- Non-governmental advisory bodies should be consulted periodically to review progress and plans concerning the research aspects of the U.S. Climate Program.

Program Alternatives

The U.S. Climate Program recommended by the Subcommittee, as outlined in the funding section that follows, seeks to activate all elements of a balanced program within three years, followed by an extended period of a decade in which there would be a systematic exploration and development of climate prediction techniques. This scheduling of the program would provide an operationally tested U.S.

monitoring effort and a research capability which can mesh with the proposed international climate research plans of the World Meteorological Organization and International Council of Scientific Unions, which appear to be focusing on a five-year preparatory period from 1975 to 1980 with a full-scale climate dynamics study effort in the decade of the 80's. The recommended funding buildup is steep in the initial years but subsequently levels out. We feel that certain elements of our desirable program deserve highest priority. Monitoring of ocean thermal characteristics and the earth's energy balance and the development of mathematical models of climate are pacing activities if a solution to the problems of climate prediction is to be achieved. Because of the potentially catastrophic consequences of destruction of the earth's protective shield of ozone by activities of man, special attention should be given to monitoring of the upper atmosphere for trace constituents. These priority efforts should be commenced early.

The Subcommittee has examined alternative program options. If the fiscal situation is such that the program we are recommending cannot be implemented immediately, then the Subcommittee recommends an option that stretches out the program by extending the time for activation of program elements to some five to six years. This has the effect of reducing additional FY 76 funding to about $26M. This

would double the implementation time for the ocean and satellite monitoring systems as well as the mathematical modeling efforts. However, all program elements would be retained. The principal pay-off would be delayed by several years, but the effort could still mesh with the proposed international activity.

If, however, the objective is to do as much as we can as quickly and as inexpensively as possible, the Subcommittee has considered a further option that would involve implementing only those aspects of the program that have the potential for reasonably short-term payoffs, such as improvement of existing forecast procedures, establishment of the early warning system and investigation of the sensitive ozone problem in the stratosphere. Such an option would abandon the longer-term objectives of the first and second program options. This would reduce incremental FY 76 funding requirements to approximately $9M. If such an alternative is adopted, the Subcommittee recommends that the goal of the program be redefined, because this modest acceleration of climate services and stratospheric investigations, while useful, would not warrant declaration of a major programmatic effort in climate.

Funding Recommendations

The funding in the following table would bring about the desirable U.S. Climate Program which the Subcommittee recommends.

The table shows the FY 75 base funding, by Agency, devoted to the achievement of program objectives and incremental funding required for FY 76, FY 77, and FY 78 over the previous year's base. The total annual costs of the recommended program are $63.7 for FY 76, $71.0M for FY 77, and $80.4M for FY 78.

A separate summary table of funding by agencies for the U.S. Climate Program also follows.

U.S. CLIMATE PROGRAM FUNDING[1]
(In Millions of $)

Objective	Agency	Direct Base FY 75	Incremental Funding FY 76	FY 77	FY 78
Establish a Climate Impact Warning System	DOC/NOAA	3.8	5.9	2.5	0.2
	NSF	0.2	0.3	0.5	0.3
	Total	4.0	6.2	3.0	0.5
	Cumulative Total	4.0	10.2	13.2	13.7
Improve Existing Climate Prediction	DOC/NOAA	0.3	0.7	0.2	0.1
	NSF	1.0	0.3	0.2	0.2
	Total	1.3	1.0	0.4	0.3
	Cumulative Total	1.3	2.3	2.7	3.0
Develop Computer Simulation and Prediction of Climate	NSF	1.9	2.5	1.7	1.3
	DOC/NOAA	2.7	3.1	2.0	1.6
	NASA[2]	1.2	1.0	0.8	0.8
	DOD	1.3	-0.7	-0.6	0
	DOT	0.9	-0.7	0	0
	Total	8.0	5.2	3.9	3.7
	Cumulative Total	8.0	13.2	17.1	20.8

Objective	Agency	Direct Base FY 75	Incremental Funding FY 76	FY 77	FY 78
Develop a Global Monitoring System for Climate	DOC/NOAA	2.5	18.9	4.6	3.3
	NASA[2,3]	2.8	4.7	-2.8	+1.1
	NSF	3.3	3.8	-2.0	0.3
	ERDA	0.2	0	0	0
	DOT	1.8	-0.6	0	0
	Total	10.6	26.8	-0.2	4.7
	Cumulative Total	10.6	37.4	37.2	41.9
Program Management	DOC/NOAA	0	0.6	0.2	0.2
TOTAL PROGRAM		23.9	39.8	7.3	9.4
Cumulative Total Program		23.9	63.7	71.0	80.4

1 Entries in the table are preliminary and not cleared by agencies.

2 NASA funding indicated supports a number of disipline areas -- e.g., meteorology, earth resources, oceanography -- but also has direct application to climate. No attempt has been made to prorate the funds among the disciplines.

3 Major development projects (flight and ground based) do not appear in these numbers, because they are primarily designed to serve other programs. They include among others Nimbus G, SAGE, and SEASAT.

A Summary of Agency Funding*
(In Millions of $)

	Direct Base	Incremental Funding		
	FY 75	FY 76	FY 77	FY 78
DOD	1.3	-0.7	-0.6	0
DOT	2.7	-1.3	0	0
ERDA	0.2	0	0	0
NASA	4.0	5.7	-2.0	1.9
DOC/NOAA	9.3	29.2	9.5	5.4
NSF	6.4	6.9	0.4	2.1
TOTAL	23.9	39.8	7.3	9.4

* Entries in the table are preliminary and not cleared by agencies.

APPENDIX 1.

EXCERPT FROM AN ADDRESS BY
THE HONORABLE HENRY A. KISSINGER
SECRETARY OF STATE
BEFORE THE SIXTH SPECIAL SESSION
OF THE UNITED NATIONS GENERAL ASSEMBLY
NEW YORK
APRIL 15, 1974

In a global economy of physical scarcity, science and technology are becoming our most precious resource. No human activity is less national in character than the field of science.

No development effort offers more hope than joint technical and scientific cooperation.

Man's technical genius has given us labor-saving technology, healthier populations, and the green revolution. But it has also produced a technology that consumes resources at an ever-expanding rate: a population explosion which presses against the earth's finite living space; and an agriculture increasingly dependent on the products of industry.

Let us now apply science to the problems which science has helped to create.

-- To help meet the developing nations' two most fundamental problems -- unemployment and hunger -- there is an urgent need for farming technologies that are both productive and labor-intensive. The United States is prepared to contribute to international programs to develop and apply this technology.

-- The technology of birth control should be improved.

-- At current rates of growth, the world's need for energy will more than triple by the end of this century. To meet this challenge, the United States Government is allocating $12 billion for energy research and development over the next five years, and American private industry will spend over $200 billion to increase energy supplies. We are prepared to apply the results of our massive effort to the massive needs of other nations.

-- The poorest nations, already beset by man-made disasters, have been threatened by a natural one: the possibility of climatic changes in the monsoon belt and perhaps throughout the world. The implications for global food and population policies are ominous. The United States proposes that the International Council of Scientific Unions and the World Meteorological Organization urgently investigate this problem and offer guidelines for immediate international action.

APPENDIX 2.

Global information and early-warning system on food and agriculture[1]

The World Food Conference

Recognizing that the capacity of governments to take prompt and appropriate measures to deal with food shortages would be enhanced by the furnishing by all countries of timely and adequate information concerning the current and prospec crop and food situation, and further recognizing the growing inter-dependence o countries in this respect,

Stressing the urgent need for establishing on a world-wide basis a Food Information and Early Warning System which would aim at (a) identifying countri and regions where acute food shortages and malnutrition problems are thought to be imminent; (b) monitoring world food supply-demand conditions so as to enable governments to take timely and appropriate measures; and (c) contributing to th effective functioning of the proposed International Undertaking on World Food Security,

Recognizing the important role of a comprehensive and timely flow of information and forecasts on the situation and prospects for agricultural production, import requirements, export availabilities, livestock health, inputs and trade in meeting the requirements of world food security and market stability, at equitable and remunerative prices in a constantly changing food and agriculture situation,

Noting that a world information system requires a regular supply of reliable reports and observations,

Recognizing that the areas most severely affected by food shortages, for which it is particularly important to have timely and adequate information, are often those which do not possess the necessary resources and techniques to suppl the information needed for the proper functioning of the System and recognizing also that the problem of inadequate food information and data collection in developing countries is largely a result of inadequate institutions,

Noting that the governments of all major food producing and consuming countries have expressed their willingness in principle to participate in expanding the existing information arrangements into a more comprehensive and global system, and also noting the importance of strengthening the information functions of FAO, International Wheat Council and other international organizations concerned with food and agriculture,

[1]Excerpt from Committee Report pending final Report of Conference

Welcoming the action being taken by FAO to strengthen its food information and early warning systems following a decision by the FAO Conference in 1973,

1. Resolves that a Global Information and Early Warning System on Food and Agriculture (hereinafter referred to as the "System") should be established and agrees that FAO is the most appropriate organization to operate and supervise the System.

2. Requests FAO, in cooperation with other concerned international organizations, particularly the International Wheat Council, to formulate arrangements necessary for the establishment of the System, and to submit them for final approval by governments participating in the System;

3. Requests all governments to participate in the System and extend full cooperation, on a voluntary and regular basis, by furnishing as much current information and forecasts as possible, including current information and forecasts obtained from the statistics and regular studies which are published, initially on basic food products, including in particular wheat, rice, coarse grains, soybeans, and livestock products and, to the extent practicable, other important food products and other relevant aspects of their food supply and demand situation affecting world food security, such as prices and production of inputs and equipment required for agricultural production, the food industry and livestock health, taking account of and respecting in full the sovereign rights of governments in this regard;

4. Requests governments to take steps, where necessary, to amplify and otherwise improve their data collection and dissemination services in these fields: and further requests FAO, WMO, WHO, the Intergovernmental Bureau for Informatics and other multilateral and bilateral sources to urgently assist interested governments with technical and financial assistance on particular aspects in strengthening existing arrangements for data collection and dissemination in the fields of food production, nutritional levels at various income levels, input supplies, meteorology and crop/weather relationships, on a national or regional level as appropriate; and to coordinate this action with the World Food Council;

5. Requests that the information thus collected be fully analysed and disseminated periodically to all participating governments, and for their exclusive use: it being understood that, where requested, certain information provided by governments would be disseminated in aggregate form particularly in order to avoid unfavorable market repercussions;

6. Requests the World Meteorological Organization, in cooperation with FAO (a) to provide, as part of the System, regular assessments of current and recent weather on the basis of the information presently assembled through the World Weather Watch, so as to identify agriculturally significant changes in weather patterns; (b) to expand and establish joint research projects particularly in

arid and semi-arid areas, to investigate weather/crop relationships taking account of the effect of soil moisture conditions; (c) to strengthen the present global weather monitoring systems in regard to the adequacy of meteorological observations, and data processing systems, at the national and regional levels, in order to make them directly relevant to agricultural needs: and (d) to encourage investigations on the assessment of the probability of adverse weather conditions occurring in various agricultural areas, and on a better understanding of the causes of climatic variations.

APPENDIX 3

THE WHITE HOUSE

WASHINGTON

August 1, 1974

Dear Fred:

Changes in climate in recent years have resulted in unanticipated impacts on key national programs and policies. Concern has been expressed that recent changes may presage others. In order to assess the problem and to determine what concerted action ought to be undertaken, I have decided to establish a subcommittee on Climate Change.

I am requesting that the Department of Commerce take the lead and chair this new Subcommittee. I would appreciate your naming, the official of your Department who you think would best fulfill this responsibility. Names of representatives to work on the Subcommittee have been requested from the Departments of the Interior, Agriculture, State, and Transportation, the Office of Management and Budget, the National Aeronautics and Space Administration, the National Science Foundation and the Council on Environmental Quality. Norman Ross of the Domestic Council Staff will coordinate staffing responsibilities.

Sincerely,

Roy

Chairman
Environmental Resources
Committee

Honorable Frederick B. Dent
Secretary of Commerce
Washington, D. C. 20250

76-572 O - 76 - 17

APPENDIX 3

THE SECRETARY OF COMMERCE
Washington, D.C. 20230

August 16, 1974

Honorable Rogers C. B. Morton
Secretary of the Interior
Washington, D. C. 20240

Dear Rog:

Thank you for your letter asking the Department of Commerce to take the lead in the assessment of the impact of climate change on national programs and policies and the determination of what concerted action ought to be undertaken.

I have named Dr. Robert M. White, Administrator of the National Oceanic and Atmospheric Administration, to chair the Subcommittee on Climate Change which you have established under the Environmental Resources Committee.

We will look to this new Subcommittee to assess the problem and recommend a concerted action plan.

Sincerely,

/s/ Frederick B. Dent

Secretary of Commerce

APPENDIX 4.

CHARTER FOR SUBCOMMITTEE ON CLIMATE CHANGE

Changes in world climate can have important implications for our national interest. A number of recent instances of climate fluctuations have demonstrated this. A Subcommittee on Climate Change is established to carry out the following tasks:

-- Determine the extent and impact of recent fluctuations in climate.

-- Examine present domestic and international programs directed at achieving improved understanding of climate and capability for predicting its changes.

-- Identify program options required to remedy deficiencies in present efforts, provide improved understanding and establish the basis for prediction.

-- Examine present national capabilities for assessment of the impact of man's activities on climate and the impact of climate change on man, recommend programs necessary to improve this national assessment capability, and suggest procedures for incorporating such assessments in national decision making.

-- Identify and recommend, any initiatives such as weather modification that offer hope of alleviating adverse impacts of climate changes.

-- Identify and recommend, any international actions that would be appropriate.

The Subcommittee will also examine and make recommendations on the Federal role in weather modification, including such aspects as operations, regulations, and research priorities.

6 December 1974, Volume 186, Number 4167 **SCIENCE**

World Climates and Food Supply Variations

Climate has great variation including drought but improved use of favorable areas could increase food supply.

James E. Newman and Robert C. Pickett

In this article we outline the major variations in the world's climates and suggest how these variations should be taken into consideration in any plans that are made to improve world food production and supply. Much has been written in recent years about climate and climatic change, particularly as it relates to agricultural production and world food supplies (*1*). Climate, the average expression of all weather events over many years, is often the least understood branch of meteorology. Yet, the abstract statistics, resulting from the ups and downs of daily weather events, relate how most of the arable land areas of the world are used for human food production.

A. H. Boerma, the director general of the Food and Agricultural Organization, stated in February 1973 (*1*), in regard to the world food situation, that ". . . there remains one vast incalculable—nature itself. One thing that has been harshly, even humiliatingly, made clear in the last 2 years is that, despite all our technological progress, despite all the buoyant hopes invested not long ago in the so-called Green Revolution, harvests are still far too often at the mercy of the weather. In this respect, at least, man has so far failed to master his natural environment." He continued, ". . . in the name of reason, can this world of the 1970's, with all its scientific prowess and its slowly growing sense of common purpose, go on enduring a situation in which the chances of enough decent food for millions of human beings may simply depend on the whims of one year's weather? Is this a tolerable human condition? Emphatically not!" He then suggested that developing countries should give much higher priority to their agriculture and that "all countries which are in a position to do so—including developing countries—should participate in concerted policies for actively building up food reserves." To date, the concept of establishing large central food reserves has met with defeat. In view of the fact that some areas of the world are known to have climates that are less favorable for food production than others, it would seem to be a more realistic goal to establish decentralized stores of food (primarily grain) in locations close to where they might be needed. In many instances, this would also be a more acceptable goal politically.

That sizable deviations in climate and weather events do affect agricultural production cannot be debated. But the extent to which such climatic deviations affect world food supplies as well as what can be done, plus the difficulty of improving the situation, have too often been treated only as forecasts of tragedies by those not experienced in the agricultural sciences and technologies.

When addressing the question of world population and food supplies, one must realize that an energy equivalent of 13 to 15 billion in food that could be consumed by human beings is currently diverted through animal agriculture. Proper concern should be given for feeding livestock primarily feed stuffs not useful directly to man.

For example, this should include perennial and annual forage crops with much fiber content, plus plant residues such as sugar cane bagasse, citrus pulp, straw, corncobs, leaves, and stems of various grain crops. The function of the ruminant animal with its four stomachs can be greatly extended in using crop residues and other organic substances to grow food for man from fibrous material that he cannot eat directly. In too much of the world these valuable ruminants are not fed, but simply forced to forage on wasteland. Animals as well as grain represent storage mechanisms for food. Further improved feeding practices in favorable times for them could result in more effective "storage" for seasons and years of stress, instead of extreme loss of weight and even death of the animals during such periods. The local on-farm storage of roughage and other feed for animals as feed reserves to be used during stress periods can be a key to further improvement of the use of animals as a human food storage mechanism.

Another important consideration has to do with the climatic requirements of staple crop production. Much of the world's staple food grains are produced in regions having alternately wet and dry seasons. Such climates, in which periods of highest solar radiation, temperatures, and seasonal precipitation are in phase, fulfill the seasonal production cycle requirements of (monoculture) annual staple grain and protein–oil seed crops (see Fig. 1). These

* The authors are professors in the Department of Agronomy, Purdue University, West Lafayette, Indiana 47907.

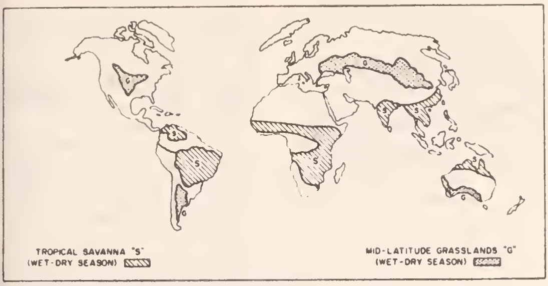


Fig. 1. A map of the world showing areas where solar radiation, temperature, and precipitation are at a maximum during the normal growing season. [Data from (*10*)]

areas in the world have a good combination of light energy for photosynthesis plus heat and moisture for the large-scale growth of a single crop.

The major wheat-producing areas of the world are confined to the grasslands of North America, South America, eastern Europe, Asia, and Australia. Corn is grown mostly in the warmer and wetter portions of these same regions. The great rice areas of India, southeastern China, and other regions of southeast Asia are largely confined to the tropical and subtropical monsoonal climates (*2*). All of these wet and dry climates of the world have a transitional gradient across them, from humid forest climates on one side to arid deserts on the other. Therefore, it is not surprising that such areas, particularly those bordering on or degrading into deserts, are often subject to drought. In many such areas little research on food crop production has been conducted in these transition zones. The rather new international research centers set up in Nigeria, Colombia, and India, in addition to the older ones in the Philippines and Mexico, are directed toward fulfilling this need. These will provide invaluable starting points, with information and experimental materials for new and expanded national food crop research programs in these countries.

World Climates and Agricultural Production

For a climate to be considered truly tropical, it must be free from freezing temperatures. Such conditions are mostly confined to 20° to 25° north and south of the meteorological equator; the meteorological equator is about 5° north of the geographic equator in most parts of the world.

The true tropical rain forest climates saddle the meteorological equator by about plus or minus 5° latitude. These climates feature a diurnal temperature change larger than the annual temperature change. There are two periods of maximum rainfall, usually just after each equinox period, and there is a surplus of water in all seasons. Solar radiation exhibits very little change during the year. The soils are impoverished because of intense leaching. There is no extensive cultivation of any one staple crop in these climates. Thus, it has been difficult to select the best crops for improvement. New research can help select the best investment potentials among the food crops available. But such research efforts are generally only in the planning stages at this time.

To each side of the tropical rain forest climates, and at higher latitudes in both hemispheres, lie the tropical monsoonal regions. They feature rainfall during the season of high sun—that is, when the sun's position shifts into the respective hemispheres directly overhead on its annual swing between the Tropic of Cancer and the Tropic of Capricorn. The tropical wet and dry climates are ideal for rice production and other staple grain and oil-seed crops because solar radiation, temperature, and rainfall are at a maximum during the same season. But they are also subject to drought in the savanna regions bordering the great deserts.

At higher latitudes north and south of the tropical wet-dry climates, beginning between 20° and 25° in each hemisphere, lie the great subtropical desert climates. These areas occupy nearly 25 percent of the land areas of the world. They are subtropical because freezing temperatures can occur, and do, in most areas during the winter season of each year. These desert regions lie between 20° and 35° latitude north and south of the meteorological equator. Successful agricultural production in the heart of these climates requires irrigation. Crop production that depends only on natural rainfall occurrence is often attempted on the borders of these areas. Such crop production attempts often include short season millets and drought resistant sorghums. In times of food shortage and consequent high grain prices, wheat production, for example, is greatly expanded into marginal areas. Russia's recently announced plan to increase grain-producing lands by 30 percent will, no doubt, require the cultivation of some marginal areas that are subject to unfavorable variations in climate, including both drought and extremely short growing seasons (*3*).

North and south of these great deserts at about 30° to 35° latitude in each hemisphere lie the so-called subtropical Mediterranean climates, where there are frequent frosts as well as maximum rainfall in the winter season, while the periods of maximum solar radiation and temperature occur in the summer. Mediterranean climates are thus not ideal for extensive crop production, but many specially adapted crops are grown successfully in these regions. Winter wheat, winter rye, and the cool season grasses are good examples of crops well adapted to the Mediterranean-type climate.

Between latitudes 35° and 55° in the Northern Hemisphere, and between 30° and 45° in the Southern Hemisphere, lie the belts of temperate climates. They exhibit large seasonal variations in precipitation, temperatures, and solar energy. In the temperate forest climates precipitation occurs the year round, similar to the tropical forest climates. Also, within these varied temperate regions lie the grassland or steppe climates. These climates exhibit wet and dry seasons, with high solar radiation, temperature, and precipitation occurring in phase in the late spring and summer—a situation similar to that in the tropical regions that have wet and dry seasons.

These midlatitude grassland climates produce a unique soil formation with a

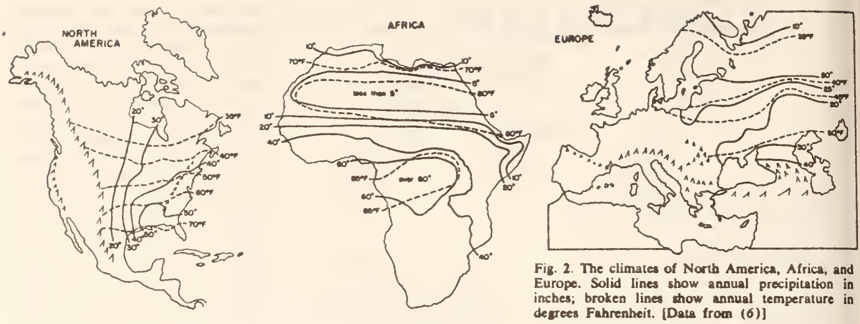


Fig. 2. The climates of North America, Africa, and Europe. Solid lines show annual precipitation in inches; broken lines show annual temperature in degrees Fahrenheit. [Data from (6)]

thick surface layer rich in plant nutrients and with topographic features well suited to extensive cultivation. This soil is a product of the natural climax vegetation produced by a unique balance between precipitation and temperature. Regions having these climates and soils are extensive in North America, eastern Europe, and Siberian Asia, and, to a much lesser extent, in the other continents. They have been described as boundless and treeless—as seas of grass. They are subhumid to semiarid, lying between midlatitude humid forest climates and the arid, cold desert climates. Normally there is enough seasonal rainfall in these regions for the cultivation of plant species that can complete their life cycle in one growing season. But drought is too frequent for perennial species that require a continuous water supply. Again, the great asset of these midlatitude grassland climates is that the periods of maximum solar radiation, temperature, and precipitation occur in phase during the normal growing season. These regions are readily adaptable to extensive staple grain production the world over. They are particularly suited to the production of wheat—"the bread of life" (*4*).

Some Reasons for the Variations in World Food Supplies

The increase in the world's human population requires that, in addition to all the land now under cultivation, additional arable land be utilized. In most instances this means that land that may be marginal in every way must be considered for food production. Among the climatic risks of crop production in these areas, drought normally heads the list because often these new lands lie in the drier areas of both the tropical and the temperate high latitudes, and wet and dry climates. As far as agriculture is concerned, a transitional zone between a climate that has wet and dry seasons and a desert climate is an area of high drought risk in all parts of the world, whether it is a midlatitude grassland, a tropical monsoonal area, or a savanna.

Further, if world climate is changing, as often postulated in recent months (*5*), then it follows that these transitional lands should usually lie where shifts in climatic factors are likely to be observable first. Such tension zones or ecotones lie at the edge of wet and dry climatic areas. This could be a plausible explanation of the changes that are being observed in the Sahel area on the south side of the Sahara Desert today.

Differences in Climatic Risks among Continents

Transitional zones in some parts of the world are more risky than others. One possible explanation for this situation is that annual isotherms (temperatures) and annual isohyets (rainfall) run parallel to each other in some parts of the world but not in others. For example, in Africa annual isotherms and isohyets run parallel from the equator north to the Sahara Desert (Fig. 2). This area probably has the steepest gradient from humid to arid conditions across a transitional zone, on a continental scale, in the world. A similar type of pattern exists in mid- and high-latitudes of eastern Europe (Fig. 2), where the annual isotherms and isohyets run more or less parallel to each other across Europe and Siberian Asia. But in the North American continent east of the Rocky Mountains the annual isotherms and isohyets run at approximately 90° to each other, particularly in the midcontinental grassland regions (Fig. 2). South America is similar to North America in this respect (*6*).

The contributing physical cause of the continental differences relates to the orientation of the major mountain ranges of the New World and the Old World continents. In the former they are oriented in a north-south direction, while on the Eurasian continent the major ranges run mainly in an east-west direction.

The earth's wind systems, because they flow primarily from west to east (the variable westerlies), or from east to west in the case of the trade winds, are influenced by the orientations of the major mountain ranges in each continent. In North America, the Rocky Mountains range causes an increased variability in the prevailing westerly flow, pushing it downward over the eastern portions of North America. This increases the north-south flow of wind and transports moist tropical air masses deep into the midcontinental regions of the North American grasslands; it also pushes polar air masses southward. This accounts for much of the observed mean isotherm-isohyet patterns in midcontinental North America. In comparison, the east-west orientation of the major mountain ranges on the Eurasian continent parallels the direction of the prevailing westerlies, allowing the mean flow of these winds to remain much more stratified. This,

in turn, allows the mean annual isotherms and isohyets to remain more parallel over the vast interior of the Eurasian continent, and results in climatic transitional gradients that are much steeper in the north-south direction (*7*).

In terms of agricultural production, these climatic features give an advantage to the New World continents. The mean annual isotherms and isohyets, because they are not parallel in the vast grassland climatic areas of the Americas, allow a favorable water balance to be extended over very broad areas in the north-south direction. Also, they allow for agricultural production areas to be less stratified in a north-south direction than they are in the Eurasian continent, and ensure against a slight mean seasonal shift in the prevailing westerly flow; thus, they reduce climatic risk. This fact was stated in another way by Glenn T. Trewartha when he evaluated U.S. agricultural climatic risk (*4*): "No other region on the Earth of equal size is so well endowed physically—in surface configuration, soil, and climate for agricultural use."

Climatic Changes and the Views of Climatologists

Among climatologists there are two general schools of thought concerning the application of weather statistics to contemporary problems. According to one school, weather events from one year to the next are independent of each other and occur at random; according to the other school, such events relate to cyclic patterns or to causes not fully understood. The important differences between these two schools is that those who adhere to the former see weather events as a static matter needing no further explanation, but those who adhere to the latter must postulate a cyclic forcing function or a dynamic cause. Since data of sufficient quality and quantity to test the several hypotheses do not exist, there has been ample opportunity for many different theories to be developed, creating a lively debate among climatologists in our time (*8*).

Currently, there is much speculation among some of the leading climatologists that a worldwide cooling trend is under way (*9*). If the world is in a gradual cooling trend, it follows that the circumpolar vortex should expand, causing the mean prevailing westerlies to shift to lower latitudes. Likewise, there could be a shift in the trade wind systems as well as the equatorial retreat of the intertropical convergence zone's annual penetrations into each hemisphere. Such shifts in worldwide atmospheric circulations could produce the current North African droughts. It would also suggest a reason for the mean midlatitude jet flow staying south of the Himalaya Mountains a few days later than normal in the Northern Hemisphere's spring season as has been recorded often during the past decade (*9*). This delayed seasonal migration of the "jet" has been associated with the delays as well as the lack of penetration of the monsoonal rains in India. A delay in the onset of the monsoons usually produces a less desirable distribution in seasonal rains in all parts of the subcontinent of India and the remainder of the southeast Asian monsoonal areas. This can cause droughts as well as floods in the same season. Further, this seasonal delay in the Asiatic monsoon is often associated with a similar seasonal delay in the onset of spring rains in the grassland (steppe) climates of the U.S.S.R. Even though these patterns have been observed repeatedly in the last decade or so, this is a very small sample of time from which to conclude that a worldwide climatic change is indeed under way. It is a matter of record that the 1930's were the warmest period recorded in recent history. But there remains the question of whether these are contrasting periods of extreme deviations from normal random fluctuations in weather or real trends. At this time there is not an abundance of evidence either way. Only additional research will clear up this question, and such research will require considerable time.

Alleviation of Food Shortages

Regardless of whether climates are truly changing or merely fluctutating in a year-to-year random manner, there is much agricultural technology and other scientific knowledge that can and must be set in motion if the tragedy of mass human suffering is to be held to a minimum.

There is one principle in climatological deviations that must be considered in any extensive planning. Climate, in a general way, obeys the law of conservation. That is, whenever one large area is getting too little precipitation, another is getting too much. The same holds for most other climatic factors as well, such as temperature deviations, pressure, and cloud cover. Further, in areas where the climatic gradient is steep, often the regions of greatest contrast between too much and too little rainfall lie adjacent to one another. This is especially true in the tropical wet and dry climates. By introducing agricultural technology that would allow quick shifts in crop production patterns between areas, plus means of adequate storage and transportation, much of the mass human tragedies witnessed in recent months could be avoided in the future. Shift in production could be done if accurate reporting of crop failures could be relayed to the nearby agricultural production areas. Such information is paramount in planning increased crop production in nearby favorable areas since the timing of the production growing seasons is often only days or weeks different in onset. Many of the present tragedies of West and East Africa have been preceded by several seasons of crop failure before relief and other measures were requested. Current accurate reporting of crop conditions is a must in any planned shifts in seasonal crop production to fulfill failures in other areas.

Even slight shortages of food bring amazing problems to human population, particularly in some of the developing countries of Africa and Asia. Government price controls fail to work to prevent these shortages and great frustrations set in for both the consumers and the governmental officials. It is well known that people tend to respond to even slight food shortages with hoarding and holding out for higher prices. Such behavior accentuates the shortage and makes more difficult the distribution of whatever supplies are available, and those who suffer are generally the poor, the old with lower incomes, and the young with the greater protein needs. Even in times of relative plenty, the protein needs of these groups are hard to meet because of the almost universally higher prices of edible legumes and animal products.

While it is not possible to predict exact drought intensities for certain seasons and for numbers of years ahead, certain zones on each continental land mass are known to be much more variable and hazardous than others. Therefore, much could be achieved by adequate planning of food production practices and by improving storage facilities, transportation, and marketing procedures. Such planning would have

to include estimates of the availability of agricultural inputs such as seed stocks and fertilizers. Thus, such planning would only be possible after a considerable amount of research investment has been made. Statistics on agricultural production would have to be gathered along with the necessary climatic, soil, and other production input data for each zone.

If a particularly unfavorable climatic period were to hit a certain zone, then the inputs could be changed (for example, instead of corn being planted, sorghum could be used; or instead of sorghum, millet) in an attempt to produce at least some food supplies during this period. Although it might only be possible to produce crops of limited size within a "disaster" zone itself, the biggest opportunity of all may lie in enlarging the capacity of the very favorable moisture zones that normally lie relatively near the dry zones. These wetter zones, although they have much higher food crop production potentials, also have inherent problems of their own, such as more weeds, diseases, insects, and wild animal feeding. With proper agricultural inputs beginning with research effort, investment in management, plus such physical inputs as storage improvement and transportation development, a less variable food supply could be cultivated across large geographical areas where high year-to-year variations in agricultural production are prevalent.

Weeds deserve special mention because of their significance in wiping out gains in food crop production in the wetter areas of the tropics and subtropics. With the increased moisture, the crop yields should be much higher where adequate soil fertility is present—except that the weeds also grow more vigorously and can reduce yields 30 to 40 percent commonly and often much more. "Too little, too late" in weeding procedures whether by hand, mechanically, or with chemicals is all too common. All too often, actual production in these zones is little higher than it is in the "disaster" or drought zones. Production losses of mature staple seed crops as a result of their being damaged in the field by birds, rodents, and weather are often 30 percent or more. A further loss of 30 percent or more can occur in storage. The largest losses during storage are caused by insects. Crop diseases caused by various fungi and bacteria also play a major role, both in the field and in storage, in reducing the amount of food that is ultimately available to mankind. The development of proper grain storage facilities is a much-needed technology in the majority of the developing countries. All of these practices can play a significant role in alleviating "disaster" in the seasonally humid tropics.

The climatically favored areas should be able to produce not only enough food for their own needs but enough to have some left over for more variable marginal areas. Many countries, such as Ethiopia, Nigeria, and India, have both drought areas and favorable humid areas within their borders, and the distribution of available food should not be difficult. In other areas, however, such as a large part of the Sahel in West Africa, international cooperation would be necessary to establish effective means of food distribution. Cooperation would also be required if relief were to be provided to nomadic peoples. In many cases the distances between dry and humid zones are not great, but lack of transportation, inadequate foreign exchange methods, and tribal differences are major barriers to adequate food production and distribution. Efforts should also be made to produce enough food in the favorable zones to permit storage from season to season, and from year to year, of quantities that could be used both in the event of unforeseeable crop losses and as buffers for the nearby stress zone. Because of more favorable grain storage conditions in the hotter and drier areas, the location of storage facilities in these areas should be encouraged. However, such production efforts will require adequate inputs in both material and management technology that are available only through international assistance in most instances.

Many people are inclined to criticize the "Green Revolution" by pointing out the high cost and the unavailability of the best package of materials and management. Proper amounts of essential elements are necessary for satisfactory crop yields regardless of the genetic origin or background of the crops grown. Supplying the necessary phosphorus, potassium, and the micronutrients through the application of chemically constituted fertilizers requires satisfactory marketing and delivery practices and, in many underdeveloped areas, transportation systems yet to be developed. The production of nitrogenous fertilizers depends on the availability of energy for fixation; production costs are, therefore, related to fossil fuel prices. The use of symbiotic nitrogen-fixing legumes or other biological systems of supplying nitrogen would thus seem to be much more important in the immediate future. The development of adequate seed stocks of superior responsive varieties, together with new management techniques and inputs, is essential. The development of new crop varieties, and the release of new varieties to farmers, must be a continuous process so that there will always be available plants with adequate resistance (to disease, insects, and drought) for cultivation in particular regions and during times of stress. Also, it must be possible to shift these varieties rapidly when disasters, biotic or climatic, develop.

Summary

Most areas of famine could be greatly reduced with proper planning. Improvements in food production in nearby relatively favorable areas could alleviate the present situation whereby a disastrous food shortage must become "newsworthy" throughout the world before the ponderous machinery of international assistance and very expensive intercontinental staple grain shipments are made. Such planning would allow man to be far less at the mercy of the annual whims of seasonal weather for his food supply.

References and Notes

1. A. H. Boerma, *Cajanus* **6**, 47 (1973).
2. W. Van Roren, *The Agricultural Resources of the World—Atlas of the World's Resources* (Prentice-Hall, Englewood Cliffs, N.J., 1954), p. 258.
3. Committee for the World Atlas of Agriculture, *World Atlas of Agriculture* (Istituto Geografico De Agostini, Novara, Italy, 1969), vols. 1–4, p. 2030.
4. S. F. Markham, *Climate and the Energy of Nations* (Oxford Univ. Press, London, 1947), p. 240.
5. T Alexander, *Fortune* **89**, 90 (Feb. 1974).
6. *Hammond's New World Atlas* (Garden City, New York, 1948), p. 343.
7. J. E. Newman, *J. Am. Soc. Farm Managers Rural Appraisers* **32**, 39 (1968).
8. L. M. Thompson, *J. Soil Water Conserv.* **28**, 287 (1973).
9. V P. Starr and A H. Oort, *Nature (Lond)* **242**, 310 (1973).
10. H Walter and H. Lieth, *Klimadiagramm, Weltatlas—World Atlas of Climatic Diagrams* (Fischer, Berlin, 1960–1964), p 245.

27 December 1974, Volume 186, Number 4170 **SCIENCE**

Climate Stabilization: For Better or for Worse?

Even if we could predict the future of our climate, climate control would be a hazardous venture.

W. W. Kellogg and S. H. Schneider

The world's climates have changed many times in the past, often with quite dramatic results, and they are changing today. We see the evidence in long-term trends in mean temperature, precipitation, variation of sea ice, and so forth. Furthermore, we experience seasonal anomalies in temperature and precipitation that affect large regions of the earth and influence agriculture and life patterns; these anomalies are also part of the set of statistics we refer to as climate. Understanding and predicting climate change has taken on considerable urgency now, since serious climate-induced food and water shortages have ravaged parts of Africa, threatened the livelihood of hundreds of millions of people in monsoon-dependent lands, and set off a spiral of increasing food prices.

So far, we do not have a comprehensive climate theory that can explain —much less predict—these trends and anomalies. Nevertheless, we understand enough about the earth-atmosphere system to recognize that humans can affect it, and surely have already, by pushing on certain "leverage points" that control the heat balance of the system. If we continue to expand our global activities, our influence on future climates will be still greater. As yet, however, we have given little serious thought to purposeful control of the climate.

If we could forecast climate changes we would be faced with several options. First, to do nothing. Second, to alter our patterns of land and sea use in order to lessen the impact of climate change. And third, to anticipate climate change and implement schemes to control it. The objective of climate control might be to reduce any natural changes, to counteract inadvertent human influence, or to cushion the effects of seasonal anomalies with a potentially disastrous social impact, such as the world experienced in 1972 and 1974 and may experience again in this decade. This is what we mean l.; stabilizing climate.

But if a climatic status quo is deemed a worthy objective, there are some serious problems to overcome before it can be realized. First is our present inability to predict what will happen if we do try to influence part of the climate system. Second is the difficulty of deciding what different peoples of the world will accept as an "optimum climate" toward which we should aim our stabilization schemes. Any imperfect climate modification (or conservation) scheme will have its winners and losers. How can we hope to satisfy the losers? After addressing these and other questions we consider some conceivable means of implementing climate control.

Causes of Climate Change

Given a fixed input such as solar radiation, the system that determines climate, on a regional or global scale, contains a variety of physical processes, many of which are fairly well understood individually. The biggest difficulties arise when we attempt to consider their interactions in nature, since these interactions create many feedback loops that act to amplify or dampen out small disturbances. In consequence, our climatic system is a highly nonlinear, interactive system that has defied a complete quantitative description. Figure 1 is a schematic representation of this system, presented here to illustrate its complexity.

So far we have no theoretical model that behaves like the climate system itself. Nevertheless, we do have models that incorporate many of the feedback loops and interactions that we now believe are most important (described below), and we are making progress in identifying the relative contributions of the dominant components of the system. This understanding, coupled with a large body of empirical and statistical evidence, gives some hope that soon we will be able to make more useful predictions of short-term climate change.

At the same time we must develop a quantitative theory of climate to understand better the factors that influence it in the longer term and to verify hypotheses and predictions derived from statistical methods. Human influence on climate, which may already be appreciable, can only be properly assessed when the natural forces at play are understood. Such a theory must include realistic modeling of atmospheric and oceanic subsystems, and these must in turn include the changing surface conditions of the planet and the masses of ice and snow at the poles.

Physical Factors Affecting the Climate; Feedback Mechanisms

The fundamental factors determining the overall climate of the earth-atmosphere system are the input of solar radiation, the earth's rotation rate, the

The authors are members of the Climate Project of the National Center for Atmospheric Research, Boulder, Colorado 80303. Dr. Kellogg has been on temporary leave at the Scripps Institution of Oceanography, La Jolla, California 92037

mass and composition of the earth's atmosphere, the properties of the oceans, and the surface characteristics of land and sea. Over a sufficiently long time the unreflected portion of the incoming solar energy (that is, the part absorbed by the earth-atmosphere system) must be balanced by the planetary infrared radiation emitted to space. The temperature dependence of the latter therefore governs the mean temperature of the earth-atmosphere system and also the distribution of temperature within it.

While on a global average, and over a long period of time (more than a year), a near balance of planetary radiation is established, this is seldom true locally in time and space. Rates of solar heating and infrared cooling are highly variable, not only horizontally over the globe but throughout the vertical extent of the atmosphere. This unequal or differential heating of the globe, coupled with the rotation of the earth, is the ultimate driving force behind the motions we recognize as winds and ocean currents. These horizontal and vertical motions regulate the distribution of temperature, cloudiness, and precipitation over the globe.

The circulation systems become more vigorous with increasing north-south atmospheric temperature gradients, so that large-scale transient eddies (storm systems) which transport additional heat poleward provide "negative feedback," lessening the increase of the temperature difference from equator to pole (*1*). The atmosphere conveys heat in two forms: sensible and latent. Transport of sensible heat involves, for example, the direct transport of warm air to a cold region. Transport of latent heat involves the water vapor which is evaporated at the earth's surface and then transported by the atmosphere. Where the air is cooled below its dew point in the presence of suitable nuclei (particles) the water will condense into drops, thereby releasing the latent heat that was needed originally to change it from liquid water to water vapor. The process of evaporation, transport of water vapor, condensation, precipitation, and reevaporation (the hydrological cycle) is responsible for one-fourth to one-third of the net heat transported across the 30°N latitude circle, sensible heat transport by the atmosphere accounts for another one-fourth to one-third; and the oceans carry the remainder, between one-half and one-third of the total heat flowing poleword (*2–4*). Figure 2 shows the magnitudes of the various transport processes as a function of latitude.

No summary of important climatic factors would be complete (at least if long-term climatic changes are to be considered) without mention of the "cryosphere," which includes the substantial areas of the earth's surface that are covered by ice and snow. Snow and ice usually have much higher albedos (reflectivities) than uncovered land or open ocean. Thus, a "positive feedback" between ice cover and temperature is suspected: lower temperatures cause more ice and snow and thus higher albedos, which result in a reduction in absorbed solar energy, which in turn results in yet lower temperatures.

However, ice and snow are primarily confined to limited regions of the earth. Globally, clouds are the dominant reflectors of incoming solar energy (*5*). In general, the hydrological cycle (which includes the cycling of water in clouds and in snow and ice fields) looms as a major factor in determining mean surface temperatures, not only through its influence on snow, ice, and clouds, but also through its control of surface vegetation and soil moisture. Since the hydrological processes are also tied to the motions of the atmosphere and oceans, the radiation balance and the dynamics of the atmosphere-ocean-ice-land system are tightly coupled through the hydrological cycle as well as through the direct dependence of radiation on temperature, and any valid quantitative theory of climate will ultimately have to treat the hydrological cycle mechanisms in detail (*3, 6, 7*).

The chief purpose of this summary of physical factors that affect climate is to emphasize the coupled nature of the climate system (Fig. 1) and to intro-

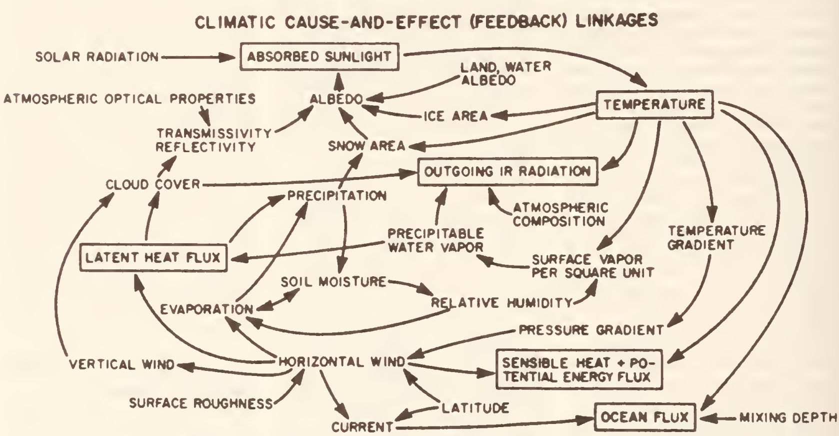


Fig. 1. The monumental challenge to atmospheric science to build a mathematical model that includes all important factors affecting the earth's climate is illustrated by this schematic figure of climatic feedback linkages. The chief difficulty is that many of these feedback processes have influences which are comparable in magnitude but opposite in direction (*43*); *IR*, infrared.

duce the important role of the numerous feedback mechanisms that operate in a physical system as complex as the earth-atmosphere system. The interactive, nonlinear nature of these climatic feedback mechanisms indicates that quantitative evaluation of how variations in any one of the system's factors affect the entire system will not be straightforward.

For example, if heat were added to the environment through human activities, we would expect the temperature of the atmosphere to rise. The amount of warming could be estimated relatively simply by comparing the magnitude of the heat input to the incoming solar energy through some straightforward radiative transfer and heat balance calculations. However, such an estimate presumes that all other factors remained constant—a highly tentative supposition. For example, the heat increment might evaporate more water and cause increased formation of clouds which would block out some sunlight and counteract the warming. Or, if the heat input were in a region with snow and ice cover, it might melt some of that frozen cover, leading to increased absorption of solar energy at the surface and a vastly accelerated warming. Or the cloudiness effect might cancel the ice and snow effect, or some other feedback process might dominate both of these, and so forth.

The range of possible interactions is staggering, but not necessarily fatal to the development of a comprehensive climate theory. We have a fairly good feel for the character of many of these feedback processes, and in numerous cases we can compute their effects with some confidence (*6–9*). Nevertheless, since individual interactions cause effects of opposite sign and comparable magnitude, the net consequence of the synergism of all climatic feedbacks is still uncertain.

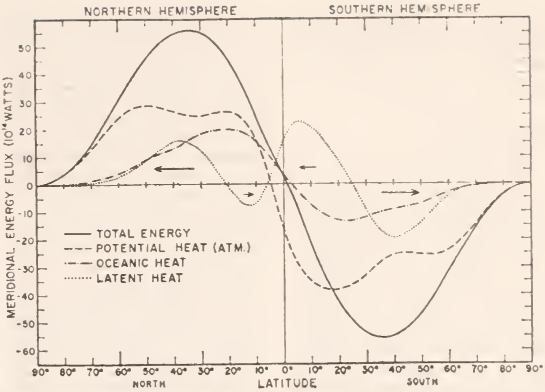


Fig. 2. Annual mean meridional flux of total energy for the earth-atmosphere system, and its apportionment between oceanic flux and atmospheric flux of potential heat and latent heat. The climate of each latitude zone is coupled to the climates of the other zones by the meridional fluxes of energy. [Source: Newton (*4*)]

Some Theories of Climate Change

There have been numerous theories of climate change, based on various combinations of the interacting physical factors. Changes external to the earth-atmosphere system are the most commonly postulated factors, and the theories treating them are the most deterministic. Such theories assume (reasonably) that the climate system responds to changed external forcing functions, for example: (i) fluctuations in solar emission, (ii) variations in the earth's orbit and axis of rotation, (iii) changes in the atmospheric carbon dioxide content, (iv) changes in the atmospheric dust content, and (v) changes in the character of the land surfaces.

While the first two factors are wholly external to the climate system (*10*), the last three could be coupled in certain ways to the climate (*6, 7, 11–13*). Natural changes in the carbon dioxide or dust content of the atmosphere or in land cover can depend on variables in the climatological state, such as wind (to carry dust), precipitation (to affect land cover), or temperature (to control the solubility of carbon dioxide in the oceans). Thus, these three factors are partially internal to the system. However, changes in these factors due to human activities (or to volcanoes) do not depend on the climatological state, and are thus external.

More recently, investigators have considered some factors that appear to be wholly internal causes of climatic change, such as (i) quasiperiodic or anomalous ocean surface temperature patterns (*14*), (ii) decreases in salinity in the North Atlantic or the Arctic Ocean, leading to increased sea ice formation (*6, 15*), and (iii) the almost-intransitivity of the climate system.

The last "cause" of climate change was proposed by Lorenz (*16*) to point out that an interactive system as complex as the oceans and atmosphere can have long-period self-fluctuations even with fixed external inputs. Internal fluctuations with time scales longer than the "standard" interval used to define a climatological average (sometimes taken to be 40 years) might easily be misinterpreted as climatic changes forced by external variations. Or, observed changes could be due to a combination (not necessarily linear) of external and internal forces.

This discussion suggests the inherent difficulty of tracing cause and effect for any climate change when climate is defined as a time average over a finite interval. Furthermore, climatic fluctuations which people would consider significant (such as seasonal anomalies) could occur on time scales shorter than any particular climate-defining interval, and might be interpreted as climatic "noise" due to short-term averaging of random, unpredictable weather events. Yet these anomalies should still be considered part of the climatic state, since it may be shown that the frequency of their occurrence is related to longer-term climatic statistics.

Therefore, merely to identify the existence of a climate change requires the skill to separate changes in the longer-term mean (the signal) from shorter-term weather fluctuations (the noise) (*8, 17*). Then to attribute cause and effect necessitates separation of internal and external forcing factors quantitatively, a step that requires a theory of

climate. While at present no completely satisfactory theory exists, many of its elements are understood, and the major tools for such understanding are climate models.

Climate Modeling

The factors affecting climate must all obey the principles of conservation of mass, momentum, and energy. These laws, together with thermodynamic and chemical laws governing changes in the material composition of land, ice, sea, and air, comprise the basis for a theory of climate. Mathematically expressed, these form a coupled set of three-dimensional time-dependent nonlinear partial differential equations, whose solutions can be obtained in principle if the initial state of the system and its external forcing boundary conditions are known (*6*).

Unfortunately, in order to solve the equations of climate theory with the knowledge and tools available to us in the foreseeable future it is necessary to ignore the details of small-scale processes, treating the system at a discrete number of points (or modes) in space (the grid) and in time (the time step). All processes occurring on scales smaller than those resolved in the model must be ignored or, at best, treated in a statistical fashion. The method of relating statistically the effects of subgrid-scale processes to those occurring on a much larger scale is called parameterization. The technique of selecting the appropriate grid size, time step, parameterization schemes, and even approximations to the basic equations is the art of modeling, and the particular choice of these elements defines the climate model (*6, 8, 18*).

The simplest types of climate models recognize the fundamental importance of the radiation balance in determining temperature, and bypass the problems inherent in dealing with a horizontal grid. These merely relate the vertical fluxes of infrared and solar radiation in the atmosphere to the atmospheric temperature profile and the vertical distribution of optically important gases, clouds, and particles. An assumption that ties the atmospheric lapse rate, or decrease of temperature with height, to vertical convective motion is usual for this class of model.

These "horizontally averaged models" are often most useful in globally averaged form, and can tell us the relative importance of different optically important constituents for the radiation balance and temperature distribution of the earth-atmosphere system. For example, the effect of increased atmospheric carbon dioxide has been studied by Manabe and Wetherald (*19*) with a radiative-convective model of the earth-atmosphere system. Despite the fact that all feedback processes associated with the horizontal redistribution of energy were absent in their model, it is widely cited as giving an order of magnitude estimate of the increase in surface temperature resulting from increased carbon dioxide.

A second kind of modeling approach is to work only with the energy balance of the earth-atmosphere system at each latitude and to parameterize by semiempirical relations the horizontal transports of heat in terms of mean latitudinal temperature difference. This has been the approach of Budyko (*20, 21*) and Sellers (*22*), who included the surface temperature–ice–albedo feedback effect. Their well-known semiempirical approach gave their models a greater sensitivity to small changes in the radiation balance than that of horizontally averaged models, which do not include the positive feedback effect of surface temperature–ice–albedo coupling. The work of Budyko and Sellers has led to concern over the stability of the earth's climate, since negative changes in energy input of the order of 1 percent of the solar constant could plunge their model climates into an ice age or, alternatively, positive changes could significantly melt the polar ice caps. Further insight into the behavior and limitations of these models has been given by Schneider and Gal-Chen (*23*), among others.

These examples show the importance of zonally averaged energy balance models in estimating to first order the effect of a change in a climatic component, but they also remind us that any feedback processes not properly included could substantially revise these estimates.

Models that include many coupled processes have been developed, but as the number of processes included and the spatial and temporal resolution are increased, so is the computation time—drastically. Three-dimensional simulations of the general circulation of both atmospheric and oceanic systems have been made, and in many instances large-scale features predicted by these models are beyond our intuition or our capability to measure in the real atmosphere and oceans. Nevertheless, while general circulation models (GCM's) are essential tools for evaluating the relative magnitudes of competing feedback processes, they may not be practical tools for long-term climate forecasting for many years (except possibly for seasonal or interannual forecasts).

Finally, it may be possible to develop a compromise model, which will probably be three dimensional, but with a sufficiently limited resolution (or coarse grid) that very-long-term integrations may be possible. Such a "statistical-dynamical" approach will require parameterization of processes that are underresolved by the coarse grid. These parameterizations could be based on a limited number of experiments with high-resolution general circulation models. Then, once the statistical-dynamical models had been calibrated against GCM's, it would remain to calibrate them and the GCM's against the real climate.

A few cautious steps along these lines are being taken at a handful of institutions around the world. The success of such efforts will determine to a large extent our potential for understanding climatic cause and effect, and will indicate the degree to which long-term climate prediction is possible.

Society's Leverage Points

The degree to which people can change the climate generally depends on the scale of the attempt. Wearing warm clothes on a cold day is probably the smallest scale, heating and cooling the air in a house is a slightly larger conventional undertaking, and changing the air temperatures (and air quality) over a large city is now quite commonplace also—although not planned. Other climate changes on a larger scale have certainly occurred because of human activities, although they are harder to document [for example, desert growth along the erstwhile "Fertile Crescent" of the Mediterranean has been attributed by some to overgrazing of goats (*6*)].

The key to any climate change is an alteration of the heat (or water) balance of the system involved. Thus, in winter the city adds primarily heat directly to the atmosphere, thereby warming it; and in summer, in addition to heat directly added, the greater heat conductivity of the materials of build-

ings and pavements causes the city to retain its heat at night longer than the surrounding countryside. Changing the reflectivity of the surface (such as by irrigating a desert or cutting down a forest) changes the absorption of sunlight and also influences the evaporation of water from the surface. Damming rivers (changing the hydrologic cycle), clearing land by the slash and burn approach (creating clouds of smoke), and doing many other things to alter the face of the land and its heat balance all contribute to climate change on a regional scale (*6*).

On a global scale human influence can now begin to be felt. While our climate models are still incomplete, we do understand enough about the system to be able to estimate the initial effect of changing some specific factor. One such factor is the ability of the atmosphere to absorb infrared radiation emitted by the ground, a change in the atmospheric content of carbon dioxide, water vapor, or ozone will have such an effect, since these are all optically important gases (*7*).

The increased use of fossil fuels since the beginning of the industrial revolution has resulted in a steady buildup of the carbon dioxide content of the atmosphere. This gas is chemically quite stable, and somewhat less than half of the added carbon dioxide appears to have gone into the oceans and the biosphere (mostly the forests), while the other half has remained in the atmosphere. It is estimated (*6*, p. 237, *11*, *24*) that the atmospheric content of carbon dioxide has risen from a pre-industrial revolution value of slightly under 290 parts per million (ppm) by volume to about 320 ppm, and that by the end of the century it may rise to 380 ppm (*24*) or about 400 ppm (*11*). (The energy crisis may have an influence on both of these estimates, but it seems probable that coal will continue to be used in increasing amounts to replace gas and oil—unless advocates of reduced economic growth have a persuasive impact on present trends.)

Estimates of the effect on climate of the increase in carbon dioxide expected by A.D. 2000 depend [illegible] on the assumptions that are made about the other adjustments that the climatic system will make to compensate for the increased absorption of infrared radiation. (For example, how much more water vapor will be taken up by a warmer lower atmosphere?) However, 0.5°C seems to be a reasonable first-order estimate for the average rise in the temperature of the lower atmosphere due to a 20 to 25 percent increase in atmospheric carbon dioxide. We believe there will be relatively less change at low latitudes and perhaps twice the average change (or more) in polar regions, as calculated by Manabe [discussed in (*18*)]. For perspective it is helpful to note that 0.5°C is approximately the magnitude of surface temperature warming experienced by the Northern Hemisphere between about 1900 and 1945. This seemingly small increase can still produce dramatic changes in some places (compare Fig. 3 with the cover photograph). Thus anthropogenic carbon dioxide increases projected to the year 2000 could be as

Fig. 3. Photograph of the town of Argentierre in the French Alps taken in the mid [illegible]. The view is essentially the same as that in the engraving shown on the cover of this issue which was made about 100 years earlier when the mean hemispheric temperature was less than 0.5°C cooler. The terminus of the glacier can [illegible] be discerned in the [illegible] part of the picture. [From [illegible] (*44*)]

influential in changing the climate as the processes active in the climatic system in the first half of this century.

If this increase continues until the atmospheric carbon dioxide doubles by about A.D. 2040 (*11*), it is doubtful that the present boundaries of glaciation or sea level will be maintained.

At the same time that humans have been adding carbon dioxide to the atmosphere, they have been adding particles, or aerosols. These aerosols come from direct injection by coal-burning plants and furnaces or by slash-and-burn practices, or they are created photochemically in the atmosphere from unburned hydrocarbon fuel and sulfur dioxide under the influence of solar ultraviolet radiation. Measurements at many places have shown a steady rise in the aerosol content of the lower atmosphere in the past few decades, and sudden increases in the stratospheric aerosol content have followed the major volcanic eruptions such as the eruption of Mount Agung in Bali in 1963.

The long-term aerosol record for the globe is far from clear, however. A particle floating in the lower atmosphere at middle latitudes will have a mean lifetime of only 3 to 4 days, since the atmosphere cleanses itself by rain (*25*). In polar regions the lifetime of particles is probably longer, and in the rainy parts of the tropics even shorter. Thus, the reported increases in aerosol content are most noticeable near the sources (except for volcanic aerosols, which remain in the stratosphere for several years and are spread worldwide), and vast regions of the world, including most of the Southern Hemisphere, have apparently experienced virtually no increase in anthropogenic aerosols. The increase is most pronounced downwind from the industrialized parts of the Northern Hemisphere and in tropical regions where slash-and-burn practices are widespread (*26*).

In regions where aerosols have increased, an effect on the heat budget will be felt, since aerosols efficiently scatter and absorb solar radiation. Over land with a moderately high surface reflectivity, typical tropospheric aerosols will tend to warm the atmospheric column in which they lie and decrease the solar flux reaching the surface. Over the oceans, which have low reflectivity, the net effect will be a cooling, since relatively more sunlight will be reflected back to space when aerosols are introduced over the dark surface. Several studies have been made of the overall effect of aerosols on the radiation or heat balance of the earth-atmosphere system, and given the (meager) available data the consensus appears to be slightly in favor of a cooling (*7, 13*). In fact, addition of aerosols has been invoked by some to explain the cooling trend in the Northern Hemisphere that set in about 1945. [For two somewhat different assessments of this point the reader is referred to Bryson (*27*) and Mitchell (*12, 28*).]

Aerosols not only affect the radiation balance, but certain kinds of particles can serve as ice nuclei (below 0°C) and condensation nuclei (in warm clouds) and thereby influence the formation of clouds and precipitation. It has been pointed out (*29*) that this could be an even greater leverage point than the radiation effect, but so far we cannot assess the direction of this effect, let alone its overall magnitude.

So far we have dealt with some leverage points that mankind could use to control the radiational heat balance of the climate system, and thereby influence the climate. In the foreseeable future anthropogenic sources of energy may become a factor in the global heat balance by their sheer magnitude. Just as the air over our large cities is now warmed by the heat released locally, society's activities in the future will warm the air perceptibly over large regions, and quite possibly over the entire earth (*30*).

Consider the present man-made energy released to the atmosphere compared to the solar energy that is absorbed at the surface. The power generated artificially worldwide amounted to (6 to 8) $\times 10^3$ gigawatts in 1970 and was increasing at a rate of 5.7 percent per year (*6*). (This was the estimated power output of all generators, factories, automobiles, heating plants, and so forth, all ending up in the environment in the form of heat. It was considerably larger than the useful power that turned our wheels.) The solar power that is absorbed at the surface is, on the average, about 150 watts per square meter, and for the whole earth this amounts to 7.5×10^7 gigawatts. Thus, on a global scale mankind generates only about 0.01 percent as much energy as the sun deposits at the surface.

Now consider a future "postindustrial society" as seen by the technological optimists, such as Weinberg and Hammond (*31*). A century from now, in about A.D. 2100, the present energy crisis will have long since been solved; nuclear, thermonuclear, solar, coal, and perhaps other forms of power generation will provide adequately for a population of, say, 20 billion people; and the reduction of pollution and extraction of resources from the earth will require high technology and will be more expensive in terms of energy than they are now. A scenario of the future can be drawn up that shows such a world to be technically possible, the main assumption being that society itself will survive. [The author of this scenario must, of course, be both a technological and a social optimist, and there are many who do not share this optimism, such as the Club of Rome or Heilbroner (*32*).]

Twenty billion people, each of whom uses four times the present U.S. per capita power consumption of 10 kilowatts, would require 8×10^6 gigawatts, and this is about 1 percent of the total solar power absorbed at the surface. (Note that the power generated would be localized on the continents, which comprise only one-fourth of the earth's surface area.) The horizontally averaged climate models show that a 1 percent increase in thermal power would raise the average temperature of the climate system by about 1°C, and zonally averaged energy balance models (including ice-albedo feedback) raise this estimate by a factor ranging from 1.3 to 3.0. Such a change would be less at equatorial latitudes and several times larger at the poles if the heating were more or less evenly distributed over the continents. These large polar changes are especially noteworthy, since they have important implications for the Arctic Ocean, the Greenland ice cap, the Antarctic ice cap, and the sea level, but this is beyond the scope of this article (*6, 9, 30*).

The lesson to be learned from this exercise is that the future physical influence of mankind can be very significant relative to that of nature. Furthermore, with so much power under its control mankind will very likely have the technological capability to alter climate purposefully as well as inadvertently. Leaving aside for the moment the question of whether it makes sense to alter or conserve climate, we will review some of the schemes that have been suggested for modifying climate on a hemispheric or global scale—

schemes that have so far been considered to be on the fringe of science fiction. The range of possibilities widens rapidly if one imagines the financial resources of the major world powers available to carry them out. These schemes are summarized in Fig. 4, and some of them will be described briefly.

One perennial suggestion—none of these should be considered yet as proposals—is to eliminate the Arctic Ocean ice pack. This layer of drifting ice that covers most of the Arctic Ocean varies in average thickness from less than 2 meters in summer to about 3 meters in the late winter (*33*), and if it were removed the characteristics of the northern polar regions would be dramatically different. An open ocean would result in much more moderate and quite possibly more snowy winters around the Arctic Basin, with January temperatures some 10° to 15°C warmer than at present (*33*, *34*). We do not know whether this could start another glaciation of northern Canada and Europe due to the increased snowfall, but this is a definite possibility. Furthermore, a change as large as eliminating the Arctic sea ice would almost surely cause important climatic changes in places far from the Arctic Basin. The question now is how to eliminate the ice pack. Of course, the temperature rise in the Arctic due to carbon dioxide or global thermal pollution that we have just described might be sufficient without any extra effort (*21*), but there are some ways to help the process along.

Spreading black particles, such as soot, by cargo aircraft is one way. A 20 percent decrease in reflectivity of a large area of the ice would cause it to disappear in a period of about 3 years, according to one model (*35*). Another suggestion is to dam the Bering Strait and pump water from the Arctic Ocean into the Pacific, thereby drawing warm Atlantic water in from the other side and raising the surface water temperature enough to melt the ice pack. A third way might be to detonate "clean" thermonuclear devices in the Arctic Ocean to fragment the ice and stir saltier, warmer water from below. Diverting northward-flowing rivers that add fresh water to the Arctic Ocean would speed the process, since the present surface layer of low salinity (and lower density) a few tens of meters deep is partially replenished by these rivers, and if it were eliminated the pack ice would grow less rapidly in winter (*6*). Other ideas will no doubt come to mind, but these may suffice to give the flavor of the argument.

It has also been suggested that a massive extension of present cloud-seeding techniques could modify precipitation patterns and the release of latent heat on a regional or hemispheric scale. The regular "steering" of hurricanes (or typhoons, as they are called in the western Pacific) by cloud seeding, if that turns out to be feasible, would change the climate of hurricane-prone regions. An alternative way of steering hurricanes might be to pump cold water to the surface before them, since hurricanes are known to respond to the surface temperature of the ocean. (Incidentally, a proposal to systematically direct hurricanes headed for the southern United States would

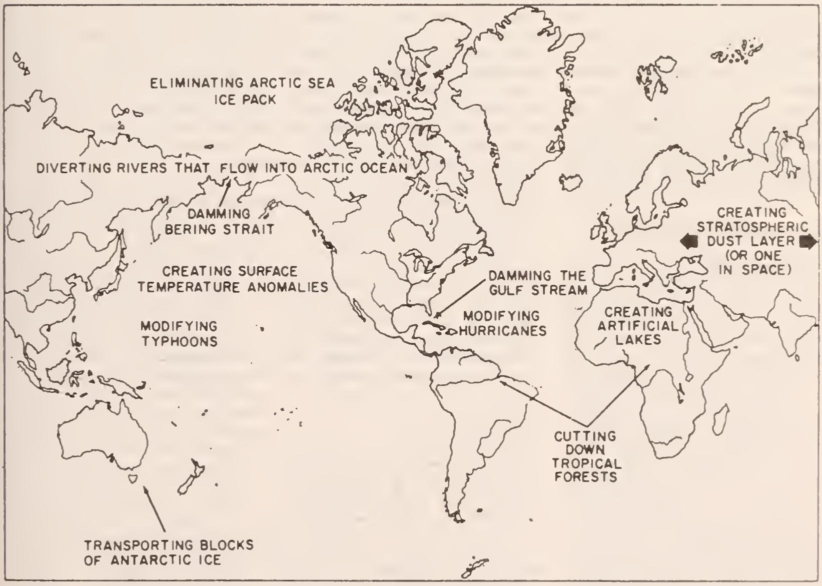


Fig 4. Schematic illustration of the kinds of engineering schemes that could be proposed to modify or control the climate.

raise some concern south of the border, since the Gulf Coast of Mexico enjoys the rainfall from these same hurricanes. This is an example of the kind of conflict of interest that we will discuss further in the next section.)

As we mentioned above, certain aerosol particles have a tendency to cool the earth on the average, and when they are injected into the stratosphere they remain there for several years and have a more prolonged cooling effect at the surface. Thus, if we were concerned about a general rise in temperature due to carbon dioxide and thermal pollution, why not inject enough of the right kind of particles into the stratosphere to counteract the warming? Perhaps a fleet of supersonic transports would help here, since they could create a kind of "stratospheric smog" at about the right level (*6, 36*). In an even more fanciful vein, why not put bigger particles (or mirrors) in orbit around the earth, where they may remain even longer?

One could go on with such suggestions, some to cool and some to warm vast regions of the earth, some to change the patterns of rainfall, some to protect from damaging storms, and so forth. They could be used to improve the current climate (for some) or to offset a predicted deterioration of climate (for some), whether the deterioration was natural or man-induced. In the next section we will discuss the pertinent question of whether we should use any newly acquired powers for climate control or climate stabilization.

Hazards of Climate Modification

Returning to our original thesis, we believe that it would be dangerous to pursue any large-scale operational climate control schemes until we can predict their long-term effects on the weather patterns and the climate with some acceptable assurance. We cannot do so now, and it will be some time—if ever—before we can. To tamper with the system that determines the livelihood and life-styles of people the world over would be the height of irresponsibility if we could not adequately foresee the outcome. However, we recognize that this may not be the opinion of some, especially those who live in the affected regions where a prediction of climatic change could be a forecast of local disaster if the predicted change were not offset.

In addition, there is need to prevent one group from using a climatic "threat" (real or imagined) by a neighboring group as a pretext for hostile actions (*37*). For example, by analogy, it is not without precedent for one Middle Eastern state to claim water rights to a river that is also vital to its neighbor, and for the neighbor to demonstrate, in the clearest terms, the consequences to the first of any diversion of the disputed river. In that case vital interests and raw power determined the course of action for those states, not rational discourse or the principles of right and wrong. In another case the United States has negotiated with Mexico over rights to the water from the Colorado River.

In the case of water rights, legally tangled though it is, it is still easy for one state to determine whether the other has effected a physical change and to assess the magnitude of that change. However, in the case of weather or climate modification (inadvertent or purposeful), it would probably be much more difficult to establish the agent and degree of responsibility for any detectable effects.

As a case in point, consider the Rapid City, South Dakota, flood of 9 June 1972. Experts have argued about whether prior cloud-seeding experiments contributed to the damage (*38*). We suspect that all but the most partisan antagonists still have reasonable doubts about the magnitude of the contribution, if any, of the seeding program. The fact remains that it is nearly impossible at present to establish conclusively cause and effect linkages (let alone magnitudes) in any single weather or climate modification experiment. In the Rapid City case there is an accepted legal authority to adjudicate potential disputes, and the ultimate ruling of the courts can be enforced. But suppose one of the bitter enemies in the Middle East were conducting weather modification experiments and its neighbor downwind felt aggrieved. Would the matter more likely end in the World Court—or in some form of military action?

Since cause and effect are hard to unravel and since no formally assembled body of impartial experts is in existence, blame would be difficult to assess. What is worse, perhaps, is that experts around the world would probably align themselves with the combatants on politically, rather than scientifically, defensible grounds if a climate-related dispute flared. Since progress in climate research necessarily depends on cooperative working relations between scientists of rival powers, the potential damage to scientific progress from a scenario like this is frightening.

Perhaps we should consider the creation of a panel of "impartial" international experts to adjudicate (or at least mediate) such disputes before one explodes. It may be too late if a conflict were to occur first, with polarization and partisanship being an accepted factor in world diplomacy. How would power be assigned to such a panel? How would its constituency be determined? These questions are as familiar and nearly unanswerable as those that accompany any effort to share power and responsibility multinationally.

Yet, we cannot escape the fact that the atmosphere is a resource that is shared by all the world's people, and is a tightly coupled system that cannot be pushed very hard in one place without making a bulge somewhere else.

Coming back to our central theme, suppose a climate disaster were forecast: wouldn't some countries propose climate stabilization measures? And, granted that they could agree among themselves to try to stabilize the climate, who would implement the stabilization scheme? In view of the potential for economic or military advantage, who would deal with errors or side effects that might affect a third party—that is, if a cause and effect chain could be established beyond a reasonable doubt?

We have raised many more questions than we are even remotely capable of answering, but we do wish to offer one "modest" proposal, for "no-fault climate disaster insurance." If a large segment of the world thinks the benefits of a proposed climate modification scheme outweigh the risks, they should be willing to compensate those (possibly even a few of themselves) who lose their favored climate (as defined by past statistics), without much debate as to whether the losers were negatively affected by the scheme or by the natural course of the climate. After all, experts could argue both sides of cause and effect questions and would probably leave reasonable doubts in the public's mind.

Short-term deterioration of climate strikes hardest at food production, whereas longer-term changes might be accommodated by changing the pattern of agriculture and perhaps by migration. This suggests that the form of reimbursement for climate-induced losses should, at least initially, be in

the form of food or food-production technology. It follows that the international insurance agency that issues the no-fault climate disaster insurance must be a holder of adequate reserves of food to reimburse the losers, together with the means to transport it where it is most needed.

A special form of such an insurance program makes sense already, in the absence of any intent to modify climate purposefully. Crop failures and famine have recently struck marginal areas of Africa south of the Sahara Desert (the Sahel) and monsoon-dependent India and Pakistan, and these failures must be attributed in part to climate variation. The cold winter and hot dry summer of 1972 in the central Soviet Union caused subnormal wheat yields, which led to a shift of international trade balances as the Soviet Union bought U.S. wheat in unprecedented quantities (*39*). All this strongly suggests that, in view of the present dwindling world reserves of food (enough grain for about 1 month, or perhaps less), there should be an urgent international effort to cushion the shock of future crop failures by creating stockpiles of food. This could be called, for the time being, "No-fault famine insurance"—or, as Schneider (*40*) recently suggested, referring to the story of Joseph in Egypt, "the Genesis strategy." Perhaps a push to increase global food supplies might also generate pressures for climate modification or control operations (*41*). However, it seems to us that control of food supply and demand is a far better method of reducing famine than attempts to control the climate.

A less ambitious trial of our original insurance plan to cover situations where weather modification efforts are taking place could be made within one country. This may be appropriate even now. Returning to the Rapid City case, for example, if the people of South Dakota had agreed in the majority that weather modification operations were likely to do more good than harm for the greatest number of people in the state, then a statewide insurance premium could have been levied and a no-fault weather modification insurance policy could have been issued to every citizen who could be affected by the operation. Of course, it could be argued that natural variability in the atmosphere (such as the risk of a damaging storm occurring in spite of the weather modifying operation) may be great enough to raise the premiums for our weather insurance beyond a level that the majority would find acceptable. This might curtail potentially valuable projects. But, until cause and effect can be traced with more certainty, it seems to us that compensation as well as benefit must be spread more equitably among all potentially affected people.

In this proposition we are referring to operational weather or climate modification projects, not to small-scale research experiments. The latter are crucial to the acquisition of the kinds of understanding that will ultimately lead to knowledge of cause and effect. Even in these limited projects, however, cooperation of those affected locally is essential to the experiment's success (*42*).

Even granted the ability to predict the effects of a perturbation to the system, or the ability to forecast seasonal anomalies some months in advance—and we are hopeful that this can be done in the decades ahead—and granted the existence of some semiperfect operational scheme to stabilize the climate, there will still be the agonizing decision about whose climate should be preserved, whose improved, and whose sacrificed. (Take, for example, the differing attitudes of the United States and Mexico toward hurricanes in the Gulf of Mexico, cited in the previous section.) Perhaps agreement could be reached (unless one lived in drought-prone central Africa) if it were simply a matter of stabilizing the present climate or preserving the status quo. But we have no international mechanism or institution or treaty for deciding what would be an overall improvement, let alone tackling the question of who would be responsible if a scheme produced (or were perceived to produce) unexpected results in someone else's backyard.

It may be useful now to summarize some important points and questions we have discussed in connection with potential climate-related conflict situations.

1) The atmosphere is a highly complex and interactive resource common to all nations.

2) Decision-making with unsharpened tools (such as climate models) may become necessary.

3) What if we could trace climatic cause and effect linkages? Accusations would abound.

4) What if one nation perceived climatic cause and effect linkages? Could this be used as an excuse for hostility?

5) What if one nation could predict climate? This would change entire international economic market strategies or might lead to pressures for climate control.

6) Who would decide and who would implement climate modification and control schemes? The costs of miscalculation (or perception of miscalculation) are immense.

We have the impression that more schemes will be proposed for climate control than for control of the climate controllers. Whether or not purposeful climate control is ever needed or realized, the problems of inadvertent climate modification, climate prediction, and feeding a growing world population suggest the timeliness of studying potential climate-related crisis and conflict scenarios. This is the first step. In any case, the object of understanding and anticipating natural, inadvertent, or purposeful climate change and its consequences for society must, in our view, continue to be a major interdisciplinary goal. While it is essential to work out international mechanisms to guarantee that any new knowledge of our climate system will have only constructive uses, the price in human suffering of continued ignorance of the causes of climate change may already have become unacceptably high.

References and Notes

1. P. D. Thompson, *Numerical Weather Analysis and Prediction* (Macmillan, New York, 1961), p. 118; E. N. Lorenz, *The Nature and Theory of the General Circulation of the Atmosphere* (Report No. 218, World Meteorological Organization, Geneva, Switzerland, 1967); H. H. Lamb, *Climate: Present, Past and Future* (Methuen, London, 1972), vol. 1; P H Stone, *J. Atmos Sci.* **30**, 521 (1973).
2. W. D. Sellers, *Physical Climatology* (Univ of Chicago Press, Chicago, 1965); T H. Vonder Haar and V. E. Suomi, *J Atmos. Sci* **28**, 305 (1971); T. H Vonder Haar and A. H. Oort, *J Phys. Oceanogr* 3, 169 (1973).
3. M I Budyko, *Climate and Life* (Hydrological Publishing House, Leningrad, 1971).
4. C. W Newton, *Meteorol. Monogr* 13 (No. 35), 242 (1972).
5. S H. Schneider, *J Atmos Sci.* **29**, 1413 (1972).
6. SMIC report, *Inadvertent Climate Modifications; Report of the Study of Man's Impact on Climate* (MIT Press Cambridge, Mass., 1971).
7. S H Schneider and W W Kellogg, in *Chemistry of the Lower Atmosphere*, S I Rasool, Ed (Plenum, New York 1973), p 203.
8. S. H. Schneider and R E Dickinson, *Rev Geophys Space Phys* **12**, 447 (1974)
9. W. W. Kellogg, in *Proceedings of the 24th Alaskan Science Conference* (Univ of Alaska Press, Fairbanks, in press)
10. ———, *Acta Astron* 1, 81 (1974); J M Mitchell, Jr., *Quat. Res* **2**, 416 (1972).
11. R Bacastow and C D Keeling, in *Carbon and the Biosphere*, G M Woodwell and E V Pecan, Eds (USAEC CONF-720510, National Technical Information Service, Springfield, Va., 1973), p. 86
12. J M Mitchell, Jr., in *Global Effects of Environmental Pollution*, S F Singer, Ed (Reidel, Dordrecht, and Springer-Verlag, New York rev ed., in press).

13. S. I. Rasool and S. H. Schneider, *Science* 173, 138 (1971); G. Yamamoto and M. Tanaka, *J. Atmos. Sci.* 29, 1405 (1972).
14. J. Namias, in *The Changing Chemistry of the Oceans*, D. Dyrssen and D. Jagner, Eds. (Wiley, New York, 1972), p. 27.
15. S. Martin and P. Kauffman, *J. Fluid Mech.* 64, 507 (1974); P. K. Weyl, *Meteorol. Monogr.* 8 (No. 30), 37 (1968)
16. E. N. Lorenz, *J. Appl. Meteorol.* 9, 325 (1970); in *Man's Impact on the Climate*, W. H. Mathews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1970), p. 179; *Meteorol. Monogr.* 8 (No. 30), 1 (1968).
17. C. E. Leith, *J. Appl. Meteorol.* 12, 1066 (1973); R. M. Chervin, W. L. Gates, S. H. Schneider, *J. Atmos. Sci.*, in press.
18. J. Smagorinsky, in *Weather and Climate Modification*, W. N. Hess, Ed. (Wiley, New York, 1974), p. 633.
19. S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* 24, 241 (1967).
20. M. I. Budyko, *Tellus* 21, 611 (1969).
21. ———, *Eos Trans. Am. Geophys. Union* 53, 868 (1972).
22. W. D. Sellers, *J. Appl. Meteorol.* 8, 392 (1969); *ibid.* 12, 241 (1973).
23. S. H. Schneider and T. Gal-Chen, *J. Geophys. Res.* 78, 6182 (1973).
24. L. Machta, in *Carbon and the Biosphere*, G. M. Woodwell and E. V. Pecan, Eds. (USAEC CONF-720510, National Technical Information Service, Springfield, Va., 1973), p. 21.
25. E. A. Martell, in *Man's Impact on the Climate*, W. H. Mathews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971), p. 421.
26. W. E. Cobb, *J. Atmos. Sci.* 30, 101 (1973); L. Machta and K. Telegadas, in *Weather and Climate Modification*, W. N. Hess, Ed. (Wiley, New York, 1974), p. 687.
27. R. A. Bryson, *Weatherwise* 21, 56 (1968); *Climatic Modification by Air Pollution, II: The Sahelian Effect* (Institute for Environmental Studies, University of Wisconsin, Madison, 1973); *Science* 184, 753 (1974).
28. J. M. Mitchell, Jr., in *Man's Impact on the Climate*, W. H. Mathews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971), pp. 133 and 167.
29. P. V. Hobbs, H. Harrison, E. Robinson, *Science* 183, 909 (1974).
30. W. W. Kellogg, in *The Energy Question*, E. W. Erickson and L. Waverman, Eds. (Univ. of Toronto Press, Toronto, 1974), p. 242.
31. A. M. Weinberg and R. D. Hammond, *Am. Sci.* 58, 412 (1970).
32. Club of Rome, *Ecologist* 2, 1 (1972); R. L. Heilbroner, *An Inquiry into the Human Prospect* (Norton, New York, 1974).
33. J. O. Fletcher, *The Heat Budget of the Arctic Basin and Its Relation to Climate* (Report R-444-PR, Rand Corporation, Santa Monica, Calif., 1965).
34. M. Warshaw and R. R. Rapp, *J. Appl. Meteorol.* 12, 43 (1973).
35. G. A. Maykut and N. Untersteiner, *J. Geophys. Res.* 76, 1550 (1971).
36. SCEP report, *Man's Impact on the Global Environment: Study of Critical Environment Problems* (MIT Press, Cambridge, Mass., 1970); C. E. Leith, Ed., *The Natural and Radiatively Perturbed Troposphere* (CIAP Monograph 4, Department of Transportation, Washington, D.C., in press).
37. S. H. Schneider, paper presented at the Annual Meeting of the AAAS, December 1972, Washington, D.C.; *New Eng.* 7, 14 (1973).
38. B. C. Farhar, *Bull. Am. Meteorol. Soc.* 55, 759 (1974).
39. L. A. Mayer, *Fortune* 84 (No. 2), 85 (1974).
40. S. H. Schneider, *National Observer*, 6 July (1974), p. 18; see also R. F. Taubenfeld and H. J. Taubenfeld, *International Organization* 23, 808 (1969).
41. ———, *Ambio* 3, 150 (1974). In the same issue of *Ambio* (p. 120) M. Falkenmark and G. Lindh suggest: "It would, for instance, be of interest to suppress part of the copious rains in Cameroon, Nigeria, and other coastal states to keep more moisture in the monsoon for condensation further inland." Such plans are not new. For example, G. A. Thompson proposed "A plan for converting the Sahara Desert into a sea" in the 10 August 1912 issue of *Scientific American* (p. 114). Obviously, more schemes will be advanced.
42. H. Landsford, *Bull. Am. Meteorol. Soc.* 54, 658 (1973).
43. W. D. Sellers, private communication.
44. E. LeRoy Ladurie, *Histoire du Climat depuis l'An Mil* (Flammarion, Paris, 1967).

45. We wish to acknowledge the encouragement of G. Kukla, organizer of the AAAS symposium "To Feed the World" (San Francisco, 27 February 1974), at which this paper was originally presented. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Viral Infection and Host Defense

Many aspects of viral infection and recovery can be explained by the modulatory role of double-stranded RNA.

William A. Carter and Erik De Clercq

Current interest in double-stranded RNA's (dsRNA's) takes on many forms. It ranges from physicochemical studies of their structure, through descriptions of the large diversity of cellular reactions brought about by these molecules, to studies of events triggered at the level of the intact animal.

We attempt in this article to develop a perspective on the heterogeneity of reactions provoked by dsRNA in biological systems. We describe how chemical lesions (bond breakage, unpaired bases) in the double-helical structure can modulate or abort biological function. Finally, we submit for consideration a hypothesis that dsRNA is both the molecular mediator of much of the morbidity and cellular damage associated with cytolytic viral infection, as well as a crucial molecular trigger that stimulates many of the organism's defenses to viral infection. By defining this dynamic role of dsRNA, we hope to signal new experimental inquiry which may permit a more detailed analysis of events at the molecular level, which until now have been described at the microscopic level as "extreme tissue damage probably due to a virus."

Before we proceed with development of ideas on the role of dsRNA in viral infection, it should be recalled that dsRNA is generally considered as not being a regular constituent of the eukaryotic cell. This view is clearly correct in a quantitative sense, although it may require some revision. For example, it has been shown that heterogeneous nuclear RNA contains double-stranded regions (*1*). Recently, dsRNA from nuclei of HeLa cells has been isolated (*2*) and shown to have molecular weight in excess of ~25,000. It is postulated that dsRNA may interact with an initiation factor thought to be necessary for messenger RNA (mRNA) translation (*3*); a helical region greater than 20 base pairs seems to be involved in this recognition. The amount of dsRNA in ascites tumor cells appears to be under control of a specific nuclease (*4*), and thus the extent and the rate of translation could be regulated by this mechanism. Such evidence supports the view that dsRNA may have a regulatory role in protein synthesis within mammalian cells.

Interferon Induction by dsRNA

Many specialized cellular functions are altered in cells exposed to dsRNA. One of the most characteristic functions triggered by dsRNA is the production of interferon. Various dsRNA's of both biological and synthetic origin have been shown to stimulate interferon production:

Dr Carter is chairman of the Department of Medical Viral Oncology, Roswell Park Memorial Institute, and is a professor and chairman of the Graduate Faculty in Microbiology, State University of New York at Buffalo, Roswell Park Division, Buffalo 14203. Dr. De Clercq is a member of the faculty of the Katholieke Universiteit te Leuven, Rega Institute, Minderbroedersstraat 10, B-3000, Leuven, Belgium

Ozone Verdict: On Faith or Fact?

'Something must be wrong . . . my readings indicate that they've decided to destroy their ozone shield with deodorant sprays . . .'

When, if ever, is there enough data to confirm an unpopular scientific theory? Fluorocarbons stand accused; when can an indictment be handed down?

BY JANET H. WEINBERG

Some have called it a scientific controversy: Are fluorocarbon aerosol propellants and refrigerants destroying the ozone layer or are they not? According to one highly respected atmospheric researcher, there is no scientific controversy.

University of California at Berkeley chemist Harold S. Johnston, the earliest theorist of ozone destruction stemming from man's activities, believes the controversy is really a philosophical one: When, if ever, is there enough data to confirm an unpopular scientific theory, one that could put a halt to a major industry and change the habits of millions of consumers? Fluorocarbons stand accused. But how much does the scientific community need to know before an indictment can be handed down?

Many prominent researchers vote for indictment now. Many others, including industry scientists, want to see the results of several more years of study before drawing any conclusions. Herein, Johnston says, lies the controversy.

Aerosol propellants and refrigerants are no small target for an accusing scientific theory. Almost every home has refrigeration and air conditioning equipment, and just about every consumer product that is sprayable is aerosol-packaged. A million Americans work in fluorocarbon-related industries, DuPont's research director, Ray McCarthy, estimates, and the annual contribution to the gross national product from the production and sales of these products is nearly $8 billion. But, many are saying now, whether fluorocarbons are big business or not, if the theories of ozone depletion are correct, the irony would be too great to continue—the irony of endangering human health and world climates through the use of a convenience packaging system or the current refrigeration technology.

At a recent all-day symposium on the fluorocarbon-ozone problem at the American Chemical Society meeting in Philadelphia, the main researchers met to compare evidence and postulates. Several who now stand ready to indict the chemicals on the basis of current evidence laid out their reasons for believing the ozone destruction model to be true. Two in particular were Johnston and F. Sherwood Rowland.

Although the propellant problem has only recently come to light with a report last June in NATURE by Rowland and Mario J. Molina, there is a large body of data "directly applicable to the problem," Johnston says. From 1971 to 1974, the Department of Transportation's Climatic Impact Assessment Program directed $50 million worth of research on atmospheric chemistry and the possible perturbations of the ozone by supersonic jets. In the light of this information, the caveat that the new model is "just a theory" should

$$\text{Freon} \xrightarrow{uv} Cl \quad (1)$$
$$Cl + O_3 \rightarrow ClO + O_2 \quad (2)$$
$$ClO + O \rightarrow Cl + O_2 \quad (3)$$

be considered carefully, Johnston says.

There are "exact parallels" between what happens when nitrogen oxides from natural sources and jet engine exhausts destroy ozone and what happens when chlorine radicals are released from propellants. "We have to 'change the labels' in our equations," Johnston says, "but we don't have to redo all of the basic work." The chlorine model, he says, is "virtually proven by analogy."

Rowland, who has already called for a ban of fluorocarbons 11 and 12, stresses several points. First, laboratory tests and preliminary direct measurements have so far confirmed the chlorine model. "Industry has had a year already to come up with a major error in the model and has been unable to do this," he says. He emphasizes that because of its long stratospheric lifetime, virtually all of the fluorocarbons 11 and 12 ever released is still hanging in the stratosphere or floating slowly toward it. And, unfortunately, all of those fluorocarbons eventually are released, even those contained within closed systems; within two months by aerosol cans, two years by car air conditioners and 15 years by home refrigerators.

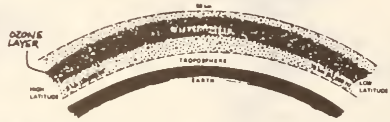
Rowland calculates that 800,000 tons of fluorocarbons are being released each year, and from that, 500,000 tons of active chlorine molecules are freed. If his ozone-destruction model and reaction rates are correct, this is about 25 times more chlorine atoms than would be allowed if an upper limit of 0.5 percent ozone depletion were established. (The Department of Transportation CIAP study mentions 0.5 percent ozone depletion as a possible acceptable limit.) Many have suggested that the search for problems with the model continue for three to five more years. That much time might be necessary to determine a precise limit to set for chlorine released in the stratosphere, Rowland says, but not for proving the model correct. "What is the likelihood that the model is off by a factor of 25, so that the current 500,000 tons will be permissible?" he asks. "I think that possibility is negligible, and that we ought to put an immediate ban on fluorocarbons 11 and 12."

The lack of serious challenges to the Rowland-Molina model, combined with strong press and public interest, has given momentum to the anti-propellant movement. Two or three aerosol valve manufacturers have closed plants or cut shifts because of flagging orders, including the Yonkers, N.Y., plant of spray valve inventor Robert Abplanalp. DuPont spokesmen declined to cite sales figures, but one industry observer sees a downswing and attributes it to consumer concern and the beginning of a shift by producers to other

Ozone destruction: A blue-sky problem

Miles above the earth, where the air is thin and sharp and silent, there is a layer of ozone (O_3), a bluish gas that protects the earth from the ravages of too much sunlight. It is formed when sunlight strikes oxygen (O_2), and it filters out harmful ultraviolet light having wavelengths shorter than about 295 billionths of a meter. The ozone layer is dynamic and changing. The amount that hangs in the stratosphere (12 to 50 kilometers above the earth) varies with the time of day, the season and the latitude. There is more ozone during the day, for example, than at night; more over northern latitudes, less over southern. (This last fact has been correlated with the larger numbers of skin cancer cases in southern latitudes.) Scientists know that the formation and destruction of ozone are part of a natural, dynamic balance. And this balance, they are discovering, is easily disturbed.

After its formation, the natural destruction is catalyzed by nitrogen oxide, one of many compounds that floats in the stratosphere. When it was announced several years ago that large fleets of supersonic transport planes were being planned, a University of California at Berkeley professor, Harold Johnston, theorized that nitrogen oxide exhausts from the jets could interfere with the natural balance of ozone formation and depletion and cause a net deficit. This, he reasoned, would allow more solar radiation to penetrate to the earth's surface, and would ultimately lead to more cases of skin cancer. Skin cancer has been correlated to exposure to light of the wavelengths that are absorbed by ozone. Several years of study have confirmed the Johnston hypothesis and both the Department of Transportation and the National Academy of Sciences have warned in recent reports that jet engines will have to be redesigned or their flight limited (SN: 4/5/75, p. 220).



Last year, University of California at Irvine chemists F. Sherwood Rowland and Mario Molina were pondering the environmental fate of fluorocarbons, better known as the inert propellants in aerosol cans and refrigerants. Direct sampling by atmospheric chemists had earlier revealed growing levels of the two most prevalent compounds, fluorocarbon 11 ($CFCl_3$) and 12 (CF_2Cl_2). These compounds are so inert to the attack of reactive species in the lower atmosphere, such as OH hydroxyl radical, that they must be floating to the stratosphere unchanged, Rowland and Molina reasoned. There, exposed to strong sunlight, they would be photodissociated, releasing chlorine atoms. And these, the team hypothesized, could act as catalysts to the destruction of ozone just as would the nitrogen oxides from SST exhausts. Chlorine would be an even stronger catalyst, though, and each chlorine atom would destroy thousands of ozone molecules. And to make matters worse, the effects of a fluorocarbon buildup would be delayed and long lasting due to the inertness of the compounds and their slow movement upward. The maximum effects of today's release, therefore, will not be felt for perhaps 10 years, and then the effects will continue for a century.

The current best estimate, based on computer models, is that if fluorocarbon use continues to grow as it has in recent years and there is no halt to production, the ozone layer will have been depleted by 13 to 20 percent by the year 2000. This depletion would cause thousands of new cases of skin cancer, perhaps a 20 to 40 percent increase in the incidence of new cases, would damage plants and phytoplankton and might possibly affect the weather adversely.

There is an urgency about the study of this problem; the longer scientists study before action is taken, the stronger will be the damaging effects of increased UV light and the longer will the effects be felt if the model is true. Many would like to wait until ozone depletion can be measured and definitely linked to fluorocarbons before action is taken. But now, the natural fluctuations in total ozone in the stratosphere are greater than the estimated 1 percent reduction from fluorocarbons, making direct ozone depletion hard to measure. And waiting a decade for a measurable increase to be manifest could increase the biological and environmental damage unnecesarily. So scientists are searching hard for chemical evidence in the stratosphere that will confirm or refute the Rowland-Molina model.

—Janet H. Weinberg

packaging alternatives Those alternatives could be roll-on containers, spray pumps or possibly other fluorocarbons, Rowland says. Fluorocarbon 22, for example, is already used in refrigerators by itself or in combination with other fluorocarbons. It degrades faster, according to the model, and could be used in refrigerators and be less of an environmental threat. "I don't offer fluorocarbon 22 as a specific suggestion or the only alternative," Rowland says, "but just to point out that there might be fluorocarbon alternatives." Industry spokesmen during legislative hearings tend to dramatize the impact of a fluorocarbon ban, Rowland says, by suggesting it would necessitate a throwback to sulfur dioxide and ammonia refrigeration. He contends this does not have to be the case.

Although industry scientists will concede privately that major efforts are under way to design new packaging alternatives—aerosols included—they remain, on the surface, unconvinced of Rowland's model. DuPont's McCarthy points to recent downward revisions in the computer model predictions of ozone depletion made by Harvard atmospheric scientists Michael McElroy and Steven Wofsy as evidence that the propellant scare may be hasty and the threat small. McCarthy also points to measurements of chlorine in the stratosphere that suggest sources other than fluorocarbons. Carbon tetrachloride (CCl_4) and methylchloride (CH_3Cl) are probably reaching the stratosphere, too, and adding more free chlorine atoms. In the case of methylchloride, which forms during the evaporation of sea water, these chlorine molecules might be a part of the dynamic natural balance of ozone creation and depletion, as are nitrogen oxides, McCarthy says If chlorine is a part of the natural ozone cycle, he says, then perhaps the addition of more through fluorocarbons would not represent a major problem (Rowland points out the addition of small amounts of nitrogen oxides against a large natural background of nitrogen oxides has already proven damaging, and he thus disagrees with McCarthy's analysis)

All of this is not to say that industry scientists are unconcerned about the problem. Industry, Government and academic scientists alike are calling for more data, and the Manufacturing Chemists Association is footing a good part of the bill—$3 million to $5 million over the next few years Atmospheric researchers in several laboratories are preparing to measure the levels of critical chemicals in the stratosphere, including the ClO radical, chlorine and the OH (hydroxyl) radical. These chemicals would, theoretically, take part in the rate-limiting step of the chlorine reaction, and measurement of them would help confirm or refute the model

Measurements of free chlorine in the stratosphere at altitudes of 30 to 50 kilometers will be taken this year from outside

Rowland: Calling for an immediate ban.

McCarthy: Up front and unconvinced.

the atmosphere by NASA's OAO-3 Copernicus satellite. A high-flying balloon to be launched from White Sands, N.M., this fall will measure stratospheric compounds. Several researchers, many of them funded by the Manufacturing Chemists Association, will use stationary devices to measure chemicals. Among them, Douglas Davis of the University of Maryland will use tuned laser fluorescence to measure the ClO radical. Donald H Stedman of the University of Michigan will do the same using chlorine fluorescence Allan Lazrus of the National Center for Atmospheric Research will continue to measure HCl. His preliminary measurements have been consistent with the Rowland-Molina model. Researchers in dozens of other laboratories are beginning to make direct atmospheric measurements. They are also studying simulated reactions in the laboratory and are working on mathematical models to predict reaction and ozone-depletion rates.

It is obvious from all of this that the field is in a state of flux and that data are being produced, revised and retuned continually During the past eight or nine months, scientists have devoted six full days to the propellant-ozone question at sessions such as ACS Philadelphia symposium As an indication of the ferment, even during the presentation and discussion of scientific papers in Philadelphia, small groups of scientists huddled together in the corners of the meeting room, whispering and scratching equations down on the backs of envelopes.

Two groups, one sponsored by the Government and the other by the National Academy of Sciences, are meeting now, charged with collecting and assessing the information as it develops and determining the environmental and legal ramifications of the fluorocarbon problem

So, for the present, most scientists involved in the propellant-ozone question are content to hasten back to the lab benches and amass data. Six months or a year from now, however, that might not be the case. Rowland thinks rapid and accurate measurement of the critical chemicals is possible, and that confirmation of the model could be reached experimentally within about six months. But McCarthy and other industry scientists are talking about three to six years for proper proof of the theory. "I hope," McCarthy said in Philadelphia, "that the measurements now planned and under way will prove effective in *unequivocally* providing information on the reaction of chlorine in the stratosphere. If not, we will seek other methods which will give us that unequivocal proof." Unequivocal is a subjective term, Johnston responded. Many are already convinced. "How many decimal places must we go before the model is proven to industry satisfaction?"

Ralph Cicerone of the University of Michigan, another early contributor to the ozone-destruction theory, thinks that scientists and public policymakers have little time or room for error on this issue. "Decision makers do not have much room to hedge their bets." Maybe they have the luxury with SST's, he says, of building them, flying them and waiting to measure ozone depletion as a result The ozone layer would return to normalcy after three years or so. "But whatever the effects of fluorocarbons will be, the full impact will not be felt for a decade after release and it will persist for many decades."

"Complete scientific proof to everyone's satisfaction will take years, so we are faced with a benefit-risk analysis. I have come to the reluctant conclusion that the risks are greater than the benefits, and the evidence is already strong" □

FORTUNE

August 1975

What We Know —and Don't Know— About the Ozone Shield

by Tom Alexander

What We Know —and Don't Know— About the Ozone Shield

Some human conveniences, notably aerosol sprays, may be weakening our stratospheric barrier against harmful ultraviolet rays, but so far the evidence does not justify panicky measures.

by Tom Alexander

In the array of environmental concerns that have been multiplying so rapidly, the ozone shield is hard to beat for sheer alarming bizarreness.

A little-known trace of rare gas floating far up in the already vanishing blue turns out to be absolutely essential in protecting man and his fellow creatures from the hostile radiation of our beneficent old sun. Then along come scientists with a growing list of human activities that they believe are capable of thinning that delicate ozone film and thereby exposing mankind to an array of afflictions that may include cancer, climatic change, and perhaps even famine.

The best studied of the potential threats to the ozone layer are jet aircraft, nuclear bombs, aerosol-spray cans, and refrigeration, but researchers are still bringing forth other possible villains. These include fertilizers, chemicals used to purify water and manufacture paper, and even the natural processes of agriculture itself.

Federal and state governments are deep in the tangled question of whether to outlaw many products of the huge refrigeration, air-conditioning, and aerosol-packaging industries. Oregon has banned the sale of the suspected spray cans after February, 1977, and some other states seem likely to take similar action. Manufacturers are trying to divine the outcome of all these regulatory moves and to revise their product lines accordingly. And both industry and government have started costly research campaigns to clarify the murky, neglected state of the science of the upper air.

Fortunately, in an era that seems to equate precipitate action with virtue, science, government, and industry on the whole have handled the ozone issue with a refreshing maturity and tentativeness. Even so, it now appears that some of the early accounts of the problem—the ones that naturally captured the most attention—were unnecessarily alarming. Some scientists were reported as prophesying "the end of the world," or "doomsday in twenty-five years."

A crisis in the armpits?

As even the more sober statements were simplified for public consumption, the impression got about that the ozone layer was a fragile, nonrenewable resource rapidly and permanently being sprayed away with each casual *pfft* of an underarm deodorant and each exhaust plume from a high-altitude jet. The problem's complex and exotic nature, conjoined with the awful word *cancer*, tended to induce a sky-is-falling attitude and a panicky instinct for action. The Minneapolis *Star* not long ago summed up the freakish aspect of the whole problem in an inspired headline: "Can Dry Armpits Mean World Crisis?"

The ozone problem seems to be real, but its actual threat to human life now or even in the distant future appears to rank very low on the scale of hazards to which we are all routinely exposed—for instance, about one-tenth the risk of being struck by lightning. If the sky is falling, in other words, it is falling very, very slowly.

Stratospheric ozone should be viewed not as a nonrenewable quantity, but as the product of a fluctuating balance between natural forces of creation and destruction. The molecule itself is a poisonous, highly reactive arrangement of three oxygen atoms (O_3), in contrast to the two-atom molecules (O_2) that make up the bulk of the oxygen in our atmosphere. The major ozone supply is distributed throughout a thirty-mile-thick region that begins about ten miles up, at the lower edge of the stratosphere. There ultraviolet light from the sun splits ordinary oxygen into single atoms that can then recombine into the three-atom configuration.

A big role for laughing gas

In the early Seventies, Harold Johnston, a chemist at the University of California at Berkeley, and Paul Crutzen, a meteorologist at the National Center for Atmospheric Research, offered a theory of how processes on earth affect these photochemical reactions in the stratosphere. Crutzen discovered that a lot of ozone was being destroyed indirectly by bacteria in the ground. As symbiotic residents in the roots of certain plants,

Research associate: Lorraine Carson

The vital ozone membrane (bright blue) most concentrated at an altitude of about fifteen miles, absorbs most of the sun's invisible but harmful ultraviolet rays (bright streaks) and converts them into heat. This process causes air temperatures in the stratosphere to increase with altitude. The temperature inversion puts a lid on convection and cloud formation, allowing ozone-destroying pollutants to accumulate in the stratosphere

George Kelvin


Mesosphere
Stratosphere
Tropopause
Troposphere
Air circulation
Earth at equator
—50 −137°F.
—45 −83°F.
—40 −29°F.
—35 +7°F.
—30 +25°F.
—25 −2°F.
—20 −29°F.
—15 −65°F.
—10 −101°F.
—5 −5°F.
—0 70°F.
Altitude (miles)

notably clover, peas, beans, and other legumes, these bacteria extract nitrogen from the air and incorporate it chemically into the structure of their hosts. When these plants decay, part of their nitrogen gets released to the atmosphere as nitrous oxide (N_2O), sometimes known as laughing gas. Relatively inert and insoluble, nitrous oxide accumulates in the lower atmosphere. Convective air movements carry it aloft to the bottom of the stable stratosphere. There it slowly diffuses up into the stratosphere itself.

As a nitrous oxide molecule rises through the ozone layer, it enters the energetic realm of ultraviolet photochemistry where, so to speak, almost nothing is inert anymore and almost everything reacts with everything else. The ultraviolet converts it into nitric oxide (NO), which goes on to engage in a chain of reactions involving ozone.

The bathtub analogy

The net effect is that some ozone molecules are converted into ordinary oxygen while the nitric oxide molecules are freed to continue their attack upon other ozone molecules. Each nitric oxide molecule thus acts as a catalyst, destroying thousands of ozone molecules before it wanders back into the lower atmosphere and combines with water vapor.

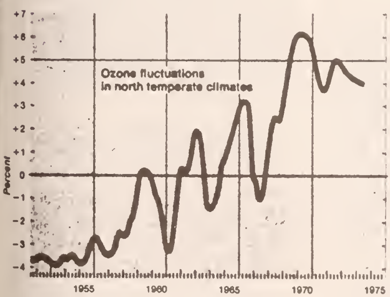
Atmospheric scientist Michael McElroy, of Harvard, compares ozone's equilibrium between the processes of creation and destruction to the water level in a bathtub with an open drain and an open water tap. Obviously, anything that serves to increase the size of the drain would lower the water level. Similarly, any additional supply of nitrogen oxides —or any other substance capable of destroying ozone—would increase the rate of ozone depletion and to some extent decrease the supply.

A yen for crank causes

The whole matter seemed scarcely more than a matter of academic interest until it came to the attention of the late James E. McDonald, a respected American atmospheric physicist but a man with a yen for seemingly crank causes. Among other things, McDonald had an interest in unidentified flying objects, and he once suggested that there might be some relation between power blackouts and UFO's. Another of McDonald's concerns was the proposed supersonic transport plane. Observing that SST engines would emit water vapor, another chemical enemy of ozone, he began campaigning to have the plane scuttled.

McDonald pointed out that ozone filters out most of a middle-frequency band of ultraviolet light known as "ultraviolet B." Since ultraviolet is damaging to organic molecules, he speculated that it was probably harmful to life. It might, for example, disrupt the complex DNA molecules in the skin, with skin cancer as one likely result.

Today, the cause-and-effect relationship between ultraviolet and some forms of skin cancer seems well established.



A puzzling increase in world ozone, despite the proliferation of its presumed chemical enemies, is especially evident in the north temperate zone, which is where most of those chemicals are released. This graph, from data compiled by government scientists James Angell and Julius Korshover, shows an ozone increase of about 8 percent in twenty-three years. The peaks at intervals of about three years may be related to periodic fluctuations in global wind patterns. The sunspot cycle may have caused the 1970 high. If so, the subsequent downtrend should soon flatten out.

Among white persons in the U.S. the incidence of skin cancer is around 150 cases per 100,000 population per year. Most of it occurs on exposed areas, such as the hands or face. The incidence roughly doubles with each ten-degree decrease in latitude. Recent measurements have also established that the thickness of the ozone layer *diminishes* with latitude (i.e., it is thinnest over the equator). The implication, of course, is that the additional ultraviolet exposure in tropical latitudes causes additional cases of cancer. A 1 percent decrease in overhead ozone appears to produce roughly a 2 percent increase in skin-cancer cases.

The effects of ultraviolet upon plants and climate remain much more problematical. Slight declines in plant growth have been detected in experiments now under way at the University of Florida, but these experiments are being carried out with powerful lamps that increase the ultraviolet dose by 100 to 400 percent, an amount that most ozone theorists now consider unrealistic. As for climatic effects, most speculation—and it is simply that—focuses on the possibility that deeper ultraviolet penetration could lower the stratosphere slightly, and somehow change the global circulation of the winds.

Identifying the culprit

When McDonald brought the matter up, the links between ultraviolet and cancer were less widely known. And perhaps because of his reputation for unconventional beliefs, he was unable to convince many colleagues or policymakers of the seriousness of the threat. It was only after several other researchers, particularly Crutzen and Johnston, got interested in the matter that the SST-ozone issue acquired scientific respectability. They pointed out that the real damage would come not so much from water vapor as from the nitric oxides emitted by the engines. They calculated that the SST's might affect the ozone layer as much as vegetable decay.

The ozone-danger arguments, among others, figured in the successful effort to persuade Congress in 1971 not to subsidize the construction of an American

Using this airborne laser, mounted in a Rockwell International Sabreliner jet, University of Maryland chemist Douglas Davis will try to measure the amounts of "OH radical" at various altitudes in the sky. This unstable and highly reactive oxygen-hydrogen molecule is important in the ozone controversy because in the lower atmosphere it destroys certain fluorocarbons and renders them harmless, while in the stratosphere it can enhance their ozone-depleting effect.

SST. But the scientific concern spurred the Department of Transportation to start a belated $20-million research program known as the "Climatic Impact Assessment Program" (CIAP). The CIAP report, issued last December, substantiated the hypothesis that large fleets of SST's would weaken the ozone shield. But the study also concluded that improved engines and fuels would greatly diminish the damage.

A chemical detective in the sky

Once CIAP focused scientific attention on interference with the ozone layer, it was only a question of time before other threats were thought of. In the Fifties, a British chemist named James Lovelock—a man who prefers the unusual role of a free-lance scientist to permanent ties to any institution—invented a device called the "electron-capture gas chromatograph." One of the most exquisitely sensitive analytical tools of chemistry, Lovelock's instrument can detect atmospheric gases in amounts as minuscule as a few parts per trillion. In 1970 he discovered that traces of two related, man-made compounds, trichlorofluoromethane and dichlorofluoromethane, were omnipresent in the skies. These compounds are more widely known as fluorocarbon 11 and fluorocarbon 12, and often simply as Freon 11 and Freon 12, the trade names used by Du Pont, now the world's largest producer of fluorocarbons.

The compounds were originally formulated by the Frigidaire Division of General Motors, which introduced them in the 1930's as inert, nontoxic, nonflammable substitutes for such dangerous refrigerants as sulfur dioxide, ammonia, and methyl chloride. Since then, a chemically varied assortment of fluorocarbon gases have come to be manufactured by some forty companies throughout the world.

Today, however, refrigeration and air conditioning utilize only 28 percent of the output. About 22 percent goes to such industrial uses as solvents, fire extinguishers, and plastic-foam "blowing agents." But the greatest use by far—about 50 percent—is as the propellant in those ubiquitous aerosol-spray cans.

Because they are expensive compared with other propellants, including propane or such compressed gases as carbon dioxide, fluorocarbons are used in only about half of the three billion aerosol cans sold every year in the U.S. They are utilized mostly with "personal" products—hair sprays, deodorants, and medicinals—where inertness and nonflammability are important. With shaving cream and other products that contain so much water that there's no flammability problem, propane is usually the propellant. Propane is also used with products such as paint, which are already so flammable that the propellant doesn't make much difference.

The sink in the stratosphere

Lovelock's chromatograph strikingly confirmed the inertness of fluorocarbons 11 and 12. He found that the two compounds are present in the world's atmosphere in amounts averaging about 230 parts per trillion (equivalent to about one drop in five full railroad tank cars). It is also possible to calculate from his measurements and others that most of the fluorocarbons ever produced are still in existence, either locked up in refrigerators and aerosol cans or floating in the atmosphere.

Lovelock's measurements piqued the

curiosity of F. Sherry Rowland, a chemist from the University of California at Irvine. He suspected that the fluorocarbons might not be permanently indestructible, as they seemed to appear. In mid-1974 he and research associate Mario Molina published a paper in the British scientific journal *Nature* theorizing that there probably was at least one "sink"—or site of destruction—for fluorocarbon molecules: the ultraviolet battleground of the stratosphere.

Drawing a direct analogy with oxides of nitrogen, Rowland and Molina argued that the fluorocarbons are making their way upwards, rapidly at first through the lower atmosphere, then much more slowly through the stable stratosphere. Finally, after ten or fifteen years, they would rise to the point where ultraviolet radiation would split them apart like any other molecular gas, releasing chlorine into the ozone layer.

Their analysis fitted in with other recent laboratory findings and raised new fears about ozone depletion. A British chemist, Michael Clyne, had reported that chlorine was apparently six times more efficient than nitric oxide as a catalyst of ozone extinction.

Researchers from Harvard and the University of Michigan had been looking for possible effects upon ozone of the chlorine-containing exhausts from the proposed space-shuttle rocket, but had found little cause for alarm. After all, neither the shuttle nor any other vehicle seemed likely to carry enough chlorine aloft to matter all that much. But Rowland and Molina suggested that such a vehicle did exist in the form of fluorocarbons 11 and 12, which were then being produced at a rate approaching a million tons a year.*

An unclear and future danger

Partly because of apparently incorrect assumptions in some of the early projections and partly because of overdramatic press accounts, a considerable confusion has arisen about the fluorocarbon threat. Even Rowland and Molina perceived the time of serious danger as fifteen years or more away, after exponential increases in production and the steady accumulation of the gases had brought the atmospheric loads to levels many times higher than they are now.

Immediately following the *Nature* article, several other theorists developed mathematical models, a few of which predicted eventual ozone depletion as high as 50 percent. These forecasts seemed so frightening as to require immediate and drastic action.

In more recent months, new data and refinements in the models have persuaded most scientists involved that the danger is probably much smaller and much further off than had been supposed. Some of the older models assumed growth rates for fluorocarbon production as high as 22 percent a year. But that figure has been reached only by fluorocarbon 11 and for only one year, 1972, apparently because there was an inventory buildup of aerosol products. Actually, total fluorocarbon output increased by an average of about 8 percent a year through the Sixties and early Seventies. But it rose only 3 percent in 1974, and during the first four months of this year, it fell 19 percent below the level of the same period a year earlier.

The recession undoubtedly accounts for part of the decline, but it is also clear that both consumers and manufacturers are responding to the adverse publicity. Such manufacturers as Johnson's Wax and Gillette are putting their advertising emphasis on fluorocarbonless aerosols, roll-on applicators, and finger-pumped sprays. Early this year, after a 40 percent drop in sales, Precision Valve Corp.—a company, founded by former President Nixon's crony, Robert Abplanalp, that dominates the spray-valve industry—closed a plant in Yonkers, New York. As matters stand now, it is a fair bet that few, if any, companies will risk introducing a major new product propelled by fluorocarbons.

One essential factor missing in some of the earlier ozone-depletion models was the property of "feedback," the comforting tendency of the ozone layer to heal itself. It is fairly obvious, though, that if ozone at high altitude is destroyed, ultraviolet light will penetrate a little deeper into the atmosphere and create more ozone at a lower altitude.

New findings, new doubts

With new research funds from government and industry, experimenters have checked other critical assumptions in the models and found them overly pessimistic. Douglas Davis, a chemist at the University of Maryland, has measured the reaction between chlorine and ozone at stratospheric temperatures and found that it occurs more slowly than earlier investigators assumed.

On the other hand, Davis has also found that chlorine reacts more quickly than expected with another stratospheric component, methane. The product of this reaction is hydrogen chloride, some of which dissolves in water to form hydrochloric acid and then, heavily diluted, falls to earth with the rain. When Davis's new findings are introduced into the various ozone-depletion models, the effect is to reduce by one-half to two-thirds the predicted rate at which ozone is destroyed and therefore the amount of depletion that will occur before a new equilibrium point is reached. Scientists caution, however, that new data are still coming in, and that they might push the destruction rate up again.

A revised model prepared by Paul Crutzen from the newest data predicts that if fluorocarbon-propellant production ceases in 1978, the maximum effect will be an ozone depletion of 1.7 percent by 1988. This compares with depletion of 1.2 percent if a worldwide ban were to go into effect this year. Assuming that fluorocarbon production continues forever at the 1974 level, another model by Michael McElroy and Steven Wofsy at Harvard predicts that equilibrium wouldn't be reached until some time in the twenty-second century, when the ozone would be diminished by 7 percent.

A decrease of that magnitude cannot be dismissed as insignificant, but it seems to fall short of global calamity. For one thing, the ozone layer varies

**A few years ago, Rowland figured in quite a different environmental controversy and on the other side of the fence: he was one of a team of California scientists who punctured the scare about mercury contamination of tuna and swordfish by analyzing museum specimens and proving that the mercury content of the fish had not increased measurably in ninety-eight years.*

naturally by amounts far greater than 7 percent. Not only does it vary geographically—diminishing about 30 percent from Minnesota to Texas—but over any one spot it fluctuates about 25 percent from day to day, and another 25 percent seasonally. Increases of about 5 percent appear at eleven-year intervals, suggesting that the ozone layer may somehow be affected by sunspots.

The overall trend during the past twenty years has been an increase of about 8 percent over the Northern Hemisphere and a slight decrease in the Southern. This, of course, has occurred just when all those suspected man-made ozone destroyers were proliferating. The long-term increase reached a high point in 1970 and ozone has since declined nearly 2 percent.

"Everybody jumped the gun"

Ozone's unpredictable behavior indicates that something is obviously incomplete—perhaps even wrong—about man's understanding of stratospheric chemistry. For example, are there unidentified reactions that serve to remove chlorine or to restore ozone? One of those who suspects this might be so is Jim Lovelock, the man who more or less started the fluorocarbon flap. "It's a funny thing about this game," declares Lovelock. "The instant you measure something, it becomes important. Freon happened to be easy for me to find, and everybody jumped the gun."

Recently Lovelock and others have been hunting further and finding the atmosphere to be full of assorted chlorine compounds—probably both natural and man-made—in total amounts that outweigh the fluorocarbons dozens of times over. These include carbon tetrachloride, methyl chloride, and methyl chloroform, all of which, Lovelock and others believe, must be capable of unloading some of their chlorine into the upper stratosphere. One implication is that nature may have some yet unidentified mechanisms for cleansing the stratosphere of chlorine before it can do much damage.

Other researchers take a different view: maybe many of those substances that Lovelock finds *do* have human origins and maybe their effects on the ozone layer haven't yet shown up strongly. Among those following up this line of thinking are Harvard's McElroy and Wofsy, who are now carefully examining the list of chemicals used in large quantities by man, trying to identify those with ozone-damaging potential.

Can we count on nature?

Among those they have found to provide some cause for concern are the chlorine-containing substances used in water purification and papermaking; methyl bromide, which is increasingly used in agriculture as a soil fumigant; and nitrate fertilizers, which release nitrous oxide. McElroy speculates that even the legumes that man plants to feed his growing population and to improve his soil may pump enough additional nitrous oxide into the system to have significant effects. The contributions to ozone destruction from all such chemicals are likely to be cumulative.

McElroy believes that man is at the point where he may no longer be able to count on nature, and may henceforth have to control ozone-damaging agents from the oceans, the atmosphere, and living organisms. Doing so, of course, would require much more knowledge than we have now, and McElroy is among the majority of experts who contend that scientists should be allowed time to reach a better understanding of the problem before we adopt legislation, including any ban on aerosol sprays. Three to five years is most often mentioned by scientists as a reasonable time to resolve some of the more baffling questions.

If one accepts Crutzen's model, a three-year delay in barring fluorocarbons would mean about 0.5 percent additional ozone depletion. In the U.S. this might translate into around 3,000 more cases of skin cancer. The number may seem large, but the increase would be undetectable among the more than 300,000 cases that occur each year anyway.

The two commonest forms of skin cancer—those most clearly related to sunlight exposure—are fatal less than 1 percent of the time; they are usually cured by simple treatments in a doctor's office. (Another form, melanoma, is a lot more deadly but a lot less common and its relationship to ultraviolet exposure is more problematical.) What all this seems to add up to is that by 1988 the fluorocarbons might cause the death of a few dozen people a year.

What, then, should be done about fluorocarbons? A federal task force recently recommended a ban on fluorocarbon sprays starting in 1978—provided that further investigation confirms their effect on the ozone shield. Delay is clearly in order, partly because of scientific uncertainties, partly to avoid sudden economic disruption for large numbers of people, and partly to let industry adopt substitutes. An immediate and total ban on fluorocarbon aerosols might even increase other health hazards. More babies and young children might die from ingesting common household substances such as medicines, pesticides, and cleaning agents. Tests indicate that it is much easier to swallow the contents of a bottle than those of an aerosol can and, in fact, that babies are repelled by the chilling spray.

Still, the aerosol problem is a minor one compared with the difficulties of dispensing with fluorocarbons for refrigeration. Given the heavy dependence of virtually every link of the food chain upon refrigeration, an immediate ban on their use would be a recipe for mass food spoilage, shortages, price increases, and wrenching economic dislocations.

The available remedies, all of which would take time, include the design of better-sealed cooling machines, particularly car air conditioners, which are notoriously leaky. Another possibility might be to introduce new or already developed refrigerants—such as fluorocarbons 22 and 31, which contain hydrogen atoms in their molecules. This makes them less inert and therefore less likely to reach the stratosphere. Fluorocarbon 22 is already widely used for commercial refrigeration.

Unfortunately, each refrigerant compound is carefully tailored to a specific range of temperatures, pressures, and compatible materials. Few are interchangeable without redesign of the equipment. Usually, a change would involve a loss of energy efficiency. A decade

or more might be needed for research, redesign, retooling, and replacement—all at considerable cost. And a typical household refrigerator contains only about as much fluorocarbon as two to three aerosol cans. Considering all these circumstances, the slow-growing refrigeration industry may pose too small a hazard to worry about.

Maybe there's too much ozone

In dealing with the ozone question, it appears that we are lucky: thanks to scientific alertness, we have the grace of time. For the moment, it should be enough to have served notice upon the industries involved that there is good reason for concern. If we avoid hasty legislation, nature or the marketplace may continue to solve the ozone problem without the usual havoc from clumsy government intervention.

After three to five years, the whole matter can be reexamined once more. Who knows, it might even turn out by then that there's too *much* ozone up there and that everybody will have to get busy with his aerosol cans again. END

Climatic Change: Are We on the Brink of a Pronounced Global Warming?

Abstract. *If man-made dust is unimportant as a major cause of climatic change, then a strong case can be made that the present cooling trend will, within a decade or so, give way to a pronounced warming induced by carbon dioxide. By analogy with similar events in the past, the natural climatic cooling which, since 1940, has more than compensated for the carbon dioxide effect, will soon bottom out. Once this happens, the exponential rise in the atmospheric carbon dioxide content will tend to become a significant factor and by early in the next century will have driven the mean planetary temperature beyond the limits experienced during the last 1000 years.*

The fact that the mean global temperature has been falling over the past several decades has led observers to discount the warming effect of the CO_2 produced by the burning of chemical fuels. In this report I present an argument to show that this complacency may not be warranted. It is possible that we are on the brink of a several-decades-long period of rapid warming. Briefly, the argument runs as follows. The ^{18}O record in the Greenland ice core (*1*) strongly suggests that the present cooling is one of a long series of similar natural climatic fluctuations. This cooling has, over the last three decades, more than compensated for the warming effect produced by the CO_2 released into the atmosphere as a by-product of chemical fuel combustion. By analogy with similar events in the past, the present natural cooling will, however, bottom out during the next decade or so. Once this happens, the CO_2 effect will tend to become a significant factor and by the first decade of the next century we may experience global temperatures warmer than any in the last 1000 years. The remainder of this report will be devoted to the elaboration of the assumptions used in constructing the curves shown in Fig. 1 which displays this projection.

Of the climatic effects induced by man, only that for CO_2 can be conclusively demonstrated to be globally significant. It is difficult to determine the significance of the next most important climatic effect induced by man, "dust," because of uncertainties with regard to the amount, the optical properties, and the distribution of man-made particles (*2, 3*). Man-made heat currently runs a poor third to CO_2 and dust. Its effects will, for at least a few decades, remain entirely local (*4*). In this report only the interaction of the CO_2 effect and natural climatic change is considered. As other anthropogenic effects are shown to be significant and as means to quantitatively predict their future influence on global temperatures are developed, they can be included in models such as this. Meanwhile it is important to consider the potential impact of the two causes of change for which we do have quantitative information.

A number of people have made estimates of the change in global temperature that would result if the atmospheric CO_2 content were to double. These estimates range from 0.8° to 3.6°C. Manabe and Wetherald's value (*5*) of 2.4°C, based on a model assuming fixed relative humidity and cloudiness, is the most widely used. The difference between this estimate and that of 0.8°C by Rasool and Schneider (*3*) has been largely resolved. When an improved infrared radiation scheme is introduced into the Manabe-Wetherald calculation, the result drops to 1.9°C (*6*). However, Manabe and Wetherald (*6*) have suggested, on the basis of some preliminary three-dimensional calculations, that the effect in polar regions is much larger than for the "typical" atmospheric column. This polar amplification leads to an enhancement of the global effect, bringing the value up to somewhat above 2.4°C. Although surprises may yet be in store for us when larger computers and a better knowledge of cloud physics allow the next stage of the modeling to be accomplished, the magnitude of the CO_2 effect has probably been pinned down to within a factor of 2 to 4 (*7*).

Table 1. Reconstruction and prediction of atmospheric CO_2 contents based on fuel consumption data.

Year	Chemical fuel CO_2 ($\times 10^{16}$ g)	Excess atmospheric CO_2* ($\times 10^{16}$ g)	Excess atmospheric CO_2 (%)	Excess atmospheric CO_2 (ppm)	CO_2 content of the atmosphere† (ppm)	Global temperature increase‡ (°C)
1900	3.8	1.9	0.9	2	295	0.02
1910	6.3	3.1	1.4	4	297	.04
1920	9.7	4.8	2.2	6	299	.07
1930	13.6	6.8	3.1	9	302	.09
1940	17.9	8.9	4.1	12	305	.11
1950	23.3	11.6	5.3	16	309	.15
1960	31.2	15.6	7.2	21	314§	.21
1970	44.0	22.0	10.2	29	322§	.29
1980‖	63	31	14	42	335	.42
1990‖	88	44	20	58	351	.58
2000‖	121	60	28	80	373	.80
2010‖	167	83	38	110	403	1.10

*On the assumption that 50 percent of the CO_2 produced by the burning of fuel remains in the atmosphere. †The preindustrial atmospheric partial pressure of CO_2 is assumed to be 293 ppm. ‡Assumes a 0.3°C global temperature increase for each 10 percent rise in the atmospheric CO_2 content. §Value observed on Hawaii for 1960, 314 ppm; value for 1970, 322 ppm (*8*). ‖Post-1972 growth rate taken to be 3 percent per year.

The response of the global temperature to the atmospheric CO_2 content is not linear. As the CO_2 content of the atmosphere rises, the absorption of infrared radiation will "saturate" over an ever greater portion of the band. Rasool and Schneider (*3*) point out that the temperature increases as the logarithm of the atmospheric CO_2 content. Thus, if doubling of the CO_2 content raises the temperature by 2.4°C, then a 10 percent increase in the CO_2 content will raise the temperature by 0.32°C.

With respect to the amounts of CO_2 to be expected in the atmosphere, we are in a position to make fairly accurate estimates. Measurements carried out by Keeling and his co-workers on the island of Hawaii over the past 15 years suggest that the CO_2 content of the atmosphere rose an average of 0.7 part per million (ppm) per year from 1958 to 1972 (*8*). Had all the CO_2 generated by the burning of chemical fuels remained in the atmosphere, the rate of increase in the atmospheric CO_2 content should have been about 1.5 ppm/year. Thus, about half of the CO_2 added to the atmosphere is seemingly being removed to the sea (through combination with the CO_3^{2-} ion) and to the terrestrial biosphere (through enhanced photosynthesis). Calculations based on the model of Broecker *et al.* suggest that uptake by the sea can ac-

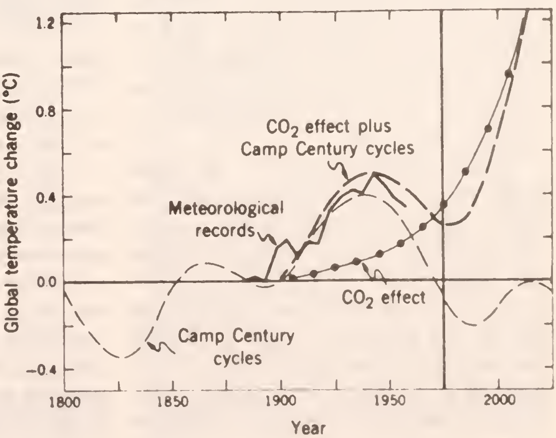


Fig. 1. Curves for the global temperature change due to chemical fuel CO_2, natural climatic cycles, and the sum of the two effects. The measured temperature anomaly for successive 5-year means from meteorological records over the last century is given for comparison.

count for the removal of 35 ± 10 percent of the CO_2 produced (*9*). Other investigators (*10*), using oceanic mixing models which neglect short-term transfer between the surface ocean and the main oceanic thermocline, conclude that considerably smaller fractions of the CO_2 have gone into the ocean. In order to match the observed rate of increase in the atmospheric CO_2 content, these authors are required to put what I consider to be an inordinately large part of the CO_2 into the terrestrial biosphere. If the ocean is currently the main sink for the "missing" CO_2, the models suggest that, if our CO_2 production continues to increase at the rate of several percent per year, the fraction of this CO_2 remaining in the atmosphere will remain nearly constant over the next several decades (*9*). If, on the other hand, a major fraction of the chemical fuel CO_2 is being removed to the terrestrial biosphere, we are not in as good a position to state how the distribution coefficient between the atmosphere and other reservoirs will change with time. On the time scale of a few decades, however, there is no reason to believe that it will change greatly.

The global temperature increase due to CO_2 in Fig. 1 is calculated on the basis of the following assumptions: (i) 50 percent of the CO_2 generated by the burning of chemical fuels has in the past and will in the near future remain in the atmosphere; (ii) the United Nations fuel consumption estimates are used to 1960 (*11*); between 1960 and 1975 a growth rate of 4.5 percent per year is used, and from 1975 on a 3 percent growth rate is predicted; (iii) for each 10 percent increase in the atmospheric CO_2 content the mean global temperature increases by 0.3°C. These calculations are summarized in Table 1.

Meteorological records of the mean global temperature are adequate only over the last century. The mean global temperature (successive 5-year means) obtained from these records by Mitchell (*12*) is given in Fig. 1. From this record alone little can be said about the causes of climatic fluctuations. It is too short and may be influenced by pollution. Obtaining comparable information from historic and natural

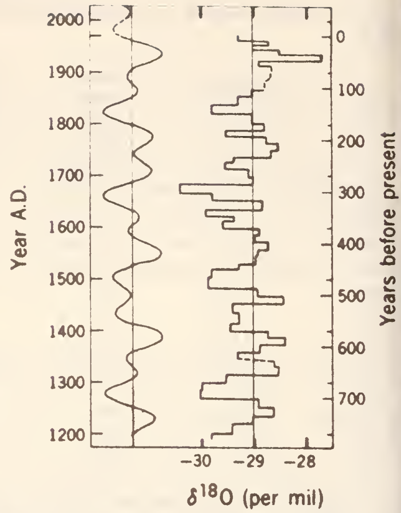


Fig. 2. Difference (per mil) between the $^{18}O/^{16}O$ ratio in decade composites of Greenland ice from the Camp Century site and mean ocean water as obtained by Dansgaard and his coworkers (*1*). A decrease of 1 per mil in the ^{18}O content corresponds to a 1.5°C drop in air temperature. The curve on the left is the simulation of the isotope curve obtained by combining sinusoidal curves with periods of 80 and 180 years.

records for previous centuries has proved very difficult. There is no simple relation between the indices used and the temperature, and regional noise tends to mask the global picture. In my estimation the only existing record which may give a picture of the natural fluctuations in global temperature over the last 1000 years is that from the ice core taken at Camp Century in northwestern Greenland. The air temperature over this site is being recorded in terms of the ratio of ^{18}O to ^{16}O in the snow which falls. Because of the polar amplification of global climatic changes [noted both in this century's meteorological records (*12*) and in models (*6*)], a strong signal emerges from the regional noise. Measurements on snow generated over a range of polar temperatures show that for each 1°C of cooling the ^{18}O content of the precipitation drops by about 0.7 per mil (*13*). The time scale is obtained by extrapolation of the accumulation rates established by counting seasonal couplets (*14*). The widely quoted results of Dansgaard and his co-

workers of measurements on the Camp Century core (*1*) are reproduced in Fig. 2. Clearly the fluctuation in global temperature documented by meteorological observations over the last century is not unique; similar changes have occurred in a more or less regular fashion throughout the last 1000 years. Dansgaard and his co-workers have shown by power spectral techniques that cycles of 80 and 180 years appear in this record. The model curve to the left of the isotopic curve (Fig. 2) is their best fit to the data based on the use of only 80- and 180-year cycles.

The amplitude of the last half "cycle" in Greenland (1900 to 1940) as recorded in the ice is about the same as that recorded by meteorological observations (both give about 1.5°C warming) (*2*, *3*). Also the ice core record is roughly in phase with the global change recorded meteorologically. Consistent with the Manabe-Wetherald model (*6*), the amplitude of the temperature change in the polar region is several times larger than the global average.

The curve of natural fluctuations drawn in Fig. 1 was obtained as follows. The pattern of the fluctuations is that obtained by Dansgaard and his co-workers (*1*), assuming that the 80- and 180-year periods dominate the natural record. The amplitude of the curve is reduced so that, when summed with the CO_2 effect, it yields a reasonable match to the global temperature curve for the last century (that is, a fourfold reduction due to polar amplification is made).

Table 2. Projections based on an analogy to individual Camp Century cycles over the last 800 years.

Warm peak No.*	Years to next cold minimum*	Projected date for next cold minimum
1	40	1980
2	25	1965
3	40	1980
4	35	1975
5	55	1995
6	30	1970
7	25	1965
8	35	1975
9	35	1975
Mean	35	1975
Simulation†	50	1990

*See Fig. 3. †See Fig. 2.

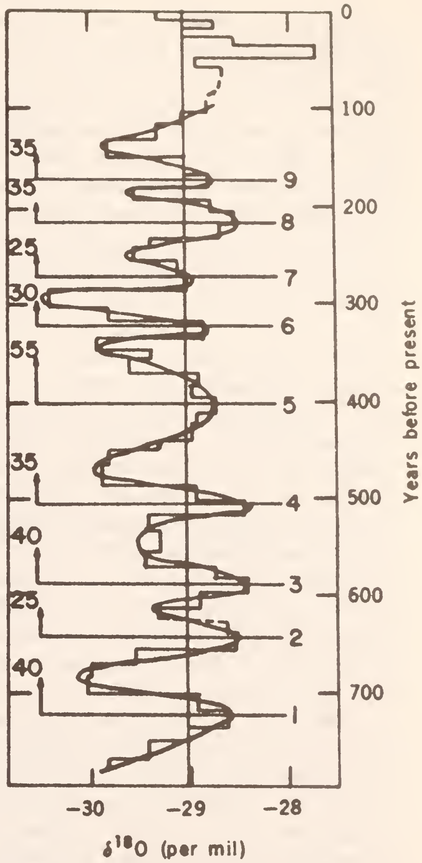


Fig. 3. Spacings between warm maxima and cold minima for the "smoothed" Camp Century ice core ^{18}O curve.

The resultant curve obtained by combining the CO_2 effect with the simulated natural curve shows dramatically what will happen if the natural cooling trend bottoms out and swings into the next warming phase according to the schedule postulated here. Global temperature would begin a dramatic rise which would continue for about four decades (that is, half the 80-year cycle). This warming would by the year 2000 bring average global temperatures beyond the range experienced during the last 1000 years. Until chemical fuel consumption is dramatically reduced, global temperatures would continue to rise. Future natural cycles would merely modulate this ever-steepening rise (40-year periods of more rapid increase followed by 40-year periods of less rapid increase).

Although the details of the argument presented here depend largely on the results of Dansgaard *et al.* (*1*), simulation of the Camp Century cycles, the sense of the argument, is not dependent on these results. As shown in Fig. 3 and Table 2, a similar conclusion with regard to the timing of the forthcoming natural minima would be reached by analogy with almost any portion of the Greenland record over the last 700 years. If anything, the simulation puts the next minimum farther into the future than would estimates based strictly on analogies with previous "cycles." Thus, whereas the exact date of the minimum shown in the extended natural climate curve (Fig. 1) is uncertain, its occurrence in the next decade is probable. The rate of warming beyond the minimum is also open to question. As the CO_2 effect will dominate, the uncertainty here lies mainly in the estimates of future chemical fuel use and in the magnitude of the warming per unit of excess atmospheric CO_2. The major point of the argument is that over the past 30 years the warming trend due to CO_2 has been more than countered by a natural cooling. This compensation cannot long continue both because of the rapid growth of the CO_2 effect and because the natural cooling will almost certainly soon bottom out. We may be in for a climatic surprise. The onset of the era of CO_2-induced warming may be much more dramatic than in the absence of natural climatic variations.

The agricultural consequences of this ensuing warming are not obvious (neither are the implications to global sea level). A knowledge of the mean global temperature tells us little about the rainfall patterns in the chief grain-producing regions. There is little doubt, however, that this gradual warming will lead to changes in the pattern of global precipitation. Our efforts to understand and eventually to predict these changes must be redoubled.

WALLACE S. BROECKER
Lamont-Doherty Geological Observatory and *Department of Geological Sciences, Columbia University, Palisades, New York 10964*

References and Notes

1. W. Dansgaard, S. J. Johnson, H. B. Clausen, C. C. Langway, Jr., in *Late Cenozoic Glacial Ages*, K. K. Turekian, Ed. (Yale Univ. Press, New Haven, Conn., 1971), p. 37; W. Dansgaard, S. J. Johnsen, H. B. Clausen, N. Gundestrup, *Medd. Grønland* **197** (No. 2), 1 (1973).
2. S. H. Schneider and W. W. Kellogg, in *Chemistry of the Lower Atmosphere*, S. I. Rasool, Ed. (Plenum, New York, 1973), p. 203; G. Yamamoto and M. Tanaka, *J. Atmos. Sci.* **29**, 1405 (1972); R. A. Bryson, *Weatherwise* **21**, 56 (1968); *Climatic Modification by Air Pollution, II: The Sahelian Effect* (Institute for Environmental Studies, University of Wisconsin, Madison, 1973); *Science* **184**, 753 (1974); J. M. Mitchell, Jr., in *Global Effects of Environmental Pollution*, S. F. Singer, Ed. (Reidel, Dordrecht, Netherlands, and Springer-Verlag, New York, 1968); in *Man's Impact on the Climate*, W. H. Matthews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971), pp. 133 and 167; W. W. Kellogg and S. H. Schneider, *Science* **186**, 1163 (1974).
3. S. I. Rasool and S. H. Schneider, *Science* **173**, 138 (1971).
4. S. H. Schneider and R. D. Dennett, *Ambio* **4**, 65 (1975).
5. S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **24** 786 (1967).
6. S. Manabe, in *Man's Impact on the Climate*, W. H. Matthews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971), p. 238; S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* 32, 3 (1975).
7. S. H. Schneider, *J. Atmos. Sci.*, in press.
8. C. A. Ekdahl, Jr., and C. D. Keeling, in *Carbon and the Biosphere*, G. M. Woodwell and E. V. Pecan, Eds. (Technical Information Center, Office of Information Services, U.S. Atomic Energy Commission, Washington, D.C., 1973), p. 51.
9. W. S. Broecker, Y.-H. Li, T.-H. Peng, in *Impingement of Man on the Oceans*, D. W. Hood, Ed. (Wiley, New York, 1971), p. 287.
10. B. Bolin and E. Eriksson, in *The Atmosphere and the Sea in Motion, Rossby Memorial Volume*, B. Bolin, Ed. (Rockefeller Institute Press, New York, 1959), p. 130; L. Machta, in *The Changing Chemistry of the Oceans*, Proceedings of the 20th Nobel Symposium, D. Dryssen and D. Jagner, Eds. (Wiley, New York, 1972), p. 121; C. D. Keeling, in *Chemistry of the Lower Atmosphere*, S. I. Rasool, Ed. (Plenum, New York, 1973), chap. 6; L. Machta, in *Carbon and the Biosphere*, G. M. Woodwell and E. V. Pecan, Eds. (Technical Information Center, Office of Information Service, U.S. Atomic Energy Commission, Washington, D.C., 1973), p. 21; R. Bacastow and C. D. Keeling, *ibid.*, p. 86.
11. United Nations, *World Energy Supplies Statistical Papers*, Series J (United Nations, New York, 1950 1959).
12. J. M. Mitchell, *Arid Zone Monograph* **20** (UNESCO, Paris, 1963), pp. 161 181.
13. W. Dansgaard, *Tellus* **16**, 436 (1964); L. Merlivat and C. Lorius, *Recherche (Paris)* **4** (No. 34), 457 (1973).
14. S. J. Johnsen, W. Dansgaard, H. B. Clausen, C. C. Langway, Jr., *Nature (Lond.)* **235**, 429 (1972).
15. Conversations with Steve Schneider of the National Center for Atmospheric Research were very helpful in straightening out questions I had with regard to varying estimates of the effects of CO_2 and dust. This work was supported by contract AT(11-1)2185 with the U.S. Atomic Energy Commission. This is contribution No. 2248 from the Lamont-Doherty Geological Observatory.

10 March 1975; revised 7 May 1975

Stratospheric Ozone—Fragile Shield?

By MARTIN I. HOFFERT
New York Univ., Div. of Applied Science
and
RICHARD W. STEWART
NASA Goddard Institute for Space Studies

Decision-makers and atmospheric scientists must face the fact that extensive uncertainties characterize studies of the stratosphere's ozone shield, making hard and fast conclusions about man's effect on it, through aerospace propulsion systems and "Freons," unsupportable

Solar radiation reaching the top of our atmosphere has a small but potentially lethal component in the ultraviolet (UV) part of the spectrum. It is known, for example, that microorganisms do not survive very long exposed to unshielded solar-flux intensities in the germicidal range (near wavelengths of 250 nm). Fortunately for life on Earth, a partial UV shield has evolved in the stratosphere in the form of a layer of ozone that absorbs the most harmful rays before they reach the surface.

Considering its biological role, the ozone shield has unimposing dimensions. Compressed to sea-level pressure and temperature all the ozone molecules in the atmosphere would form a spherical shell at the Earth's surface less than half a centimeter thick. Furthermore, the shield is somewhat "leaky" and admits some UV through at diminished intensities. Terrestrial organisms have apparently evolved some capacity to tolerate the present surface levels or to repair their damage, but there is evidence that skin cancer in animals is induced by the band of UV radiation in the same wavelength interval that causes erythema (sunburn) in humans and is absorbed by deoxyribonucleic acid (DNA) molecules (280-320 nm, called UV-B).

The possibility that man may now further reduce the effectiveness of this shield by technologies as diverse as supersonic transports and aerosol spray cans recently brought the question of stratospheric ozone into sharp focus in the scientific community. Indeed, the history of the ozone problem illuminates the relationship between scientific research, technology, and environmental policy-making.

Atmospheric oxygen and the ozone shield are currently thought to have evolved interdependently with the evolution of life on Earth. Berkner and Marshall have developed this theory in considerable detail.[1] If living organisms profoundly affected the formation of atmospheric ozone (and vice versa), naturally you will ask if men and their technology will add a new phase to this interaction.

You can approach this question by examining the basic photochemistry of oxygen; when you do this, you uncover the first set of many uncertainties in our knowledge of the stratosphere and its "ozone layer."

In the absence of external energy, such as UV radiation or electrical discharge, oxygen at normal atmospheric temperatures and pressures takes the diatomic form, O_2.

In 1930 Sidney Chapman explained the conversion of O_2 to ozone (O_3) in terms of a five-step system of photolytic and collisional reactions[2]:

1. Photodissociation of O_2 to atomic oxygen (O) by UV at wavelengths below 240 nm, where molecular oxygen has a large photoabsorption cross section in the Schumann-Runge continuum (F-1; note that 1 nm = 10 A): $h\nu + O_2 \rightarrow 2O$.
2. Below 80 km, the O-atoms thus formed tend to recombine to form ozone: $O + O_2 + M \rightarrow O_3 + M$, where M is a third body (N_2 or O_2).
3. Ozone can be photodissociated both by UV radiation below about 350 nm and by visible radiation: $h\nu + O_3 \rightarrow O_2 + O$. The region between 350 and 200 nm contains the very strong Hartly absorption bands and the Huggins bands of O_3, while visible light is relatively weakly absorbed by the Chappius system (F-1).
4. Below 50 km, collisional recombination to molecular oxygen occurs primarily by $O + O_3 \rightarrow 2O_2$.
5. The three-body reaction $O + O + M \rightarrow O_2 + M$ exerts itself at high altitudes.

These Chapman ("pure air") reactions shape a simple photochemical equilibrium model for vertical ozone distributions in terms of laboratory-measured values of photoabsorption cross sections and collisional reaction rates of the system. Using the best current measurements of these parameters, the photochemical equilibrium Chapman model predicts qualitatively correct O_3 profiles—in the sense that computed number densities peak in the vicinity of 25 km and drop off at higher and lower altitudes (F-2 and F-3)—but overpredicts the concentration and total amount of ozone.

The Chapman system apparently exerts qualitative control over the ozone profile, but actually offers only a crude approximation of the real world. It requires specification of an "effective" solar zenith angle averaged over diurnal cycles; it neglects the influence of atmospheric transport; it neglects the nonlinear contributions of horizontal non-uniformities; and it neglects the role of trace species other than O and O_3 on atmospheric chemistry—all potentially important factors in tuning the basic Chapman model to obtain agreement with observations.

For many years, only a relatively small group of specialists treated such problems. However, the role of trace species (particularly oxides of nitrogen and chlorine) introduced into the stratosphere by man's activities recently aroused public concern. Some

atmospheric scientists claimed trace substances could significantly deplete the ozone shield.

During the Congressional debate over the U.S. SST, Harold H. Johnston of UC-Berkeley raised this question forcefully in terms of catalytic depletion of ozone by nitrogen oxides.[3]

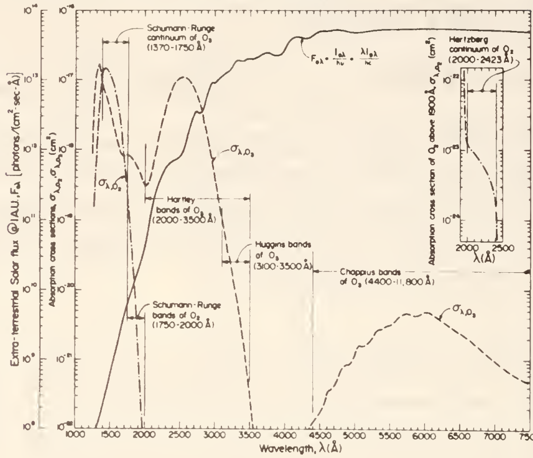
In the stratosphere N_2O, a natural consituituent, reacts with excited atomic oxygen to form nitric oxide ($O(^1D) + N_2O \rightarrow 2NO$). In 1970, Crutzen[4] proposed a catalytic cycle that interconverts NO and nitrogen dioxide (NO_2) as follows:

$$NO + O_3 \rightarrow NO_2 + O_2$$
$$NO_2 + O \rightarrow NO + O_2$$
Net: $$O_3 + O \rightarrow 2O_2$$

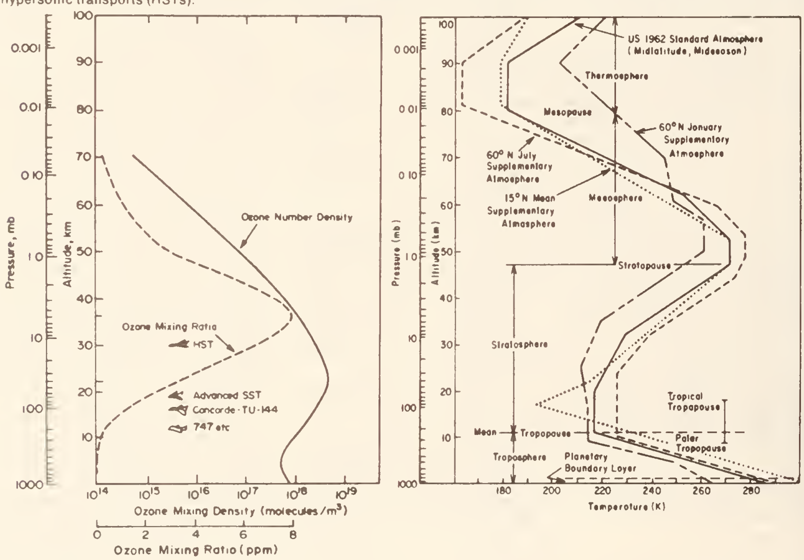
This conserves the total amount of NO_x ($NO+NO_2$) but has the net effect of destroying ozone. The amount of NO_x in the stratosphere was not very well known in 1970, but plausible concentrations in the parts per billion (ppb) range suggested that omission of the NO_x system might be partially responsible for the Chapman scheme's overprediction of ozone concentrations.

Johnston suggested projected SST

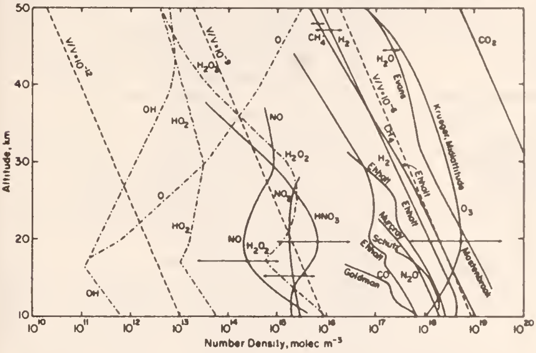
F-1 MOLECULAR OXYGEN AND OZONE PHOTOABSORPTION CROSS-SECTIONS AND SOLAR FLUX DISTRIBUTION
At the top of the Earth's atmosphere vs. wavelength.



F-2 TYPICAL VERTICAL OZONE PROFILE
In relation to thermal structure of atmosphere. The stratosphere is a major region of ozone formation as well as a region where vertical turbulent diffusion is inhibited by the buoyantly stabilizing effect of positive temperature gradients on turbulent eddy fluctuations. The left graph shows cruise altitudes of subsonic aircraft in the 747 class, existing SSTs in the Concorde/TU-144 class, advanced SSTs in the class of the original U.S. (Boeing) proposals, and a design point for projected hypersonic transports (HSTs).



F-3 NUMBER DENSITY OF PROFILES OF MINOR CONSTITUENTS IN THE STRATOSPHERE
Some concentrations are measured[22] (solid lines) and others computed from an atmospheric model[14] (broken lines). On the logarithmic number density scale, contours of constant mixing ratio, or volumetric concentration (V/V), decrease roughly linearly with height because of the exponential fall-off in air density.



fleets could inject sufficient amounts of NO_x from engine emissions into the stratosphere to deplete the ozone shield seriously.[4] More specifically, during the 1970-71 SST debates Johnston claimed that (based on an NO_x-augmented Chapman photochemical equilibrium model, with an NO_2 emission index of 23 g/kg fuel) 500 Boeing SSTs would reduce global ozone between 3 and 23%, depending on the distribution of exhaust gases, and reduce ozone near intensive traffic zones as much as 50%.[3] Others asserted that systematic, long-term reduction of ozone by as little as 1% would increase skin cancer cases in the U.S. by 8000 per year.[5]

In a related development, Stolarski and Cicerone[6] discovered an analogous catalytic cycle interconverting atomic chlorine (Cl) and chlorine oxide (ClO) ($Cl+O_3 \rightarrow ClO+O_2$, $ClO+O \rightarrow Cl+O_2$. Net: $O_3+O \rightarrow 2O_2$) could work the same way as the NO_x cycle to deplete ozone, but about five times faster. Although the existence, not to mention the concentration, of stratospheric chlorine has not been well established, certain potential artificial sources have aroused concern.

In the environmental impact statement for the Space Shuttle,[7] NASA estimates that effluents from the solid-propellant boosters contain about 25% by weight of hydrochloric acid. It is therefore conceivable, but by no means proved, that extensive Shuttle operations might inject enough chlorine into the stratosphere to deplete ozone to some extent.

Subsequently, Molina and Rowland published the idea that fluorocarbons (CF_xCl_y, commercially known as Freons), widely used as propellants in aerosol spray cans and as working fluids in refrigerators and air conditioners, would photodissociate in the stratosphere, release chlorine, and thus act as a catalytic sink for stratospheric ozone.[8] The most important of the fluorocarbons, Freons 11 ($CFCl_3$) and Freon 12 (CF_2Cl_2), are chemically nonreactive in the troposphere and not very soluble; and Molina and Rowland estimate overall atmospheric residence times for these species in the range of 40-150 years. They do absorb radiation, however, in the far-UV, and stratospheric photolysis would occur mainly in the "window" at 175-220 nm between the more intense absorptions of the Schumann-Range regions of O_2 and the Hartley bands of O_3 (F-1).

The putative effects of Freons on stratospheric ozone, as in the SST case, have been calculated from models, not measured.

The CIAP Study and Modeling

In 1970, concerned with environmental questions, including ozone depletion, Congress requested the Department of Transportation (DOT) to "gather all available and pertinent information and definitive data needed to determine whether or not environmental degradation could result from a fleet operation of SST-type aircraft."[9]

In response, DOT began the Climatic Impact Assessment Program (CIAP), with Alan J. Grobecker as manager. As it turned out, the CIAP study dealt largely with the NO_x ozone-depletion problem.

Concern over SST combustion products had been largely focused by Johnston's original analysis.[3] But it was open to criticism on grounds that it employed an oversimplified photochemical equilibrium model. The model did not account for the transport of a constituent from one part of the atmosphere to another by the general circulation or by turbulent eddies; nor all the chemical reactions which could play a role in ozone formation; nor time-dependent effects.

During the CIAP study, various research groups developed atmospheric models aimed at solving the conservation-of-mass equations for each

MARTIN I. HOFFERT (M), Research Associate Professor at New York Univ., holds a Ph.D. (1967) in astronautics from Brooklyn Polytechnic Institute and an M.A. (1969) from the New School for Social Research, where he did graduate work in sociology and economics. His research has ranged over plasma physics, re-entry phenomena, turbulence, the planetary boundary layer, atmospheric chemistry, air-pollution dispersion, and the terrestrial carbon cycle. Most recently he completed a tenure as Natural Research Council senior research associate at the NASA Goddard Institute for Space Studies, collaborating with the co-author on models of the natural and perturbed stratosphere. **RICHARD W. STEWART**, staff scientist at NASA Goddard Institute for Space Studies, has been active in planetary atmospheres since receiving a Ph.D. in physics from Columbia Univ. (1967). Dr. Stewart is also Visiting Assistant Professor of Physics at the City Univ. of New York. His most recent research concerns assessing the impact of aerospace and industrial activity on the stratosphere.

T-1 NAS CLIMATIC IMPACT COMMITTEE PHOTOCHEMICAL REACTION SET FOR COMPUTING STRATOSPHERIC OZONE[24]

The authors of the NAS study claim that, although additional reactions of N_2O_5 NO, HNO_3, CO, H_2CO, H_2O_2, and various atomic and free-radical species may be important for special problems, they do not materially change the predictions of stratospheric ozone based on this 51-step model.

a. Classic Chapman, pure air reactions
- (1) $O_2 + h\nu$ (below 242 nm) $\rightarrow O + O$
- (2) $O + O_2 + M \rightarrow O_3 + M$
- (3) $O_3 + h\nu$ (uv and visible) $\rightarrow O_2 + O$
- (4) $O_3 + O \rightarrow O_2 + O_2$

b. Nitrogen oxide (NO_x) catalyzed destruction of ozone
- (5) $O_3 + NO \rightarrow O_2 + NO_2$
- (6) $NO_2 + O \rightarrow NO + O_2$
- (7) $NO_2 + h\nu$ (below 400 nm) $\rightarrow NO + O$

c. Pure air reactions, considering excited oxygen atoms
- (3a) $O_3 + h\nu$ (below 310 nm) $\rightarrow O_2 + O(^1D)$
- (3b) $O_3 + h\nu$ (above 310 nm) $\rightarrow O_2 + O(^3P)$
- (4a) $O_3 + O(^1D) \rightarrow O_2 + O_2$
- (4b) $O_3 + O(^3P) \rightarrow O_2 + O_2$
- (8) $O(^1D) + M \rightarrow O(^3P) + M$

d. Destruction of ozone by free radicals (HO_x) based on water
- (9) $HO + O_3 \rightarrow HOO + O_2$
- (10) $HOO + O_3 \rightarrow HO + O_2 + O_2$
- (11) $HO + O \rightarrow H + O_2$
- (12) $HOO + O \rightarrow HO + O_2$
- (13) $H + O_3 \rightarrow HO + O_2$
- (14) $H + O_2 + M \rightarrow HOO + M$

e. Sources and sinks of NO_x
- (15a) $O(^1D) + N_2O \rightarrow 2NO$
- (15b) $O(^1D) + N_2O \rightarrow N_2 + O_2$
- (16) $N_2O + h\nu \rightarrow N_2 + O(^1D)$
- (17) $NO + h\nu$ (below 192 nm) $\rightarrow N + O$
- (18) $N + NO \rightarrow N_2 + O$
- (19) $N + O_2 \rightarrow NO + O$
- (20) $N + O_3 \rightarrow NO + O_2$
- (21) N_2 + cosmic rays $\rightarrow N + N$
- (22) $HO + NO_2 \xrightarrow{M} HNO_3$
- (23) $HNO_3 + h\nu \rightarrow HO + NO_2$
- (24) $HO + HNO_3 \rightarrow H_2O + NO_3$

f. Sources and sinks of HO_x radicals
- (25a) $O(^1D) + H_2O \rightarrow 2HO$
- (25b) $O(^1D) + H_2 \rightarrow H + HO$
- (25c) $O(^1D) + CH_4 \rightarrow HO + CH_3$
- (26) $HO + CH_4 \rightarrow H_2O + CH_3$
- (27) $CH_3 + O_2 \rightarrow CH_3OO + M$
- (28) $CH_3OO + NO \rightarrow CH_3O + NO_2$
- (29) $CH_3O + O_2 \rightarrow H_2CO + HOO$
- (30) $HO + HOO \rightarrow H_2O + O_2$
- (31) $HOO + HOO \rightarrow H_2O_2 + O_2$
- (32) $H_2CO + h\nu \rightarrow H + HCO$
- (33) $HCO + O_2 \rightarrow CO + HOO$
- (34) $H_2O_2 + h\nu \rightarrow HO + HO$
- (35) $HO + H_2O_2 \rightarrow H_2O + HOO$
- (36) $O + H_2O_2 \rightarrow HO + HOO$

g. Coupling of NO_x and HO_x systems
- (37) $HOO + NO \rightarrow HO + NO_2$
- (22) $HO + NO_2 \xrightarrow{M} HNO_3$
- (23) $HNO_3 + h\nu \rightarrow HO + NO_2$
- (24) $HO + HNO_3 \rightarrow H_2O + NO_3$
- (38a) $NO_3 + NO \rightarrow 2NO_2$
- (38b) $NO_3 + h\nu (< 580\ nm) \rightarrow NO_2 + O$

h. NO_x reactions during the night
- (39) $NO + O_3 \rightarrow NO_2 + O_2$
- (40) $NO_2 + O_3 \rightarrow NO_3 + O_2$
- (41) $NO_2 + NO_3 \xrightarrow{M} N_2O_5$
- (42) (N_2O_5 photolyzed during the day)
- (43) $NO_2 + NO_3 \rightarrow NO_2 + O_2 + NO$

i. Reaction of chlorine species
- (44) $Cl_2 + h\nu \rightarrow Cl + Cl$
- (45) $HO + HCl \rightarrow H_2O + Cl$
- (46) $O(^1D) + CF_2Cl_2 \rightarrow ClO + CF_2Cl$
- (47) $CF_2Cl_2 + h\nu$ (below 210 nm) $\rightarrow CF_2Cl + Cl$
- (48) $Cl + CH_4 \rightarrow HCl + CH_3$
- (49) $Cl + O_3 \rightarrow ClO + O_2$
- (50) $ClO + O \rightarrow Cl + O_2$
- (51) $ClO + NO \rightarrow Cl + NO_2$

j. Ionic reactions (see CIAP Monograph 1, Chapter 5)

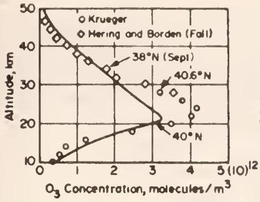
reactive atmospheric constituent.[10-21] Typically, each differential equation in the system contains a contribution from transport, a contribution from collisional reactions which create or destroy the constituent, and a contribution from photolysis, important for UV-absorbing species and their products. The solution, generally obtained numerically, gives the distribution of atmospheric constituents in space and time.

In formulating a photochemistry/transport atmospheric model, the researcher must decide which constituents and reactions to include, and do so at least partly subjectively. Even with the *simplest* one-dimensional (1D) transport model, the number of possible trace species and reactions in the stratosphere makes some *a priori* screening a necessity. The fact that the rates of certain plausible reactions have not been measured in the laboratory, and that the ones which have often exhibited large scatter, increases the difficulty of screening. Furthermore, some important reactions or species can easily be left out. This has happened frequently in aeronomy, since new processes are constantly being discovered.

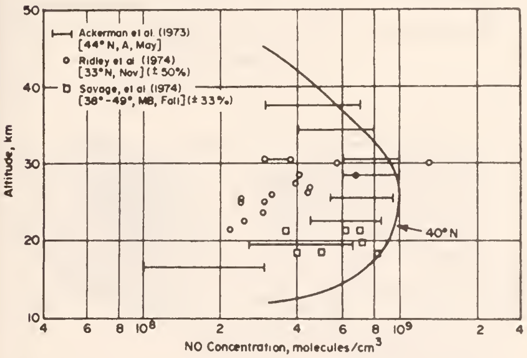
F-3 displays vertical profiles of certain stratospheric constituents classed as important during the CIAP. Only a *fraction* of these have been measured directly.[22] Others, particularly reactive radicals, have been inferred from model calculations.

All the CIAP models included at least the Chapman system involving O, O_2 and O_3, the NO_x catalytic cycle involving NO and NO_2, and some HO_x radicals derived from water vapor (OH, HO_2, etc). The more photochemically complex models included photolysis and reformation of nitric acid (HNO_3) and other nitrogen species, such as N, N_2O, NO_3, N_2O_5, and NH_3; reactions involving excited and ground states of atomic and molecular oxygen $O(^1D)$, $O(^3P)$, $O_2(^1\Delta)$ and $O_2(^1\Sigma)$, and reactions involving methane, CH_4, and organic methane derivatives (CH_3, CH_3O, CH_3OO, CH_3OH, HCO, etc.)

Our own one-dimensional model included over 100 reactions among



F-4 VERTICAL PROFILES OF UNPERTURBED OZONE (O_3) AND NITRIC OXIDE (NO) AT MIDDLE LATITUDES
Observations compared with calculated fall-season values from Widhopf's 2D zonally averaged model.[19]



such species.[13]

During the early phases of CIAP, the chlorine catalytic cycle had not yet been discovered, so the related species did not appear in the CIAP-model reaction sets. More recently, a 51-step reaction set (T-1) proposed by an NAS-NAE study group included the chlorine catalytic cycle and Freon 12 (CF_2Cl_2) photodissociation and reactions with $O(^1D)$. But there is no guarantee that the NAS-NAE reaction set will remain definitive for calculations of stratospheric ozone.

The importance of vertical transport below certain altitudes can be inferred from the O_3 density profiles in F-2 and F-3. Ozone is photochemically formed primarily in the mid-stratosphere. Little O_3 forms in the troposphere because the stratosphere absorbs most of the UV. But observations show tropospheric ozone number densities of the same order of magnitude as those at an altitude of, say, 35 km, a level of intense photochemical production. Apparently, this is the result of ozone diffusing down to the surface, where reactions at the ground destroy it. Calculations show the ozone profile to be photochemically dominated above about 35 km and diffusion-dominated below about 20 km. Coupled transport and chemistry effects govern concentrations in between—the region of maximum ozone.

The 1D CIAP models[10,12-16,20] average the species-concentration equations over longitude and latitude so that only the vertical (altitude) coordinate appears explicitly. This approximation embodies the effects of vertical mixing in the vertical profile of *turbulent eddy diffusivity*, which is specified as input. The various CIAP investigators assigned different profiles for this diffusivity according to their differing interpretation of empirical data. In these models, one must treat *nonlinear* photochemical source terms linked by interacting differential equations for many atmospheric constituents. Boundary conditions take the form of prescribed concentrations or concentration gradients (fluxes) at the upper and lower boundaries of the computational domain. Generally, the researcher first runs his model on a computer until the system produces a "steady state"—the average unperturbed state of the natural atmosphere.

The 2D models[11,18,19,21] average the species conservation equations over longitude and short-period temporal fluctuations (zonal averaging), so that the time-dependent PDEs (partial differential equations) contain altitude and latitude as explicit physical coordinates. Its equations yield a more realistic picture—although still very complex—which includes horizontal diffusion of ozone. The 2D model also admits the realism of a latitudinally varying solar-zenith angle.

The 2D models in CIAP interpolated and extrapolated atmospheric-circulation data to characterize winds, temperatures, and diffusivities in the troposphere and stratosphere during the four seasons—a rather voluminous array of input data, which had to be specified at each computational gridpoint.

The 2D model developed by George Widhopf at Aerospace Corp. was extensively used in the CIAP study.[19] F-4 and F-5 compare the vertical profiles of O_3, NO, NO_2 and HNO_3 in the unperturbed (spun-up) stratosphere computed from the Aerospace model with observations at mid-latitudes. This level of agreement is fairly typical of the 1D models as well, although the latter obviously cannot resolve latitudinal variations. F-6 shows the reduced thickness of the total ozone column (in Dobson units—that is, its thickness in cm x 10^3 at standard temperature and pressure, STP) as a function of latitude. The Widhopf model produces the observed mid-latitude peak.

The 1D and 2D models described thus far do not characterize dynamic or thermodynamic interactions. Besides solving simultaneously the relevant momentum and energy equations, a fully interactive 2D model would have to invoke some "closure hypothesis" to relate turbulent transport terms to the model variables. Temperature profiles computed from a 1D thermally-interactive model by Callis et al[23] are shown in F-7.

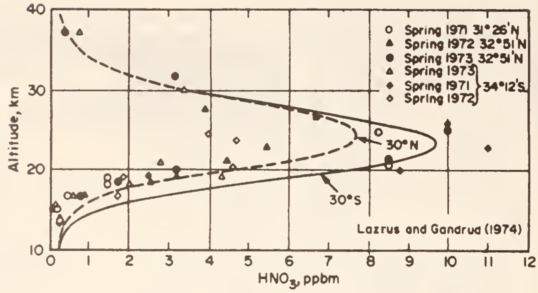
The closure problem can be dealt with somewhat differently in a 3D *interactive model*, since it resolves the larger turbulent eddies explicitly. (Studies show you need full three-dimensional time-dependent treatments of the fluid dynamics to gain proper statistical description of turbulence in numerical simulations.) Nonetheless, fluctuations on a subgrid scale cannot be resolved and must be

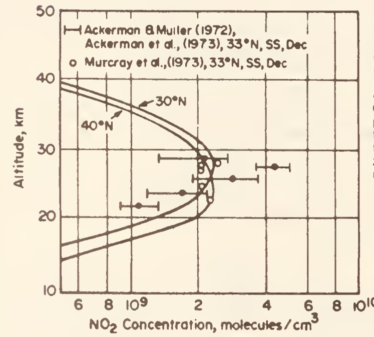
modeled in some way even with a 3D approach. Generally speaking, numerical integration of the "primitive" equations of motion in conventional general circulation models (GCMs) takes a very long time even on the largest machines, and only limited simulations of atmospheric motion with coupled photochemistry have been carried out through the long times needed for photochemical spin-up.

Recently, a new type of 3D code was developed at MIT. It is computationally fast enough to have been used in the CIAP study.[17] It represents all variables along horizontal surfaces (equally spaced in units of the logarithm of atmospheric pressure between the surface and the upper boundary) by global spherical harmonics, with the smallest resolutions equivalent at mid-latitudes of 2000 km in the longitudinal coordinate and 2900 km latitudinally. To gain computational speed, the code assumes a quasi-geostrophic balance with radiative heating, subgrid turbulence, and surface drag modeled in a semi-empirical way.

This brief review gives some idea of the complexity of the various atmospheric models used in CIAP to compute the natural and SST-perturbed stratosphere. The models differed in significant detail within a given dimensional class (0D, 1D, 2D or 3D)—in chemistry, atmospheric transport and diffusion, background levels of NO_x, and other ways. What did they show about SST emissions?

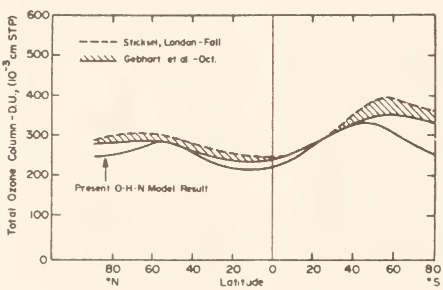
In the time-dependent models, the



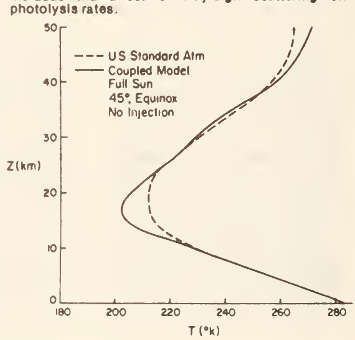


F-5 VERTICAL PROFILES OF UNPERTURBED NITRIC ACID (HNO_3) AND NITROGEN DIOXIDE (NO_2) AT MIDDLE LATITUDES
Observations compared with calculated fall-season values from Widhopf's 2D zonally-average model.[19]

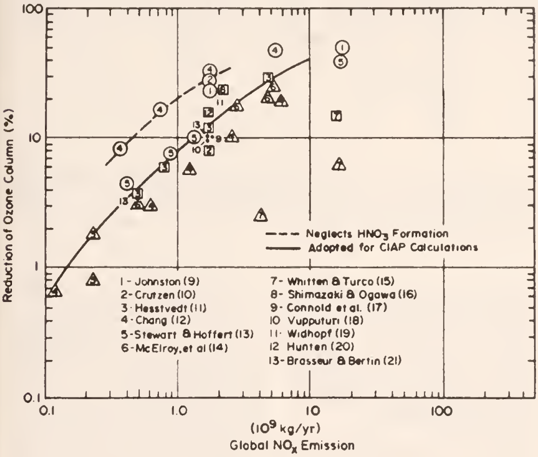
F-6 ZONAL (LONGITUDINAL) AVERAGES OF OZONE-COLUMN THICKNESS
In Dobson units, vs. latitude during the fall season. Observations compared with Widhopf's 2D model.[19] The mid-latitude peak is thought to result from poleward transport of ozone formed near the equator.



F-7 STRATOSPHERIC VERTICAL TEMPERATURE PROFILE
Computed by Callis et al using a thermally interactive photochemical model.[23] The calculation includes the effect of Rayleigh scattering on photolysis rates.



F-8 AN OVERVIEW OF OZONE-REDUCTION ESTIMATES
Summary of CIAP calculations of percent total ozone reduction from a uniformly distributed stratospheric NO_x source at 20 km. The circled "1" data points identify Johnston's original photochemical equilibrium (OD) calculations. The other models assume 1D vertical transport except for the 2D (vertical and latitudinal) transport models of Hesstvedt, Vupputuri, Widhopf and Brasseur and Bertin and the 3D (MIT) model of Cunnold et al. Numbers in parentheses denote reference numbers in this *A/A* article.



unperturbed (spun up) atmosphere's composition marks the initial state for purposes of computing ozone depletion caused by SST emissions. The SST exhaust (source strength, S, in grams per year) is typically given by:

$$S = 8766\ NnFf(\mathrm{EI})$$

with N the number of aircraft, n the number of engines per aircraft, F the mass of fuel flow per engine in kg h^{-1}, f the fraction of the day that each aircraft stays at cruise height, the emission index (EI) the number of grams of exhaust component per kilogram of fuel burned, and 8766 the average number of hours in a year. The analyst adds the NO_x computed in this way to the relevant species-conservation equation at the specified cruise altitude and, in the 2D and 3D models, over the specified horizontal flight corridor(s), and then computes the perturbed composition of the stratosphere. For a uniform global emission rate of NO_x, this process yields a new steady-state compositional structure after several simulated years.

F-8 shows percent reduction in total global ozone computed using various CIAP models for NO_x injected at 20 km. Despite relatively large model-to-model variations, the trend originally predicted by Johnston's relatively simple photochemical equilibrium model seems to have been verified by the more complex atmospheric models. Notice the disparity of at least an order-of-magnitude, however, in the amount of ozone depletion predicted by different models at a given level of injection. (We have taken this opportunity to correct the data points for our own model and Widhopf's erroneously plotted in Ref. 9. The circled points numbered 5 correspond to a ten-year numerical integration with a constant NO_x source at 20 km.) A portion of the disparity can be attributed to the neglect by certain models of nitric acid-formation reactions that act as an NO_x sink, and therefore lessen the role of the catalytic cycle. Other sources of this scatter will be discussed later.

The solid line of F-8 and a corresponding line for injection at 17 km were used to assess ozone-depletion potential from various types of stratospheric aircraft in DOT's recently published *Report of Findings*.[9] SSTs in

T-2 CIAP ESTIMATED PERCENT OZONE REDUCTIONS PER 100 AIRCRAFT OF SPECIFIC TYPES[9]

Aircraft Type	Fuel Burned Per Year* (kg/yr)	Altitude km (kft)	NO_x Emission Index (EI) Without Controls (g per kg fuel)	Percent Ozone Reduction in Northern Hemisphere		
				Without Controls	EI Controls 1/6 Today	EI Controls 1/60 Today
Subsonic**						
707/DC-8	1×10^9	11 (36)	6	0.0034	0.00070	0.000070
DC-10/L-1011	1.5×10^9	11 (36)	15	0.010	0.0020	0.00020
747	2.0×10^9	11 (36)	15	0.014	0.0025	0.00025
747 – SP	2.0×10^9	13.5 (44)	15	0.079	0.014	0.0014
Supersonic						
Concorde/TU-144	4×10^8 3×10^9	13.5 (44) 16.5 (54)	18	0.39	0.068	0.0068
Advanced SST	3×10^8 6×10^9	16.5 (54) 19.5 (64)	18	1.74	0.32	0.032

*Subsonics assumed to operate at high altitude, 5.4 hours per day, 365 days per year. Supersonics assumed to operate at high altitude, 4.4 hours per day, 365 days per year.

**The present subsonic fleet consists of 1,217 707/DC-8s, 232 DC-10/L-1011s, and 232 747s flying at a mean altitude of 11 km (36 kft) and is estimated to cause a 0.1 percent ozone reduction.

T-3 OZONE REDUCTION AND ERYTHEMAL RADIATION
NAS estimated percent ozone reductions and increases of erythemally effective radiation for illustrative aircraft fleets.[24]

Fleet	Height (km)	Fuel Flow (10^9 kg/yr)	NO_x (10^6 kg/yr)	$X(NO_x)$ 10^{-9}	O_3 (% Decrease)	Erythemally Effective uv Radiation (% Increase)
1. 400 wide-body present subsonic	10.5	10.4	156	0.058	0.082	0.16
2. 100 wide-body projected subsonic	13.5	2.6	39	0.113	0.16	0.32
3. 100 present SST	16.5	3.49	62.8	0.52	0.72	1.44
4. 100 large SST	19.5	9.13	164	2.37	3.27	6.5
5. CIAP 1990 upperbound fleet	16.5	1.62	29.2	0.24	11	22
	19.5	30.6	551	7.96		
6. CIAP 2005 upperbound fleet	16.5	8.09	146	1.20	> 30	Large
	19.5	155	2790	40.3		

* The first four lines are intended for orientation and are not meant to indicate expected traffic, except for Line 1, which represents long-distance traffic for 1974. Lines 5 and 6 are taken, in simplified form, from the CIAP upperbound fleets. $X(NO_x)$ is the increase in mixing ratio (ratio of NO_x concentration to total atmospheric concentration) in the ozone layer after equilibrium has been reached. The last two columns are estimates of the corresponding percent reduction of ozone and percent increase of erythemally effective uv radiation. Confidence limits are estimated to be a factor of 2 for flight at 19.5 km, a factor of 3 for flight at 16.5 km, and a factor of 10 either way for subsonic aircraft.

the Concorde/Tupolev class, for example, consume less fuel and cruise at lower altitudes than advanced SSTs, such as the design proposed by Boeing in 1971.

T-2 shows the ozone depletion associated with various types of aircraft, including present subsonic aircraft, as given in the DOT report. According to these figures, 100 advanced SSTs without NO_x emission controls (equivalent to a uniform NO_x source of about 5.4 x 10^6 kg/yr at 17 km and 1.08 x 10^8 kg/yr at 20 km, with an emission index of 18 g/kg fuel) would reduce total ozone in the northern hemisphere between 1 and 2%. Presumably, the increased UV transmitted to the Earth's surface would cause an increase in skin cancer, although this was not spelled out too precisely in quantitative terms by the *Report of Findings*.

The Aftermath of CIAP— The NAS Study, COVOS, and Minority Reports

The CIAP study lasted four years and involved hundreds of scientists and engineers at universities, governmental labs, and private research organizations. The CIAP *Report of Findings*, a document some two inches thick, summarizes six monographs providing "in depth" documentation of the study. Obviously, a nonspecialist or decision-maker in government would be disinclined to penetrate the "fine print" of these documents. An "Executive Summary," also issued as a separate document, therefore distills the essential CIAP findings.

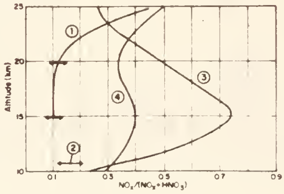
The CIAP study has been evaluated, interpreted and criticized by a number of groups and individuals.

First came an official review and independent evaluation of the environmental impact of supersonic flight by a special committee of the National Academy of Sciences and National Academy of Engineering—the Climatic Impact Committee. Their final report, largely drafted during a summer study at Woods Hole, Mass., in 1974, has recently been released.[24]

The NAS-NAE Committee used essentially the same methods as CIAP. It again calculated percent ozone depletion at 17 and 20 km as a function of NO_x emission rates from a 1D model[20] for various types and numbers of aircraft (T-3), but put more emphasis on large fleets without emission controls and cited estimates of increases in skin cancer more than did DOT's Executive Summary.

It is interesting to compare quantities cited by the CIAP and NAS-NAE studies (T-2 and T-3). Consider, for example, the percent ozone reduction from 100 Concorde/TU-144-class SSTs and from 100 advanced (large) SSTs. In both cases, the NAS-NAE study predicts about twice as much ozone reduction as CIAP. This difference certainly comes within the scatter of the various models in F-8.

F-9 COVOS OBSERVATIONS
COVOS[25] compares with 2D Hesstvedt[11] model calculations of the concentration ratio $NO_x/(NO_x + HNO_3)$: 1 Balloon and aircraft measurements at 45 deg N. 2 Aircraft measurements at 65 deg N. 3 Model calculations at 30 deg N. 4 Model calculations at 60 deg N (NO_x = NO + NO_2).

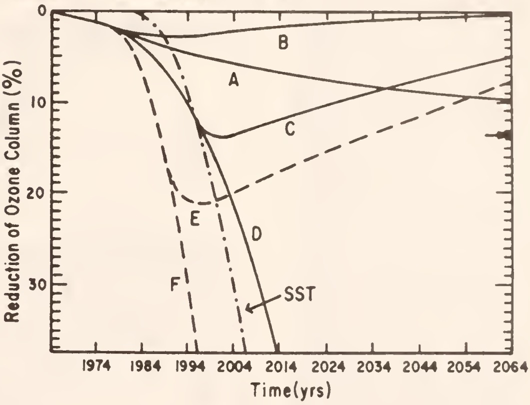


The NAS-NAE results do not include the ameliorative influence of emission controls, but do include the effect of the "CIAP upperbound fleet," a scenario involving *thousands* of supersonic aircraft.

The European atmospheric-science community developed a CIAP-type research program of its own during the early 1970s, Les Comite D'Etudes des Consequences des Vols Stratospheriques (COVOS). A COVOS meeting in Oxford, England, in September 1974, presented new measurements of stratospheric nitric acid (HNO_3) that suggest that CIAP models have overestimated ozone depletion from the NO_x catalytic cycle.[25] The effect of HNO_3 on NO_x ozone reduction is embodied in the ratio of concentrations $(NO_x)/(NO_x+HNO_3)$: the smaller the ratio, the greater the relative amount of reactive nitrogen invested in nitric acid, and hence the smaller the ozone depletion at a given level of nitrogen oxide injections.

F-9 shows that COVOS measurements of this ratio—smaller by a factor of 3 to 5 at 20 km than the corresponding values computed by Hesstvedt's 2D CIAP model (comparable to Widhopf's 2D model discussed earlier). The COVOS measurements, published after DOT's *Report of Findings*, suggest the CIAP models underestimated the influence of HNO_3, and therefore *overestimated* ozone depletion from SSTs.

F-10 SCENARIOS OF FREON ACTING ON GLOBAL OZONE
Percent global ozone reduction over time projected for six scenarios of Freon use by Wofsy et al.[30] Emissions of CF_2Cl_2 and $CFCl_3$ were assumed as 3.5×10^5 and 2.2×10^5 metric tons, respectively, in 1972. The growth rates for each of these Freons were taken as 10% per year (7-yr doubling) for curves B, C, and D; 22% per year (3.5-yr doubling) for E and F; and production held constant for A. For curves D and F growth continues indefinitely; but for B, C, and E emissions are terminated in 1978, 1995, and 1987, respectively. Shown for comparison, the ozone diminutions computed for NO_x injections from CIAP's upperbound SST fleet. The arrow shows the steady-state percent ozone reduction approached by model A (constant production) after long times. (Copyright 1975 by the American Association for the Advancement of Science.)



Some researchers did not believe the CIAP calculations overestimated ozone depletion—quite the opposite. They found the Executive Summary of the *Report of Findings* misleading. They said that by creating the impression that present SSTs would be relatively benign with respect to skin cancer, it cast doubt on the credibility of the atmospheric scientists who originally sounded the alarm. In a special report circulated within the CIAP community,[26] Harold Johnston claimed that while the study had carried out its charge, under the direction of Alan J. Grobecker, with great efficiency and effectiveness, "it has evaded giving a clear, candid statement of its own findings in its *Report of Findings* Executive Summary of December 1974.

Specifically, Johnston felt that the following conclusions, derived from the "fine print" of the *Report of Findings*, ought to be disseminated more widely[26]:

1. The artificial nitrogen oxides from a fleet of 125 Concordes/TU-144s would reduce ozone in the northern hemisphere by 0.5%, and thus would eventually increase skin cancer cases in the U.S. by 1% (5000 per year or 100,000 over a 20-year lifespan of the aircraft). The 375 SSTs projected by the EPA (Environmental Protection Agency) for 1990 would result in threefold greater effects.

2. The artificial nitrogen oxides from 500 Boeing SSTs as described in 1971 (but with the Concorde's emission index for NO_x) would have decreased ozone by 12%, increased U.S. skin cancer cases by 120,000 per year, and increased U.S. skin cancer by 2.4 million per 20 years.

3. A future fleet of SSTs predicted for the year 2025 . . . would reduce ozone by substantially more than a factor of three. Even if NO_x emissions are reduced by a factor of 60, such a fleet would reduce ozone in the northern hemisphere by more than 5%.

Thomas Donahue, president of the Solar Planetary Relations Section of the American Geophysical Union (AGU), made a similar criticism in a letter to the editor of *Science*.[27] Grobecker responded on the same pages.

We do not believe that present understanding of stratospheric processes justifies assigning specific confidence levels to numerical values of ozone depletion computed for high-altitude NO_x injection. Too many uncertainties are still present in the models. We shall discuss the nature of some of these unknown factors shortly.

Regardless of position on results of the various CIAP investigations, few knowledgeable scientists would contest that the program accelerated the development of atmospheric models and focused well-deserved attention on the photochemistry of atmospheric ozone. That attention soon riveted on the action of halogens, particularly chlorine released by photolysis of Freon, as well as NO_x.

The chlorine catalytic cycle closely resembles the NO_x one. It was discovered during the CIAP study; and the calculation of its effects on stratospheric ozone was aided by atmospheric models developed for the SST-NO_x problem.

Molina and Rowland[8] showed that fluorocarbons are released from aerosol spray containers, refrigeration units, etc. at a global rate within a factor of about 2 of the natural formation rate of NO from N_2O; that it takes about a hundred years to arrive at a steady state between fluorocarbons released at the ground and stratospheric destruction by photolysis; and that usage of these substances has been rapidly increasing. Stolarski and Cicerone had already pointed out that the ClO molecule is about five times more effective than NO_2 per molecule in destroying ozone.[6] Photochemical equilibrium calculations by Crutzen[28] and Cicerone et al[29] supported a suspicion that Freon is a source of stratosphere chlorine and leads to a sink for ozone.

Recently, using a 1D time-dependent atmospheric model to follow the evolution of ozone in some detail, Wofsy et al[30] at Harvard Univ. assessed the impact of various scenarios of Freon consumption. F-10 summarizes the results of this exercise. It implies that using Freons at the present rate will cause a 13% ozone reduction late in the next century. An accelerated rate (growth of 10% per year) would reduce ozone 37% by the year 2014. If release is terminated at some point, the biggest ozone reduction occurs some five years later, with a recovery half-life of 50 years.

It now appears that carbon tetrachloride (CCl_4) and methyl chloride (CH_3Cl) may also contribute free chlorine to the stratosphere.[31] Furthermore, new measurements confirm that chlorofluoromethanes do penetrate high into the stratosphere. Philip Krey of ERDA's Health and Safety Laboratory in New York City found Freon-11 ($CFCl_3$) at concentrations of about 60 parts per trillion (ppt) in the lower stratosphere, consistent with earlier measurements;

at 19 km, the concentration had dropped off to 20 ppt. The air samples collected from high-altitude aircraft at various latitudes also contained Freon 12 (CF_2Cl_2) and traces of CCl_4.

An interesting development is the measurement of high tropospheric levels of CH_3Cl, some 530 ppt, by R. A. Rasmussen of Washington State Univ.[31] Similar concentrations in the lower atmosphere have been detected by James Lovelock of Reading College in England, who also found CH_3Cl in sea-water at concentrations of about 3000 ppt. There is no evidence yet that CH_3Cl and related halomethanes such as chloroform ($CHCl_3$) reportedly formed in the treatment of sewage with chlorine and in chlorinating drinking water actually penetrate the stratosphere, but these measurements foster speculation that natural and perturbed chlorine cycles are at work in the stratosphere even in the absence of Freons. If so, the stratosphere may have historically been exposed to high and perhaps fluctuating levels of chlorine with no detrimental effect on long-term ozone levels. Accordingly, continued use of Freons may not represent the drastic increases of chlorine predicted.

The fluorocarbon-ozone depletion thesis draws intense scientific and environmental-policy controversy. A recent government report on the problem has urged research in the following areas to substantiate the need for regulatory action[32]:

1. Instruments and subsequent field programs to measure chlorine oxides and radicals such as OH and HO_2.

2. Specific difficult reaction-rate determinations by competent laboratories.

3. More attention to establishing the intensity of vertical mixing above about 20 km.

As indicated earlier, the solid-propellant boosters of the NASA Space Shuttle use, as the oxidizer, ammonium perchlorate, a potential stratospheric source of reactive chlorine. Based on a scenario of 50 missions per year, the NAS-NAE, using current models, estimates a potential ozone reduction of 0.36%.[24] In view of uncertainties in transport and chemistry, the authors of the NAS-NAE study feel the actual reduction may be as much as 1%. We might add, it may turn out to be so small as to be negligible.

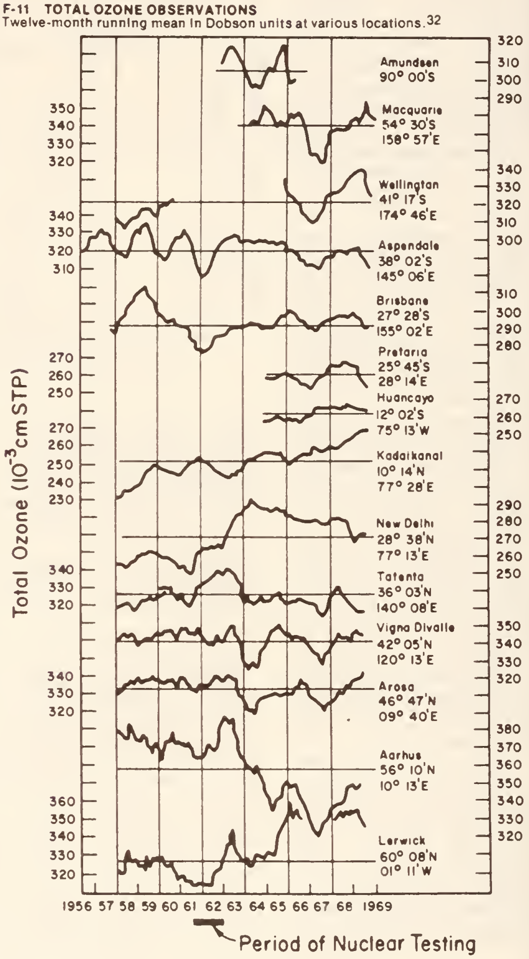
Sensitivity and Uncertainty—
The Problem of Decision

Threats to the ozone shield attributed to man's activities have been calculated from *mathematical atmospheric models*. Does any direct, *observational* evidence link man's activities with depletion of atmospheric ozone?

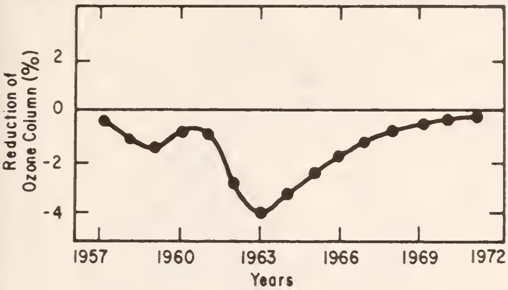
Large-scale injections of NO_x and /or Cl at the appropriate stratospheric altitudes for the express purpose of measuring the corresponding ozone diminution prove difficult and very expensive, and in fact have not been done.

The closest thing to a purposeful large-scale experiment of this type was the extensive atmospheric nuclear testing from 1957-62, the most intense activity coming in 1961-62. Thermonuclear explosions create expanding spherical blast waves which dissociate molecular oxygen and nitrogen to form nitric oxide (NO). These waves create a

F-11 TOTAL OZONE OBSERVATIONS
Twelve-month running mean in Dobson units at various locations.[32]



F-12 THERMONUCLEAR-BOMB EFFECT ON OZONE
Percent ozone reduction in the northern hemisphere from bomb-generated NO_x as calculated by Chang.[33] The maximum calculated ozone reduction was 4% in 1963 falling to 2% by early 1966.



large volume of NO because it becomes chemically "frozen"—it does not revert to N_2 and O_2—because the air behind the wave cools rapidly. Calculations show that the amount of stratospheric NO_x created in this way should have reduced global ozone by 2-4% from 1957-62.[33]

F-11 shows the variations with time of total ozone over a 14-year period for stations at a variety of places on Earth in several latitudes.[34] Few data exist before 1957. Long-term reliable ozone records before 1950 are only available at two stations: Arosa, Switzerland, and Tromso, Norway. From the F-11 data the DOT *Report of Findings* concludes that, although nuclear testing during 1961-62 might have significantly reduced global ozone, the record reveals no statistically significant changes.[9]

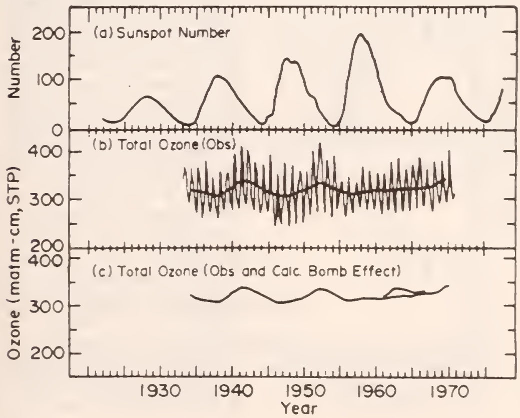
The NAS-NAE study went somewhat further into the question, and presented arguments, based on the work of Foley and Ruderman[35] and Ruderman and Chamberlain,[36] which suggest that the effect of nuclear testing might, despite appearances, have nonetheless been reflected in the ozone record. It is worth examining these arguments because of their ingenuity, and because they provide the only possible link we are aware of between observations of ozone and artificial NO_x injections.

Note first the calculations by Chang in F-12 of the percent ozone diminution from nuclear testing. It is essential to the explanation of Ruderman and Chamberlain[36] to accept that a correlation exists between total ozone and sunspot activity, as suggested by panels (a) and (b) of F-13. This has some statistical basis, although, as noted, we lack good data for periods before F-11.

Additionally, Ruderman and Chamberlain developed a cause-and-effect sequence: The solar cycle affects the flux of cosmic rays into the Earth's atmosphere; the cosmic rays produce ions and nitric oxide in the polar stratosphere; the nitric oxide strongly and promptly affects ozone in the upper polar stratosphere; and, upon transport and dilution, nitric oxide weakly and somewhat later affects ozone in temperate and tropical zones. As shown in panel (c) of F-13, the ozone peak that would presumably have appeared in the 1962-66 period may have been "taken out" by a compensating reduction of ozone from nuclear testing. This argument is tempting but in view of the additional assumptions introduced, and a lack of hard data, it must still be regarded as speculative.

In brief, scientists lack a clear validation of atmospheric-model predictions. This raises serious questions regarding the confidence levels which ought to be attributed to them. One might, for example, cite the level of agreement between measured and observed unperturbed ozone profiles—within about 20% at 25 km in Widhopf's F-4 comparison. However, the accuracy to which the unperturbed ozone profile is computed is not a good measure of the accuracy of ozone depletion calculations because the unperturbed O_3 profile is qualitatively determined by Chapman chemistry.

F-13 POSSIBLE CORRELATION OF NORTHERN HEMISPHERE OZONE WITH BOMB TESTS
A Eleven-year sunspot cycle over the past 55 years. B Northern-hemisphere total ozone measurements showing sharp seasonal oscillations about the 12-month running mean. A phase-lagged correlation of the ozone running mean (secular) trend with sunspot activity is suggested with peaks in 1941 and 1952—but the expected peak in 1963 is absent. C Northern hemisphere total ozone running mean with Chang's (F-12) nuclear-bomb effect inverted and added. With Chang's correction the 1963 ozone peak "reappears." (It is generally recognized, however, that the data before 1960 is too sparse to support firmly an 11-year total-ozone cycle.)



while perturbations depend on a variety of "second-order" effects whose nature and interactions are less well understood, and for which there is not direct observational evidence.

In the NO_x problem, theory suggests that the validity of the ozone-depletion calculations can be measured, in part, by the model's ability to properly predict the ratio $NO_x/(NO_x+HNO_3)$. COVOS measurements suggest this ratio may have been overpredicted in the CIAP models, corresponding to an overprediction of ozone depletion from the NO_x catalytic cycle. Another potential source of error arises from backward extrapolation of percent ozone decrease to very small values of NO_x injection—say, from low emission engines. Antonio Ferri has pointed out such extrapolations are incorrect for low values, because the effect of water vapor from engine emissions, at low NO_x emissions, counteracts the influence of NO_x on ozone removal.[37]

Many potential error sources of this type characterize the photochemistry adopted for any particular atmospheric model—important reactions omitted, reaction rates inaccurate, nonlinear interaction between constituents. And they may well cause incorrect extrapolation of the model. The CIAP and NAS-NAE studies did not, apparently, probe too deeply into the sensitivity of models to uncertainties in photochemistry. To a degree they did attempt to treat uncertainties in vertical turbulent diffusivity, based on an interesting study by Chang.[38]

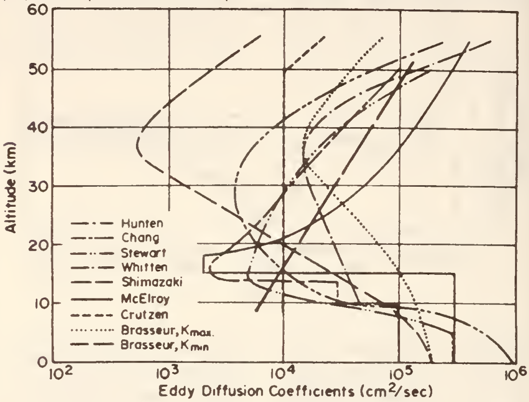
F-14 shows the various eddy-diffusivity profiles adopted by 1D CIAP modelers. Note that these models generally differ in other (photochemical) respects as well. Chang recomputed the percent ozone reduction from NO_x injection using these different eddy diffusivities, *but the same photochemistry*. The results for NO_x injections at 20 km and 17 km showed easily an order-of-magnitude scatter in O_3-reduction owing to this factor alone (F-15).

This type of analysis was used in CIAP to estimate "subjective" uncertainty multipliers—in the range of 0.3 to 1.5 in the stratosphere—for percent ozone reduction at various altitudes (F-16). Thus, in estimating how errors propagate through the cause/effect sequences of the NO_x-ozone-reduction chain, Schainker et al[39] show a few percent error in estimated NO_x emission rates amplifying by about an order of magnitude when "processed" through the CIAP models (F-17).

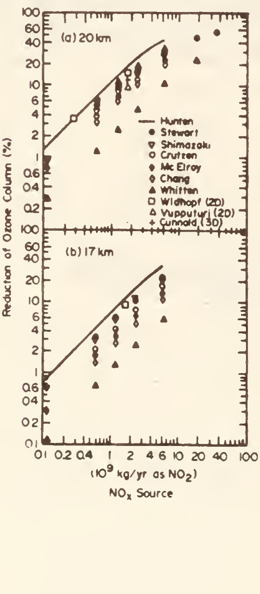
Ultimately, the CIAP and NAS-NAE studies both estimated uncertainty factors of about 3, although, as we noted earlier, the NAS-NAE study predicted about twice as much ozone reduction using Hunten's model as CIAP, which used an average of several models (see, for example, F-15). We wish to emphasize, however, that these uncertainty factors for the model results *do not include potentially much larger uncertainties in the photochemistry*. Uncertainties in laboratory-measured reaction rates commonly run a factor of two and more—an order of magnitude not being unusual for an estimated rate. Accordingly, linear superposition is inadmissible; and to assess the uncertainty in ozone-reduction estimates, model calculations have to be made corresponding to each independent combination of upper and lower error bounds for each reaction rate in the set. For a system of n independent elements (the reaction rates), each of which can exist in either of two states (the upper and lower error bounds), the total number of independent states of the system as a whole is 2^n. For the NAS-NAE reaction set, n=51 (see T-1). This means $2^{51} \simeq 2.25 \times 10^{15}$ calculations! Assuming a large computer could be dedicated to this task continuously, and assuming 50 calculations/hr, the task would take some 5×10^9 years, about the current age of the Earth.

This example dramatically illustrates why we believe a comprehensive analysis of photochemical uncertainties is hopeless at present. This point should

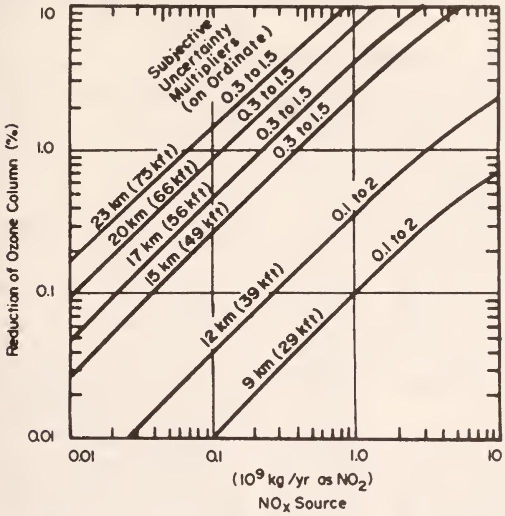
F-14 EDDY DIFFUSIVITY
Representative vertical profiles of eddy diffusivity coefficient K (z) used in CIAP 1D models. Model-to-model variations reflect uncertainties with regard to the proper description of vertical transport.



F-15 OZONE VS. NO_x EMISSION AT 20 KM
A Percent global ozone reduction as a function of uniform NO_x emission strength at 20 km as calculated by Chang for six different K (z) profiles.[37] The solid line gives Hunten's prediction.[20] Points are included for 2D and 3D models. B The same except NO_x source is at 17 km.

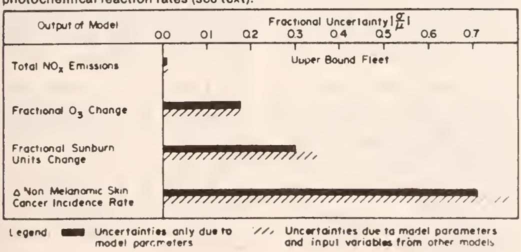


F-16 CIAP OZONE-REDUCTION SUMMARY
Percent ozone reduction from NO_x emissions at various altitudes from *CIAP Report of Findings*.[9] The "subjective uncertainty" relates to the statistical spread of K (z) in the 1D models.



be borne in mind when assessing model-based prediction of man's impact on stratospheric ozone. We recognize that uncertainties complicate any decisions with regard to SSTs, the Space Shuttle, and Freons. But it is important to place assertions regarding the SST in the popular press and even in the CIAP and NAS-NAE reports in a realistic perspective. Alarmist statements that continued use of halomethanes "could well drive life on Earth back to where it was hundreds of millions of years ago" have had their share of publicity.[31] These have led to calls for an immediate ban on Freon production "because the danger is too great to wait even a single year." In the light of our knowledge, such statements are unsupportable.

F-17 Propagation of fractional uncertainty (absolute value of ratio of standard deviation to the mean value) through the NO_x-skin cancer cascade.[38] Uncertainties in the fractional O_3 change do not reflect uncertainties in the photochemical reaction rates (see text).



Our drive to understand man's impact on the stratospheric environment has just begun—it is less than five years since Harold Johnston's SST/NO_x paper appeared in *Science*, and less than two years since Molina and Rowland's paper on Freons. We believe the tasks just ahead involve—

—Careful measurements of trace atmospheric species, particularly reactive radicals which have only been predicted by models thus far.

—Interactive development and validation of atmospheric models based on these measurements.

Only as models evolve which accurately depict a broader variety of observed features of the natural atmosphere, should we expect accurate predictions of man's impact.

Acknowledgment

We thank Professor Antonio Ferri for his constructive review of this manuscript. This work was supported, in part, by the National Aeronautics and Space Administration, under NASA grant NSG-5033.

References

1. Berkner, L. V., and Marshall, L. C., "The History of Oxygenic Concentration in the Earth's Atmosphere," *Proc. Faraday Soc. Disc.*, *37*, 122-141, 1964; "On the Origin and Rise of Oxygen Concentration in the Earth's Atmosphere," *J. Atmos. Sci.*, 225-261, 1965.
2. Chapman, S., "A Theory of Atmospheric Ozone," *Mem. Roy. Meteor. Soc.*, 103-125, 1930.
3. Johnston, H. S., "Reduction of Stratospheric Ozone by Nitrogen Oxide Catalysts from SST Exhaust," *Science*, *173*, 517-522, 1971.
4. Crutzen, P. J., "The Influence of Nitrogen Oxides on the Atmospheric Ozone Content," *Quart. J. Roy. Meteorl. Soc.*, 320-325, 1970.
5. McDonald, J. E., "Assessment of Possible SST Effects on the Incidence of Skin Cancer," paper presented at informal meeting of the Conference on the Climatic Impact of Supersonic Aviation, National Center for Atmospheric Research, Boulder, Colo., March 1971.
6. Stolarksi, R. S., and Cicerone, R. J., "Stratospheric Chlorine: A Possible Sink for Ozone," *Can. J. Chem.*, 1610-1615, 1974.
7. *Environmental Impact Statement for the Space Shuttle Program. Final Statement*, NASA Headquarters, Washington, D. C., July 1972.
8. Molina, M. J., and Rowland, F. S., "Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom Catalyzed Destruction of Ozone," *Nature*, 810-812, 1974.
9. Grobecker, A. J., Coroniti, S. C., and Cannon, R. H., Jr., "The Effects of

Stratospheric Pollution by Aircraft, Report of Findings," Doc. No. DOT-TST-75-50, National Technical Information Service, Springfield, Va., Dec. 1974.

10. Crutzen, P. J., "SSTs—A Threat to the Earth's Ozone Shield," *Ambio*, *1*, 41-51, 1972; "A Review of Upper Atmosphere Photochemistry," *Can. J. Chem.*, 1569-1581, 1974.

11. Hesstvedt, E., "Effects of Supersonic Transport Upon the Ozone Layer Studied in a Two-Dimensional Photochemical Model with Transport," *AGARD Conf. Proc. No. 125 on Atmospheric Pollution by Aircraft Engines*, 6-1—6-8, 1973; "Reduction of Stratospheric Ozone from High-Flying Aircraft Studied in a Two-Dimensional Photochemical Model with Transport," *Can. J. Chem.*, 1592-1598, 1974.

12. Chang, J. S., "Global Transport and Kinetics Model," *First Annual Report, DOT-CIAP Program*, UCRL-51336, Lawrence Livermore Laboratory, Livermore, California; Hindemarsh, A. C., and Madsen, N. K., "Simulation of Chemical Kinetics Transport in the Stratosphere," UCRL-74823, Lawrence Livermore Laboratory, Livermore, Calif., 1973.

13. Stewart, R. W., and Hoffert, M. I., "Stratospheric Contamination Experiments with a One-Dimensional Model," AIAA Paper 73-531, presented at the AIAA/AMS International Conference on the Environmental Impact of Aerospace Operations in the High Atmosphere, Denver, Colo., June 1973; "Response of Stratospheric Ozone to the Simulated Injection of Nitric Oxide," paper presented at the Fall AGU Meeting, San Francisco, Calif., 1973; "A Chemical Model of the Troposphere and Stratosphere," *J. Atmos. Sci.*, 32, pp. 195-210, 1975.

14. McElroy, M. B., Wofsy, S. C., Penner, J. E., and McConnel, J. C., "Atmospheric Ozone: Possible Impact of Supersonic Aviation," *J. Atmos. Sci.*, *31*, 287-303, 1974.

15. Whitten, R. C., and Turco, R. P., "A Model for Studying the Effects of Injecting Contaminants into the Stratosphere and Mesosphere," AIAA Paper 73-539, presented at the AIAA/AMS International Conference on the Environmental Impact of Aerospace Operations in the High Atmosphere, Denver, Colorado, June 1973; "The Effects of SST Emissions on the Earth's Ozone Layer," *Proceedings of the International Conference on Structure, Composition and General Circulation of the Upper and Lower Atmosphere and Possible Anthropogenic Perturbations*; paper presented at the IAMAP/IAPSO First Special Assemblies, Melbourne, Aus., Jan. 1974.

16. Shimazaki, T., and Ogawa, T., "Theoretical Models of Minor Constituents' Distributions in the Stratosphere and the Impact of SST Exhaust Gases," *Proceedings of the International Conference on Structure, Composition and General Circulation of the Upper and Lower Atmosphere and Possible Anthropogenic Perturbations*; paper presented at the IAMAP/IAPSO First Special Assemblies, Melbourne, Australia, Jan. 1974.

17. Cunnold, D. M., Alyea, F. N., Phillips, N., and Prinn, R. G., "First Results of a General Circulation Model Applied to the SST-NO_x Problem," paper presented at the Second AIAA/AMS International Conference on the Environmental Impact of Aerospace Operations in the High Atmosphere, San Diego, Calif., July 1974; Alyea, F. N., and Prinn, R. G., "Stratospheric Ozone Destruction by Aircraft-Induced Nitrogen Oxides," *Science*, *188*, 117-121, 1975.

18. Vupputuri, R. K., "The Role of Stratospheric Pollutant Gases (H_2O, NO_x) in the Ozone Balance and its Implications for the Seasonal Climate of the Stratosphere," *Proceedings of the International Conference on Structure, Composition and General Circulation of the Upper and Lower Atmosphere and Possible Anthropogenic Perturbations*; paper presented at the IAMAP/IAPSO First Special Assemblies, Melbourne, Aus., Jan. 1971.

19. Widhopf, G. F., "Meridional Distributions of Trace Species in the Stratosphere and the Effect of SST Pollutants," paper presented at the AGU Fall Annual Meeting, San Francisco, California, Dec. 1974; "A Two-Dimensional Photochemical Model of the Stratosphere Including Initial Results of Inert Tracer Studies," paper presented at the Fourth CIAP Conference, DOT Transportation Systems Center, Cambridge, Mass., Feb. 1975.

20. Hunten, D. M., "Stratospheric Pollution and How it Dissipates," unpublished, quoted in Ref. 9, 1974.

21. Brasseur, G., and Bertin, M., "A Theoretical Two-Dimensional Model for Minor Constituents Below 50 km," unpublished, quoted in Ref. 9, 1974.

22. Hard, T. M., "Stratospheric Trace Gas Measurements," Technical Report, Transportation Systems Center, Cambridge, Mass. May 1974.

23. Callis, L. B., Ramanathan, V., Boughner, R. E., and Barkstrom, B. R., "The Stratosphere: Scattering Effects, a Coupled 1-D Model, and Thermal Balance Effects," paper presented at Fourth CIAP Conference, DOT Transportation Systems Center, Feb. 1975.

24. *Environmental Impact of Supersonic Flight*, Climatic Impact Committee, National Academy of Sciences and National Academy of Engineering, Washington, D. C., 1975.

25. *Bulletin Trimestriel du COVOS*, Secretariat General A L'Aviation Civile, 93 Boulevard du Montparnasse, Paris, Dec. 1974.

26. Johnston, H. S., "Comments on and Extension of the Department of Transportation's Report of Findings, Executive Summary, of December 1974," Department of Chemistry, University of California, Berkeley, Jan. 1975.

27. Donahue, T. M., "*The SST and Ozone Depletion*" (letter to the editor and reply by A. J. Grobecker) *Science*, 1142-1145, 1975.

28. Crutzen, P. J., "Estimates of Possible Future Ozone Reductions from Continued Use of Fluoro-chloromethanes," *Geophys. Res. Let.*, 205, 1974.

29. Cicerone, R. J., Stolarski, R. S., and Walters, S., "Stratospheric Ozone Destruction by Man-Made Chlorofluoromethanes," *Science*, 535-537, 1975.

30. Wofsy, S. C., McElroy, M. B., and Sze, N. D., "Freon Consumption: Implications for Atmospheric Ozone," *Science*, 535-537, 1975.

31. Hammond, A. L., "Ozone Destruction: Problem's Scope Grows, Its Urgency Recedes," *Science*, 1181-1183, 1975.

32. *Fluorocarbons and the Environment: Report of the Federal Task Force on Inadvertent Modification of the Stratosphere* [*IMOS*], Council on Environmental Quality and Federal Council for Science and Technology, GPO Stock Number 038-000-00226-1, U.S. Government Printing Office, Washington, D. C., June 1975.

33. Chang, J. S., and Deuwer, W., "On the Possible Effect of NO_x Injections in the Stratosphere due to Past Atmospheric Nuclear Weapons Tests," paper presented at AIAA/AMS International Conference on the Environmental Impact of Aerospace Operations in the High Atmosphere, Denver, Colorado, June 1973.

34. Newell, R. E., "Climatology of the Stratosphere from Observations," *Proceedings of the Survey Conference on CIAP*, DOT Transportation Systems Center, Cambridge, Mass., Sept. 1972.

35. Foley, H. M., and Ruderman, M. A., "Stratospheric Nitric Oxide Production from Past Nuclear Explosions and its Relevance to Projected SST Pollution," *J. Geophys. Res.*, 4441-4450, 1973.

36. Ruderman, M. A., and Chamberlain, J. W., "Origin of the Sunspot Modulation of Ozone: Its Implications for Stratospheric NO Injection," Doc. No. JSS-73-18-3, Institute for Defense Analysis, 1973.

37. Ferri, A., "NRC and the Zero-Impact SST," (letter to the editor) *Astronautics & Aeronautics*, May 2, 1975.

38. Chang, J. S., "Simulations, Perturbations and Interpretations," *Proceedings of the Third CIAP Conference*, Doc. No. DOT-TSC-OST-74-15, DOT Transportation Systems Center, 1974.

39. Schainker, R. B., Atherton, R. W., Brennan, R. P., Lan, R. W., Patmore, J. W., and Wirschling, J. E., "*CIAP Error Variance Analysis*," Vols. 1 and 2, Doc. No. DOT-OS-40042, DOT, 1974. ■

FLUOROCARBON FILE

The ozone layer

Dr John Gribbin
is at the Science Policy Research Unit, University of Sussex

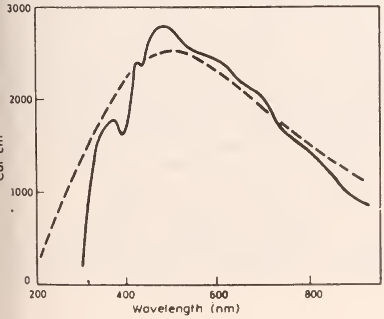
Ozone (O_3) is a blue gas with a distinctive odour familiar to anyone who has worked with electric sparks (or sniffed around the back of a colour TV set) or who has used ultraviolet radiation for sterilising in the "germicidal" band of wavelengths below 280 nm (2800 Angstroms). Ironically, in view of its association with health, vitality and fresh sea breezes—and its importance as a shielding layer in the atmosphere—ozone is toxic to humans at a concentration as low as one part per million in air.

Historically, the presence of ozone in the atmosphere in significant quantities has been suspected for very nearly 100 years. The key evidence, which became available in the early days of spectroscopy, is that the spectrum of solar radiation reaching the Earth's surface cuts off abruptly close to 290 nm (see Figure 1). The first suggestion that this cutoff is due to absorption in the Earth's atmosphere was made in 1878. Two years later the so-called "Hartley bands" of absorption by ozone, extending from about 210 to 320 nm, were discovered and linked with this atmospheric absorption. Confirmation of the presence of the associated absorption processes in the terrestrial atmosphere came in 1890 with the detection of absorption in this range of wavelengths in the spectrum of Sirius.

For more than 20 years after these discoveries it seems to have been accepted that the absorbing ozone was present in the lower reaches of the atmosphere. Attempts were made to find the upward extent of the absorption by making observations from mountain tops, but these observations still showed the cutoff in the solar spectrum, making it clear that the "ozonosphere" must be situated high in the atmosphere.

In 1917 observations of the rising and setting Sun were used to provide an indication of the distribution of ozone in the atmosphere. Because of the changes in the absorption spectrum which occur as the Sun is observed through successively longer columns of air as it sets (or shorter as it rises) it was possible 60 years ago to determine that ozone concentrates in a layer between 40 and 60 km above sea level. More modern observations, using the same technique, give better limits of 10 to 50 km, with concentration maximum at an altitude of about 25 km. This pattern has been confirmed by direct measurements from balloon-borne instruments and from spectra obtained using rockets and satellites.

Figure 1 The dashed line shows the energy output of the Sun for a surface temperature of 6000 K; the solid line shows the observed spectrum at ground level, with an abrupt cut-off at 290 nm caused by absorption in the ozone layer



The layered structure of the Earth's atmosphere and the place of the ozone layer in that structure can be seen best by considering the variation of temperature with altitude (Figure 2). The atmosphere is kept warm by the Sun. Some solar radiation is reflected away into space at the top of the atmosphere, ultraviolet and infrared frequencies are absorbed in the upper regions, but by far the bulk of this incident energy penetrates to the ground.

The warm ground provides heat to the atmosphere immediately above it, partly by conduction but mostly by radiation at infrared frequencies, which are strongly absorbed by atmospheric water vapour and carbon dioxide. In turn, the lower atmosphere re-radiates part of this energy, some returning to the surface for another trip around the cycle, and some going upwards.

Atmospheric blanket

The net result is that the surface is rather warmer than it would be if it received the same heat from the Sun but had no atmospheric blanket—the well-known "greenhouse effect". The heat also produces convection in the atmosphere, at least in the lower regions, and this plays a key role in determining the circulation patterns of weather and climate. But this convection is confined within a well-defined layer, the troposphere, by the presence of ozone in the stratosphere above.

Through the troposphere, the layer of the atmosphere in which weather occurs, the temperature falls by about 6°C for every kilometre increase in height. This fall slows down at around 10 km altitude, stops near 15 km, and from 20 km to 50 km temperature increases from a minimum of roughly −60°C at the bottom to a maximum of 0°C at the top. This warming layer—the stratosphere—corresponds closely to the layer of ozone concentration, and the presence of the ozone is related to the warming. The temperature inversion inhibits convection, and this is what keeps the weather in its place in the troposphere.

An increase in temperature must mean that energy is being absorbed, and that energy can only be coming from the Sun. The photodissociation of molecular oxygen (O_2) by ultraviolet radiation provides the mechanism for absorbing energy, but the amount absorbed at different altitudes depends on how many molecules of oxygen there are to be dissociated and on how much of the solar ultraviolet has penetrated to that layer without being absorbed in still higher layers. Consequently, the greatest concentration occurs where there is a balance between intense radiation (higher altitude) and denser oxygen concentration (lower altitude). The vagaries of the interactions also ensure that the atmosphere does not increase in temperature throughout the entire range from the base of the stratosphere upwards.

When an oxygen molecule absorbs solar ultraviolet energy and dissociates, the resultant free oxygen atoms (O) can combine with other oxygen molecules to form ozone. The second step in the ozone production process depends on there being plenty of undissociated oxygen molecules around to combine with, and it seems to take place more efficiently in the presence of other molecules, which catalyse the reaction. So the greatest concentration of ozone is found between 20 and 30 km altitude. But the free atoms

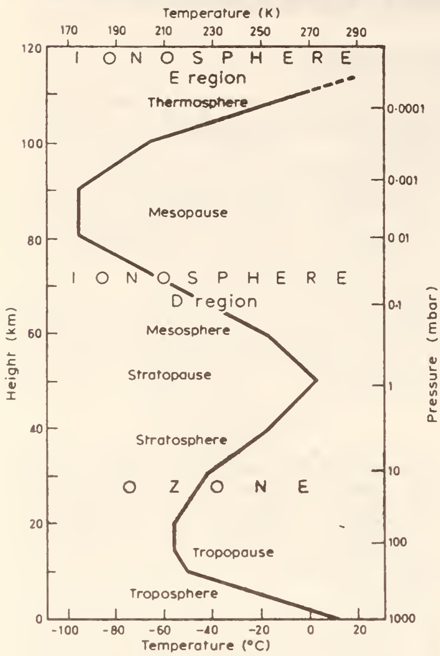


Figure 2. Variation of atmospheric temperature with height, showing layering of the atmosphere

of oxygen may also recombine as ordinary molecular oxygen, or a single atom of oxygen can react with an ozone molecule to produce two atoms of molecular oxygen. The ozone itself is unstable against photodissociation by radiation below about 300 nm (this is the very feature that revealed the presence of the ozone layer in the first place), the effect being to produce one oxygen molecule and one free atom of oxygen from one ozone molecule.

In spite of these complexities, it is fairly straightforward to calculate the equilibrium balance, which gives the expected concentration of ozone as a function of altitude, and this agrees well with observations, at least for altitudes above 10 km. Because the pattern of reactions is fairly complex, the way in which ozone concentrations vary is not always obvious—this is one reason why it is very difficult to assess the effect of man's polluting activities on the ozone layer.

Ozone sinks

According to the US National Academy of Sciences report, *Environmental Impact of Stratospheric Flight*, published earlier this year, there are three "fairly easily identifiable sinks of ozone". These are the Earth's surface, which is estimated to destroy about 1 per cent of the ozone produced globally; the reaction between oxygen atoms and ozone molecules (17 per cent); and breakdown of ozone by hydroxyl and hydroperoxyl radicals (11 per cent). Thus, "about 70 per cent of the ozone formed is unaccounted for by these sinks".

Because of the catalytic cycle of ozone destruction by nitrogen oxides, "within the uncertainty of the observed NO and NO_2 distributions, the NO_x system is capable of destroying 70 per cent of the ozone produced between 0 and 45 km" and it appears that this system is the most important sink for ozone in the stratosphere, and is therefore largely responsible for maintaining the balance between ozone generation and its destruction.

Variable equilibrium

Even the time taken for equilibrium to be reached if the balance is disturbed depends strongly on altitude. Although it only takes a few minutes to reach equilibrium at altitudes above 50 km it can take several days for the region below 30 km. Because of this, the lower region is never really in equilibrium, but is disturbed by the meteorological circulation. As the affected layer is also the region of greatest ozone concentration, ground based observers looking upward through the whole ozone layer see a strong correlation between changes in ozone concentration and meteorological changes in circulation and weather patterns. More obviously, the change of solar input with latitude and with the seasons affects the ozone concentration throughout the atmosphere; less obviously, however, even though ozone is produced by sunlight there is no tendency for it to go away at night.

The surprising observation that ozone concentration tends to increase slightly at night emphasises the dangers of drawing "obvious" conclusions about how other factors will affect the layer. The probable reason for this increase is that at altitudes above 40 km the equilibrium balance is shifted away from ozone by the presence of solar ultraviolet radiation, so that when the radiation is absent there is a tendency for ozone to persist. At lower altitudes there would be a tendency for ozone concentration to decrease at night—but as it takes days to reach a new equilibrium at those altitudes there is no chance for the effect to become noticeable.

Although ozone is mixed downwards into the troposphere in very small quantities, it is soon destroyed in the low atmosphere, and is only found in measurable quantities at the surface of the Earth in photochemical smog.

Above the stratosphere, from 50 to 80 km altitude is the mesosphere, another layer in which cooling dominates. The minimum mean atmospheric temperature of any layer (about −100°C) is reached at the top of the mesosphere, and from there on outwards temperature increases monotonically through the thermosphere. At these altitudes the heating mechanism is again primarily dissociation of oxygen molecules by solar radiation, but the shortage of molecules and the energy of the radiation ensure that no ozone is produced; rather, the absorption of energy goes a stage further than dissociation of molecules, with at least half the oxygen atoms produced being energised into an excited state. There is increasing ionisation at higher altitudes, and greater numbers of free electrons, so that the whole region above the stratosphere is also known as the ionosphere, subdivided into three layers (D, E and F) defined by the degree of concentration of free electrons. The structure of the ionosphere varies according to the input of energy from the Sun, and is powerfully affected by the roughly 11-year cycle of solar activity.

In a sense, the top of the thermosphere is at the temperature of interplanetary space, 1000°C or more, but at such low densities the concept of temperature is no longer very useful. By about 500 km the atmosphere is so tenuous that collisions between its component molecules and atoms are so rare that it is meaningless to regard it as

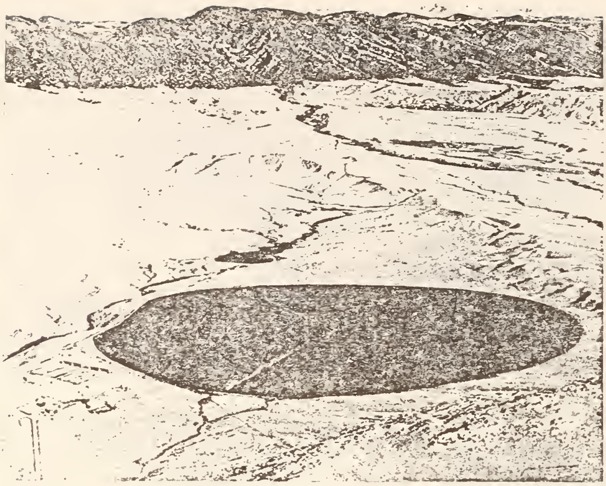
FLUOROCARBON FILE

Figure 3. Average global distributions of total ozone (in milliatmosphere-cm)

a continuous gas, and this is the point above which the components can leak away into space (the exosphere). At such altitudes, magnetic effects become more important for the ionised gases (or plasma), and the region where they interact with the Earth's magnetic field to form the radiation belts and magnetosphere forms the outer boundary of the atmosphere for all practical purposes.

Although the ozone layer is of particular importance to land-based life on the Earth, it is only one part of an atmosphere in which many components are balanced. Ozone is constantly being produced and destroyed by the interactions involving sunlight, and it is misleading to think of it as a finite resource, like oil, which can be destroyed once and for all. What could happen is that the balance of the set of equilibrium reactions which maintain the layer may be shifted, either in favour of less ozone or in favour of more (which could be equally damaging).

Like the ionosphere, the ozone layer is affected by the solar cycle of activity, and it is debatable whether Man's effects are as large as natural variations; there certainly must be a very stable balance in favour of such a layer for it to have persisted for the 3000 million years during which life has been releasing oxygen into the atmosphere, or even the 400 million years for which life has existed on land.



Holland Dreves Reilly, Inc., photo

Land and food: An appraisal

A. E. HANNAH

PRESERVATION of land for food production in the more favorable climatic areas of the world is one of the urgent challenges facing the community of nations as it develops plans to produce food in adequate quantities for the world's people.

First, we must define what is meant by today's food challenge and what relation it has to future food production. If we assume that the world's people will be fed by providing adequate supplies of traditional foods, then we may face the dire prediction of Thomas Malthus, who prophesied in 1789 that population would overtake food production and the world would end in disaster. But if we assume that the real challenge is to ensure an adequate supply of nutrients — proteins, starches, and fats — whether in simulated or natural form, then the world faces a much different challenge with greater possibilities for success.

A. E. Hannah is assistant deputy minister of the Food Systems Branch, Agriculture Canada, 849 Sir John Carling Building, Ottawa, Ontario K1A OC5. This article is an adaptation of the paper he presented in August at the Society's 30th annual meeting in San Antonio, Texas.

In either case there is a need and a major challenge to develop the political will to organize resources for food production within deficient areas, and to ensure adequate distribution and marketing systems so that we can truly achieve a more equitable distribution of resource use and nutrient availability. These and many other decisions will have a major influence on the adequacy of available soil and climatic resources.

Temperature, moisture, soils, and topography have been described as the four frontiers of agriculture because of their importance in determining the absolute limits of cultivability (*12*). Agricultural settlements located near or at these limits are restricted in their choice of crops or food animals since the physical requirements vary from one species to the other. Climatic variations can be particularly limiting in such frontier areas as northern Canada, the fringe areas of deserts in Africa, and the monsoon floodplains of Asia. A small change in any one climatic factor may mean the difference between acceptable crop production and crop failure.

The Soil Resources Available

The world's land surface is a fixed area of about 33 billion acres. In 1967 the U. S. President's Science Advisory Committee characterized about 24 percent of this land area as potentially arable. However, more than half of this potentially arable land consisted of highly weathered, strongly leached soils in the tropical rainforests; areas of dry tropical soils requiring irrigation; and soil types considered uneconomic or unsuitable for agriculture under today's conditions.

The United Nations Food and Agriculture Organization assessment of 1961 (7) seemed more realistic in suggesting that 10 percent of the world's land area has soil and climatic conditions suitable for agriculture production as we know it today (Table 1). Another 2 percent has potential for conversion to agricultural production by the year 2000.

The western world has about 45 percent of the potentially arable land and less than 20 percent of the world's population. By the year 2000, if population projections are correct, the western world will have more than one acre of food-producing land for each person. Meanwhile, eastern countries will have to achieve a productivity capable of feeding four to five persons per acre—more than double their 1960 food production (3). To achieve adequate nutrition with present crop species, much of the land in Asia will have to provide food for six or more people on each acre cultivated. To attain this high level of productivity, these lands will have to produce more than is presently obtained from the intensively managed lands in Japan.

To counterbalance these statistics, an FAO survey (7) determined that

only 45 percent of the arable land available in the developing countries was used for crops in 1962, which provides for a potential increase in locally produced foods in the future. On a world basis, only 3.4 billion acres of the 7.8 billion acres of land that could be used to produce food crops and raise livestock are presently being used (*2*).

The world's land base therefore appears adequate to feed many more people than are now on the planet Earth. However, many other factors must also be considered.

The land's capacity to provide food is determined by the inherent productivity of the soil and the use to which the land is allocated. For example, in Australia, under highly favorable conditions, sufficient rice can be grown on one acre of land to meet the annual caloric needs of 18 to 20 people. In North America, with cooler climates and people with a predilection for meat, dairy products, and fruit, the effective land productivity requires two acres for one person.

Table 2 gives the average productivity for the world's major food and feed grains. Further productivity increases are possible with more intensive fertilizer use and the application of new technology.

The western world's increased agricultural productivity has been based on a strong industrial sector, which provides substantial inputs for the agricultural and food sectors. A comparable green revolution in the developing countries will demand comparable resources. Economic, social, educational, and technological developments are requisite to sustaining agricultural productivity increases. Failure to develop these concurrent policies will render the technological advances inoperative.

There are many conflicting demands that compete with food production for agricultural land (*10*). These include such things as urban developments, space for parks, recreation areas, water supply storage, production of construction materials, provision of fuel, production of fibers for clothing, and many of the necessities of life required for man's well-being. Therefore, development of intelligent land use policies is as important to future food production as policies for research, trade, health and welfare, and similar policies being developed to make a better way of life for mankind.

Influence of the Climatic Resource

Since grains are a critical part of the world food supply, the so-called world food crisis has aroused considerable public concern about our ability to continue to produce these crops. Numerous reports have appeared about the effects of weather and climate on crop production. The droughts in the southern Sahara, East Africa, Northwest India, and midwestern United States; torrential rains and floods in the United States and the Philippines; as well as other weather aberrations have prompted a number of scientific and popular articles suggesting that the world is experiencing major climatic changes.

Climate—the variability of weather over long periods of time and over large regions—is much more stable than short-term fluctuations in weather. There was an upward trend in the mean annual temperature of about 3°F in the middle latitudes from the latter part of the seventeenth century until about 1940. The temperature fluctuation from decade to decade was on the order of 4°F. Since 1940, there has been a gradual cooling trend in the northern hemisphere (*1*). This cooling trend, some people argue, has disrupted world wind patterns, blocking monsoons from extensive interior land areas.

Temperature declines will reduce the frost-free period and for many crop species will result in longer periods of time to reach maturity, thus endangering the successful harvest of some crops. Any temperature decline therefore will have a tremendous influence on the areas that can be cropped as well as the species that can be grown, particularly in the frontier areas. For example, in Canada's prairie areas, a 2°F decline in temperature norms would seriously reduce wheat acreage, while a 5°F decline would have severe consequences for a relatively short season crop, such as barley (*11*).

Thermal conditions must therefore be weighted equally with water conditions in evaluating agricultural environments. In Canada and the USSR, for example, the northern margin of significant agricultural settlement corresponds to a line of 120 to 130 degree-months — the sum of mean monthly temperatures over 32°F for the summer months. The 200-degree-month threshold determines the northern limit of the zone in which corn will mature as a grain crop.

Most world grain is produced in the middle latitudes, where summer temperatures average between 70° and 75°F. Production in lower latitudes is limited by high summer temperatures. In higher latitudes, the limit is the short growing season. However, within this area, the highest grain yields usually occur in summers of lower than normal temperatures. Cooler weather often is associated with higher rainfall and more effective use of moisture. It also permits greater storage of photosynthate.

The moisture factor in agriculture cannot be assessed solely on the basis of annual precipitation. Temperature and distribution of moisture over the growing season have a major influence on crop yields. Moisture availability—in adequate quantities at the right time—is essential for maximum yields of the crop varieties that gave rise to the green revolution.

Table 1. World land use (000 acres).

Region	Total Area	*Agricultural Area* Arable Land	*Agricultural Area* Permanent Meadow and Pasture	Forest and Woodlands	Other Land
Africa	7,490,324	517,066	1,969,570	1,495,247	3,508,441
North and Central America	5,551,242	675,705	871,170	1 941,194	2,063,172
South America	4,405,904	214,767	950,809	2,215,557	1,024 771
Asia	6,806,190	1,190,391	1,325,876	1,403,562	2,886,362
Europe	1,218,648	356,568	224,031	347,188	290,860
Oceania	2,102,722	115,664	1,156,774	209,776	620,508
USSR	5,535,785	574,358	927,400	2,248,714	1 785 313
Canada	2,465,194	108,152	61,520	1,094,925	1,200 596
USA	2,313,711	472,109	603,630	722,688	515,284
World	33,110,814	3,644,519	7,425,630	9,861,238	12,179,427

Source: FAO *Production Yearbook*, vol. 27, 1973.

The lower limit of precipitation under which dryland farming can be practiced appears to be around 10 or 11 inches a year. Irrigation frequently is practiced in areas of much higher annual preciptation to ensure greater uniformity in moisture supply over the growing season. Therefore, supplemental water is as important in stabilizing crop yields as it is in increasing yields.

Climate is a major factor in the broad regional productivity gradients for arable land resources. Spatial variations in the yield of individual crops and overall crop composition closely relate to the combined effects of moisture and temperature. Production plans to meet world food needs must necessarily consider these two basic factors since the factors will be the limiting or enabling factors in agricultural production.

A major problem throughout the world is the diversion of agricultural land in more favored environmental areas to urban and other uses required for housing, recreation, etc. (*10*). Future land use plans must give priority to maintaining and preserving all productive lands for agricultural and food uses, whether required immediately or in the future. Parks, recreation, or other uses compatible with agriculture must be encouraged as interim measures to protect productive land for the longer term.

Man's activities tend to influence climate in local areas as well as globally. There are at least three ways, for example, in which pollution might become a factor in climatic change:

1. As a result of burning fossil fuels, carbon dioxide is accumulating in the atmosphere, where it has a warming effect.
2. Smoke particles and dust screen out the sun's energy.
3. Lead or other particles that provide nuclei for precipitation increase total precipitation or disrupt normal precipitation patterns (*9*).

Carbon dioxide is believed to have a warming effect on the earth's temperature by creating a greenhouse effect. It allows transmission of the sun's energy as short rays but absorbs the longer rays re-radiated from the earth's surface. The release of carbon dioxide is increasing at a rate of about 0.2 percent a year due to burning fossil fuels. It is estimated that an increase of 10 percent in carbon dioxide would increase the earth's temperature between 0.5° and 0.6°F.

Dust, smoke, or other particulates screen out the sun's energy by reflecting light rays. However, many of these particulates soon settle or wash out of the atmosphere in rainfall. Therefore, programs designed to reduce smoke or similar pollution will ameliorate this factor in climatic change. Mechanisms to reduce lead particles and similar materials going into the atmosphere will, in turn, prevent excessive precipitation and the cooling effect associated with it, since these particles provide the nuclei around which water droplets form.

Human activities significantly affect climate on a local basis as well. Irrigation contributes to increased precipitation locally when water evaporates from irrigated fields. In some midwestern states, it is estimated that 10 percent of the precipitation occurring locally is due to evaporation from irrigated areas.

Pollution around cities can increase local precipitation. Cities also tend to be a few degrees warmer due to the greater release of energy from the burning of fossil fuels.

Vegetation tends to increase humidity, and local climatic changes will occur when man removes forest or grassland, exposing soil to the sun's rays and causing greater evaporation.

Although man's activities have caused climatic changes in local areas, there is little likelihood that such activities have contributed to the long-term trend in temperature or other climatic changes.

The World Food Market

The adequacy or inadequacy of land and climatic resources to meet world demands for food will depend largely on market characteristics and the ability of governments to provide monetary and distribution systems that permit an equitable use of resources to meet man's needs (*8*). The world market presents a complicated demand picture that, in part, is characterized by the following factors:

1. North America cannot hope to feed the world with surplus production from its highly efficient, mechanized farms.
2. Food exporting countries cannot continue to carry emergency stocks or over-produce to supply food aid at the expense of a lesser return on investment, which, in essence, provides periodic bargains to food importing countries without compensating reductions in goods we must buy.
3. Food aid in the real sense should only be used as emergency aid or to buy time while a country develops its own food resource base. Used in any other context, it will only delay development of the world's food production capacity.
4. About 60 percent of the people

Table 2. World production of food grains and feed grains, 1973.

	Wheat		Rice		Corn		Barley	
Region	Harvested (acres) Area	Production (short tons)	Area Harvested (acres)	Production (short tons)	Area Harvested (acres)	Production (short tons)	Area Harvested (acres)	Production (short tons)
Africa	21,896,550	9,394,000	9,623,120	7,768,200	39,954,720	18,902,400	12,643,930	4,006,200
Asia	184,854,800	97,075,000	300,794,130	323,515,500	66,964,170	53,630,500	57,551,000	32,712,900
Europe	65,417,950	90,361,700	1,020,110	2,190,100	29,479,450	50,085,200	43,936,360	62,538,300
Oceania	23,054,980	13,634,500	148,200	369,600	202,540	345,400	4,905,420	2,989,800
USSR	155,992,850	120,762,400	1,141,140	1,941,500	9,956,570	14,537,600	72,585,890	60,548,400
South America	17,146,740	10,879,000	14,424,800	11,341,000	42,145,610	31,014,500	2,571,270	1,399,200
Central America	1,472,120	2,300,100	1,701,830	1,659,900	24,023,220	13,399,100	595,270	355,500
North America								
Canada	24,349,260	18,103,800	—	—	1,309,100	3,093,200	11,952,330	11,245,300
USA	53,850,940	51,234,700	2,168,660	4,631,000	61,732,710	157,678,400	10,524,670	10,168,400
World	547,806,130	413,805,700	331,019,520	353,417,900	275,768,090	342,686,300	217,266,140	185,944,000

Source: FAO *Monthly Bulletin of Agricultural Economics and Statistics*, 1974, vol. 23, no. 10/11.

n the world today depend directly on subsistence agriculture for the basic necessities of life. At present, these people cultivate 40 percent of the world's arable lands. To increase the productivity of these lands will require substantial social and cultural changes concurrent with the introduction of technological improvements. Such policies must be planned in the context of the cultural and social conditions of the country concerned.

5. Affluent people in the world have a cultural and social attachment to low-efficiency forms of food and a tendency to overconsume and waste. Those that can afford the tariff eat primarily for status and recreation. Nutrients, as necessities of life, are only of secondary importance. North Americans and others may have to abandon such inefficient food habits if we are to meet our responsibilities in a hungry world.

6. Inefficiencies in world food distribution systems must be eliminated if land resources are to be used effectively for world food production. Such problems are particularly severe in the developing countries, but they are by no means limited to these areas.

7. In many cases, domestic policies influence the incentive in the marketplace that is required to bring forth food and fiber supplies. Some countries maintain an inefficient agriculture for a variety of reasons, the most prominent being national defense. In other words, free market forces are seldom allowed to operate completely in world food markets. Efficient food-producing areas must compete in an atmosphere of controlled markets and usually lower product prices. Under such restrictions, financial resources tend to move to more remunerative sectors of the economy, leaving agriculture with inadequate investment.

The above factors illustrate the complexities that the community of nations must face in planning a world food program. The problems are not unsolvable, but a great deal of understanding and flexibility in developed and developing nations alike will be needed to achieve the objective of providing adequate nutrients for all. For Canada and the U. S., both large food exporting countries, the problem of satisfying the domestic market while meeting export commitments will require changes in traditions and lifestyles, perhaps even a reduction in living standards.

A Look to the Future

The technology for much greater nutrient production is available. Used effectively, it could support a much larger population than now exists.

Among the resources available to mankind to provide the basic food requirements are the following:

1. *Land and climate.*

2. *Energy conversion system.* This is perhaps the most critical resource at present. The conversion of nutrients and water in soil to food can only be accomplished through photosynthesis, that is, green plants using the sun's energy to provide nutrients for human and animal use. Science has not been able to duplicate this process, the essential link in the food system. Therefore, man must preserve an environment that will permit green plants to flourish so our food base can be maintained and expanded. The technology is available to maintain such a balance in a fragile ecosystem.

3. *Science and technology.* Research is the mechanism by which productivity can be increased. To achieve the ultimate objective, world governments must ensure a greater investment in research, particularly in the food area. Sea farming, single-cell protein production, and use of simulated meat products from plant proteins are all possibilities for increased food production that research has made possible. Research can also develop possibilities for the future.

4. *Managerial capability.* Surplus food production in the past tended to limit incentives in the agricultural and food sectors. As a result, managerial talent moved to other sectors of the economy at a time when some nations found it cheaper to buy food than to produce it. This situation cannot exist if we are to maintain managerial talent in the food system.

With the above resources, food production per se need not be a problem. However, population control will be essential if the production capability is to keep pace. We must also consider the impact of population concentrations competing for agricultural land relative to other uses of land: recreation, housing, roads, and those many other aspects of living required for man's well being. Nations must plan their use of land to harmonize these needs with food needs.

Mass starvation need not be an imminent threat in our lifetime. With the exception of local situations, there is an adequate land base in favorable climatic zones to ensure nutrient needs if proper marketing and distribution patterns are achieved, if available technology is used, and if population control is achieved. The immediate challenge is to help food-deficit countries achieve an adequate level of nutrition by increasing their own food production, which can be supplemented by food from exporting countries.

Economic productivity must also be encouraged in third world countries so an expanded trade base is possible. The developed nations must agree to expanded trade with developing countries so that items not produced locally can be purchased to provide a more complete balance of their needs.

The real problem is not technological, but rather ensuring the required political will and understanding to achieve equity of resource use throughout the world.

REFERENCES CITED

1. Baier, Wolfgang. 1975. *Weather and world food situation.* Canada Agriculture: 15-17.
2. Blakeslee, L. L., E. O. Heady, and C. F. Framingham. 1973. *World food production, demand and trade.* Center for Agr. and Rural Development, Iowa State Univ., Ames.
3. Clark, J. S. 1974. *Land for life, land for living.* Agrologist 3(3): 11-14.
4. Economic Research Service, U. S. Department of Agriculture. 1974. *The world food situation and prospects to 1985.* Foreign Agr. Econ. Rpt. 98. Washington, D. C. 90 pp.
5. Economic Research Service, U. S. Department of Agriculture. 1975. *The food and fiber system—how it works.* Agr. Information Bul. 383. Washington, D. C.
6. Field, N. C. 1968. *Environmental quality and land productivity: A comparison of agricultural land base of the USSR and North America.* Canadian Geographer 12(1): 1-14.
7. Food and Agricultural Organization, United Nations. 1969. *Provisional indicative world plan for agricultural development.* New York, N. Y.
8. Poleman, T. T. 1975. *World food: A perspective.* Science 188: 510-518.
9. Thompson, L. M. 1975. *Weather variability, climatic change, and grain production.* Science 188: 535-541.
10. Williams, G. D. V. 1973. *Urban expansion and the Canadian agroclimatic resource problem.* Greenhouse-Garden-Grass 12(1): 15-25.
11. Williams, G. D. V 1974. *Physical frontiers of crops: the example for growing barley to maturity in Canada.* Studies in Geog., Monograph 1 Univ. Alberta, Edmonton. pp. 79-91.
12. Zimmermann, E. W. 1951 *World resources and industries.* Harper and Brothers, New York, N. Y. 832 pp. □

CRS-302

EXECUTIVE SUMMARY

Upper Atmospheric Research Program

December 1975

NASA
National Aeronautics and Space Administration

UPPER ATMOSPHERIC RESEARCH OFFICE
OFFICE OF SPACE SCIENCE
WASHINGTON, D. C. 20546

CONTENTS

INTRODUCTION

The NASA Upper Atmospheric Research Program has been created to develop a better understanding of the physical and chemical processes occuring in the upper atmosphere, with immediate emphasis on the stratosphere. The stratosphere is an almost cloudless and relatively quiescent region of Earth's atmosphere that is especially susceptible to contamination. The stratospheric physics and chemistry are extremely complex, and their study has become increasingly significant in view of the possible perturbing effects caused by natural and man-made activity. The NASA goal is to determine the normal composition of the upper atmosphere with emphasis on understanding the dynamic processes occurring and perturbation resulting from both natural and man-caused events. The problems of upper atmospheric pollution are believed to be of such concern that immediate attention is being given to assessing the degree, cause, and effect of ozone reduction.

A GROWING AWARENESS

In 1971, only a few scientists had expressed concern that man-made material released at the Earth's surface or in the lower atmosphere could ultimately reach the stratosphere

and have far-reaching consequences for humanity. However, their concern was sufficient to awaken some citizens to the imminent dangers of pollutants in the stratosphere which could cause a reduction in the ozone that shields the Earth's biosphere from the harmful components of solar ultraviolet radiation. Without this protective shield of ozone, life on Earth, as we know it, would not have developed.

The first Federally sponsored concentrated study of pollutants in the stratosphere was by the Department of Transportation (DOT) in 1972. The Climatic Impact Assessment Program (CIAP) emphasized the biological and climatic effects of ozone reduction resulting from subsonic and supersonic aircraft. It was terminated in 1974, with the issuance of six monographs describing the results of the study (Ref. 1). NASA initiated a low-level program in 1973 to assess the environmental effect of Space Shuttle operations. In 1974, the first scientific paper was published (Ref. 2) raising the issue of possible harmful effects of discharges into the atmosphere of chlorofluoromethanes (CFMs) principally fluorocarbon-11 (F-11), $CFCl_3$) and fluorocarbon-12 (F-12, CF_2Cl_2). This article was followed closely by others (Refs. 3, 4) on the oxides of hydrogen (HO_x), oxides of nitrogen (NO_x) and oxides of chlorine (ClO_x), and their roles in

atmospheric chemistry. These papers stressed the possibility that fluorocarbon propellants used in some aerosol containers can cause a significant reduction in stratospheric ozone.

CONCERN AND ACTION

A national concern was soon developed. Many hearings were held in both Houses of Congress and several bills proposing action on fluorocarbon control were introduced. The NASA Authorization Act of FY 1976 provides for NASA to develop and carry out a comprehensive program of research, technology, and monitoring of the upper atmospheric phenomena to provide an understanding of and to maintain the chemical and physical integrity of the Earth's upper atmosphere.

The act provides that NASA, in cooperation with other Federal agencies, arrange for participation by the scientific and engineering communities of both the nation's industrial organizations and institutions of higher education in planning and carrying out research, in developing necessary technology, and in making necessary observations and measurements of the stratosphere. Also, NASA is instructed to make every effort to enlist the support and cooperation of appropriate scientists and engineers of other countries and international organizations.

ASSIGNMENT WITHIN NASA

NASA's efforts in upper atmospheric research had been carried out rather independently in each of its four major program offices. Recognizing the need to better focus NASA's stratospheric efforts, the Associate Administrator assigned the overall responsibility for NASA's research activities to the Office of Space Science (OSS). With its new charter, the OSS reviewed the ongoing work within the agency and negotiated the transfer or integration of the relevant activities into a coordinated program.

Recently, the Office of Upper Atmospheric Research (OUAR) has been established within OSS to organize, develop, and implement the Upper Atmospheric Research Program. The Director of OUAR reports to the Associate Administrator for Space Science and is responsible for the program plan and its modifications.

NASA'S APPROACH

NASA recognizes the need for both a long- and short-term program in upper atmospheric research. The long-term objective is to develop an organized solid body of knowledge regarding the physics, chemistry, and transport processes occurring in the stratosphere and other regions of the upper

atmosphere. These objectives are being pursued through a Basic Science Subprogram in which data are acquired from a coordinated effort in field measurements, laboratory experiments, and theoretical studies.

The short-term objectives address current problems that have been identified as having the potential to cause harmful effects in the stratosphere. These are:

(1) Space Shuttle Operations. Two engine exhaust products, HCl and Al_2O_3, from the Space Shuttle's solid-rocket motors could undergo reactions leading to stratospheric ozone reduction and changes in radiation processes.

(2) Chlorofluoromethanes (CFMs), or Fluorocarbons. Widely used as refrigerants and aerosol propellants, the CFMs are postulated to diffuse into the stratosphere where they are photodissociated into chlorine atoms that can catalytically destroy ozone.

(3) Aircraft Operations. Subsonic and supersonic aircraft emit large quantities of oxides of nitrogen and particulate matter that could adversely affect the ozone chemistry and radiation transmission in the stratosphere.

(4) Other Chemicals. Chemicals such as bromine compounds, which have been identified as potential ozone destroyers, are also pursued through a coordinated effort of field measurements, laboratory experiments, and theoretical studies.

These short-term objectives have been incorporated into an Assessment Subprogram with established schedules and times for completion. While Basic Science Subprogram data are rather general, Assessment Subprogram data are more specific. The two are strongly coupled and any separation is somewhat arbitrary.

Basic Science Subprogram

The Basic Science Subprogram is envisioned, at a minimum, as a 5 to 10-year program. The long time period is dictated primarily by the long lead time necessary to develop the instrumentation and measuring platforms for the essential field measurements.

NASA plans to develop a reservoir of scientific knowledge on the upper atmosphere by assisting in the establishment and concentration of an institutional base for conducting atmospheric research. The base will be composed primarily of talent from universities, but will provide for sufficient

support from within NASA to ensure competent direction of the effort and application of research results.

NASA proposes to support several centers for atmospheric research. More than half of the centers will be established at major universities as Institutes for Atmospheric Research; two will be established at NASA organizations, at the Goddard Space Flight Center and at the Jet Propulsion Laboratory. This proposed institutional base is capitalizing on the interest and capability already established in the scientific community.

The focus at the Centers for atmospheric research will be to:

(1) Determine the natural background concentrations of trace constituents, which play a major role in stratospheric chemistry. Ozone, a trace constituent, is believed to be responsible for the increase of temperature with height, the phenomenon that distinguishes the stratosphere from the troposphere and mesosphere. Other trace constituents are believed to control the ozone level in the stratosphere.

(2) Determine the nature of the dynamic processes, including transport, in the stratosphere, which

must be understood if realistic assessments are to be made of man-made perturbations. The net dispersion of trace constituents is dependent on the cumulative effects of various types of atmospheric motions. These motions have been classified as: (a) mean meridional circulations, (b) quasi-stationary waves, (c) transient disturbances related to remnants of tropospheric disturbances, (d) gravity waves, and (e) small-scale turbulence. These various types of motion do not necessarily operate independently of one another. For example, the stratospheric mean meridional circulations (circulation remaining after averaging all motions around a latitude circle) seem to be induced primarily by the action of the quasi-stationary waves.

(3) Determine what controls the ozone variability in the stratosphere. The natural variability in ozone makes it extremely difficult to detect man-made influences on the amount of total ozone in the stratosphere. More data on ozone trends in the stratosphere must be acquired before a complete understanding of its variability is acquired.

76-572 O - 76 - 21

(4) Determine the minimum detectable change in average stratospheric ozone concentration. It is only through a long-term program of ozone observations that a realistic determination can be made of the minimum change in average ozone that can be detected using all available measuring systems.

(5) Determine the sources and sinks of gases of stratospheric significance. It is essential that a strong program in laboratory experiments be maintained in order to identify and study possible chemical reactions that could be sinks for stratospheric pollutants.

In the implementation of the Basic Science Subprogram, field measurements and laboratory experiments will supply the information necessary for model development and verification, which are part of the theoretical studies. Models, once they are developed and verified, will be the primary tools in making the necessary assessments of pollutants in the stratosphere.

The theoretical study phase also includes data analysis, primarily data obtained from stratospheric field measurements, and the calculation of spectroscopic constants needed in the interpretation of data from the use of spectroscopic

techniques in the field measurement and laboratory experiment phases.

The field measurement phase is designed to obtain fundamental information about the stratosphere. Measurements of the natural stratosphere are necessary and are stressed to establish a baseline for future stratospheric perturbations. Field measurements also include the investigations of transitory perturbations such as those caused by rocket plumes and stratospheric flights.

Field measurements utilize all major platform systems: ground-based instruments, aircraft, balloons, sounding rockets, and satellites. A long-range goal of the field measurement phase is the development of a global monitoring system capable of detecting all major trace constituents. Other measuring platforms will be used to develop such a system and to provide fundamental information for the Basic Science Subprogram.

Laboratory experiments are a key element of the Basic Science Subprogram and are expected to lead to the development of new instrumentation and measuring techniques.

Assessment Subprogram

The short-term (3 to 5 years) Assessment Subprogram addresses the stratospheric effects of Space Shuttle

operations, aircraft operations, CFMs, and other chemical pollutants. For the Space Shuttle, the impact studies are aimed at:

(1) Determining the effect of HCl on stratospheric ozone. Hydrogen chloride is converted to active chlorine atoms by reaction with OH and O and by photodissociation. These chlorine atoms react with the oxygen atoms to regenerate atomic chlorine. How effective this process is in destroying ozone must be determined before a realistic assessment can be made.

(2) Determining the role, if any, of Al_2O_3 particles in stratospheric chemistry: their distribution and reactivity. Preliminary experiments show these effects to be small, but NASA will continue to support measurements in this area.

(3) Identifying the effect on the stratosphere caused by the vertical distribution of effluents.

(4) Determining the overall effect of 60 Shuttle launches per year on stratospheric chemistry and physics.

(5) Determining the degree of uncertainty of the predictions.

For aircraft operations in the Assessment Subprogram, NASA supports the Federal Aviation Administration (FAA), which has overall cognizance for aircraft pollution, by:

(1) Studying the chemistry and physics of the oxides of nitrogen and of hydrogen along with particulate matter through a program of field measurements, laboratory experiments, and theoretical studies. The goal is to contribute to a better understanding of the impact of aerospace operations in the stratosphere and assess the efforts.

The approach chosen to study the effects of the CFMs is to:

(1) Determine whether the CFMs are reaching the stratosphere. This is being done by measuring the vertical profile of the CFMs. Recent measurements show that the CFMs are reaching the stratosphere at concentrations and vertical distributions very close to those predicted.

(2) Determine the vertical concentration profiles of CFMs. Two methods are being used: (a) an infrared spectroscopic method using absorption spectra of

F-11 and F-12, and (b) a grab-sample method in which air samples are captured and analyzed in the laboratory using highly sensitive techniques such as gas chromatography and mass spectroscopy.

(3) Determine whether CFMs are being dissociated in the stratosphere. One method is to differentiate between the vertical profiles of F-11 and F-12. Because F-11 has a higher photolysis rate than F-12, its concentration above 30 km should drop more rapidly than F-12. An initial observation of this effect has been made by scientists at the National Center for Atmospheric Research (NCAR). NASA will continue to support measurements of the CFMs in the stratosphere aimed at providing more information on the photodissociation process.

(4) Determine whether the released chlorine is reacting with ozone. A measurement of the Cl:ClO ratio will help to answer this question. Spectroscopic techniques in the ultraviolet, infrared, and microwave regions will be used along with resonance fluorescence techniques to determine Cl and ClO in the stratosphere.

(5) Distinguish between the atomic chlorine from the CFMs and that from other chlorine compounds in the stratosphere. Detection of the residue molecule from the CFM dissociation is one indication that the CFMs are producing chlorine atoms in the stratosphere. Infrared spectroscopy is being used to detect CF_2O and HF. A filter-capture method is also being used to measure HF in the stratosphere.

(6) Identify the sources and sinks for the CFMs and other chlorine compounds. NASA continuously supports atmospheric measurements using all available techniques to identify sources and sinks of all trace stratospheric constituents.

NASA will also evaluate other chemical pollutants in the stratosphere to determine, through theoretical studies and laboratory experiments, the potential immediate threats of other discharges of pollutants into the upper atmosphere, and to initiate appropriate research efforts. Atmospheric sources identified as potential perturbations are agricultural burning, fertilizer usage, paper pulp bleaching, sewage treatment, and other industrial activities. These are to be

investigated along with the natural sources from volcanic activities and oceanic processes.

The immediacy of the atmospheric pollution issue requires concentration on the chemicals and reactions that have been identified as potential reducers of stratospheric ozone. Schedules for critical field measurements and laboratory experiments have been carefully developed to meet essential reporting dates. A timetable has been established to meet specific accomplishment milestones for assessing the Space Shuttle impact, aircraft impact, and CFM effects.

Determination of the impact of Space Shuttle Operations is scheduled for May 1976. At that time, data will have been collected and analyzed to allow a tentative decision to be made whether or not to use the existing propellant in the solid-rocket motors or to change to an alternate. Following this decision, the environmental impact statement process will begin, culminating in a reassessment and final statement in June 1977 with implementation in July 1977, the latest date a change of propellant, if necessary, can be made without adversely affecting the Space Shuttle development schedule. Studies are now underway on possible alternate propellants in the event that the final assessment in 1977 shows that

the current solid propellant will cause harmful stratospheric effects. Data acquired to date in the Space Shuttle Environmental Effects Program ensures that this timetable can be met.

The first preliminary assessment of CFM effects is scheduled for July 1976. This is dictated by the time it takes to obtain critical field measurements, and follows the issuance of the National Academy of Sciences report in April 1976. The assessment must await the measurement of stratospheric ClO and/or Cl. The first assessment will be preliminary in that more measurements, especially a Cl:ClO ratio, are necessary before a complete assessment can be made. The plan calls for these analyses to be available by the fall of 1977. At that time, NASA intends to issue a formal report that can be used to assist the regulatory agencies in making their decisions by January 1978. This date, suggested by the Federal Task Force on the Inadvertent Modification of the Stratosphere (IMOS), is the time when regulations on the use of fluorocarbons in aerosol spray cans could become effective. When data are acquired, they

will be made available to the regulatory agencies on a continuing basis.

NASA will work closely with the FAA in assessing aircraft operations in the stratosphere. As new data become available, they will be utilized in existing models to update aircraft assessments. The timetable for making these assessments is dictated by FAA requirements and is expected to occur annually.

When there is evidence that other, new chemicals or processes could possibly produce harmful effects in the stratosphere, they will be included in NASA's Assessment Subprogram, and a timetable for acquiring the necessary data will be set.

INVOLVEMENT OF THE SCIENTIFIC AND ENGINEERING COMMUNITIES

The FY 1976 Authorization Act, in assigning responsibilities to NASA, directed NASA to encourage participation of the external science and engineering communities in the planning and implementation of its program. There is full recognition that the success of a research program depends on the ideas and technical abilities of scientists wherever they exist to assist in planning, developing, and conducting the program.

One of the first steps in the implementation of the Upper Atmospheric Research Program was to assemble more than 50 experts from all areas of atmospheric science to review ongoing efforts. This meeting, referred to as the Stratospheric Workshop, chaired by D. Hunten of Kitt Peak National Observatory, convened on May 28-30, 1975, to consolidate the several efforts contributing to upper atmospheric research and to identify the most useful approaches to solve or bring a better understanding of the most critical issues. The group represented 15 universities and 13 other organizations in the public and private sector. Their recommendations, which serve as the basis for the Upper Atmospheric Research Plan, are included in the report (Ref. 5).

In July 1975, the OSS established the Stratospheric Research Advisory Committee, which held its first meeting on July 31 and August 1. The Committee, which is composed of experts in several scientific disciplines from universities and other institutions, is advising NASA on the various aspects of stratospheric research. The deliberations of the Committee are also being considered in this Program Plan.

COORDINATION OF THE FEDERAL EFFORT

An average of $10 million over each of the last two years has been spent by other agencies of the Federal

Government in research of the upper atmosphere. Since 1974, the Interdepartmental Committee for Atmospheric Sciences (ICAS) of the Federal Council for Science and Technology (FCST) has acted as a coordinator for the member Federal agencies involved in stratospheric research efforts pertaining to the fluorocarbon-ozone problem. ICAS membership includes representatives from DOD, DOT, NOAA, ERDA, EPA, NSF, and NASA, thus representing the total Federal Commitment in atmospheric research.

NASA was requested by the Chairman of the FCST to assume a lead agency role for the development of instruments for atmospheric measurements. A subcommittee of ICAS was formed to hasten the development of instruments and measuring systems many times more sensitive than existing techniques. This subcommittee, called the Subcommittee on Instrumentation and Measuring Systems (SIMS), is chaired by Dr. J. King, Jr., NASA Program Director.

COORDINATION WITH INDUSTRY

The present problem of the impact on the environment from releases of CFMs has led the fluorocarbon industry to ask the Manufacturing Chemists Association (MCA) to evaluate the problem. MCA is an international association with Headquarters in Washington, DC, representing an industry

producing $6 to $8 billion annualy in goods. To implement the industry research program, MCA supports $1.1 million in research in Canada and the United States, and intends to spend $5 million during a 3-year period to develop scientific evidence to define the impact of fluorocarbons on the stratosphere.

MCA's program is being coordinated through contact between the office of Dr. J. King and Dr. J. R. Soulen of the MCA committee investigating the fluorocarbons. At present, NASA and MCA are utilizing each organization's resources and unique capabilities to efficiently assess the fluorocarbon threat.

THE INTERNATIONAL PROGRAM

Congress has stated that international coordination of upper atmospheric research must be encouraged, as stratospheric pollution is a problem affecting the entire globe. CFMs are produced by various nations, with the United States accounting for about one-half of the total. If it becomes necessary to limit the release of CFMs into the atmosphere, the problem certainly cannot be solved without internation action.

There is a substantial amount of upper atmospheric research being conducted outside of the United States.

The United Kingdom, France, and Belgium have used as a platform the Concorde aircraft on which high-quality work has been performed that aided the development of instruments such as novel spectroradiometers and other remote-sensing devices. The use of the Concorde as a platform will continue. The French also maintain a strong balloon program that involves balloon development and launches from both hemispheres. They started in 1960 and now launch about 80 balloons per year. Launches are made for their own research programs as well as for those of other countries. An active balloon program is also pursued in Canada.

Attempts are being made to increase coordination between American, Canadian and European programs. Three European scientists have been invited to serve on the NASA Stratospheric Research Advisory Committee. There is a full exchange of information and data, including short-term and long-term cooperative aircraft and space projects. Some stratospheric research is being conducted in Japan; however, it primarily involves natural processes rather than pollution effects. The Japanese did participate, to a limited degree, in the CIAP.

Cooperative opportunities are being explored with other countries. The Italian Aerospace Research Center is

amplifying a current cooperative satellite proposal they have made to NASA by adding a radiometer to detect atmospheric ozone. Letters soliciting proposals for joint stratospheric work will be sent to appropriate organizations in Australia, India, Brazil and other countries. To encourage this cooperation in upper atmospheric research, an International meeting for the exchange of views and review of progress toward objectives is being planned for September 1976.

FUNDING

Before NASA's expanded role in upper atmospheric research, the level of effort in stratospheric research was about $7 million annually. The FY 1976 budget for stratospheric research, originally planned for approximately $7.1 million, is tentatively set at about an $8.5 million level, with approximately $2.5 million for the Transition Period.

FY 1977 funding for NASA's Upper Atmospheric Research Program is still under consideration, but it is expected that funding above current levels will be provided.

REFERENCES

1. Climatic Impact Assessment Program (CIAP) Monographs (Six Volumes), Department of Transportation, September, 1975, Washington, DC.

2. Molina, M. J., and Rowland, F. S. (1974). "Stratospheric Sink for Chlorofluoromethanes - Chlorine Atom-Catalysed Destruction of Ozone," Nature, Vol. 249, pp. 810-812.

3. Cicerone, R. S., Stolarski, R. S. and Walters, S. (1974) "Stratospheric Ozone Destruction by Man-Made Chlorofluoromethanes," Science, Vol. 185, pp. 1165-1167.

4. Wofsy, S. C., McElroy, M. B. and Sze, N. D. (1975). "Freon Consumption: Implications for Atmospheric Ozone," Science, Vol. 187, pp. 535-536.

5. The Stratosphere, 1970-1980. (1975), Report of a Workshop, May 28-30, 1975, D. Hunten, ed., Goddard Space Flight Center, Greenbelt, MD., 62 pp.

Hurd C. Willett
Professor of Meteorology, Emeritus
M.I.T.

The Sun as a Maker of Weather and Climate

Is worldwide climate today undergoing significant change, or is it merely fluctuating randomly around a long-term norm calculated on the basis of perhaps a century or more?

The question was first suggested by the strong warming trend observed throughout the world between 1920 and 1940. Gilbert N. Plass of Texas A and M University in 1956 probably originated and certainly best articulated the theory that an increase of atmospheric carbon dioxide produced by the combustion of fossil fuels could best explain this warming. His theory stimulated considerable popular concern and a scientific debate which has yet to be resolved. This paper presents an alternative explanation, proposing that variations in solar activity best fit recent observed climatic fluctuations, and offering a very sketchy physical hypothesis. On the basis of these observations are ventured some climatic predictions for the next century.

We begin with definitions: climatic fluctuations are described in terms of fluctuations in the pattern of general atmospheric circulation, notably the westerlies of the middle latitudes and the subtropical easterlies. General circulation patterns are designated as being strongly or weakly zonal (that is, concentrated and strong or dispersed and weak, relative to the normal); they are designated as being at high or low latitudes as the pattern is displaced poleward or equatorward of the seasonal normal. The patterns are further designated as being strongly or weakly meridional, depending upon the intensity of the north-south winds which exchange polar and tropical air masses. Weak zonal and strong meridional circulation tend to occur together to constitute climatic stress. Such stress is marked by strong longitudinal contrasts of temperature and precipitation and by strong seasonal contrasts between maritime and continental air — hence by extreme contrasts between continental summer and winter temperature.

The processes which result in earth's weather — and in the longer range its climate — are both complex and subtle. The author describes his speculations on the effect of one variable — the cyclical magnetic activity of the sun which results in the sunspot and secular cycles which are familiar to solar scientists. "The solar-climatic hypothesis best fits the observed climatic changes of the past 700 years," writes Dr. Willett, and by extrapolating these correlations into the future he concludes that, "barring an interruption of predictable solar cycles, the next ice age is unlikely for at least 10,000 years . . ." (Photo: N.O.A A.)

Forty Years of Warming Weather

The sequence of recent weather patterns on earth may be characterized as follows: the substantial warming trend that began about 1920 peaked in the higher middle latitudes during the 1930s, in the lower middle latitudes in the early 1950s and in subtropical latitudes in the late 1950s or perhaps as late as the early 1970s. A substantial cooling trend began in the polar and higher middle latitudes in the 1940s, in the lower middle latitudes in the late 1950s, and in the subtropical latitudes even later — perhaps only now. In general, the lowest temperatures in the middle latitudes occurred in the early and middle 1960s, followed by a slight warming trend in the late 1960s and early 1970s.

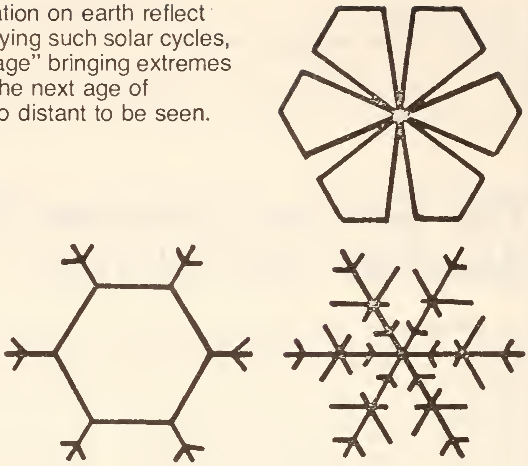
Geographical patterns of precipitation departures are more local and of much smaller scale, depending on topography and moisture sources, than are those of temperature departures. Though comprehensive data are therefore largely unavailable, the following summarizes our understanding of recent rainfall variations:

The warm decade of the 1930s brought the most severe droughts of the century to many regions of the middle latitudes, notably the dust bowl in our western plains; severe Russian droughts triggered liquidation of the Kulaks, and there were severe droughts in southern Australia and in other mid-continental — as opposed to east coastal — parts of the world. The 1940s brought generous rains to the drought regions of the 1930s, though there was a tendency to substantial deficiencies in east coastal regions.

The early- to mid-1950s, like the 1930s, were a markedly dry period in the marginal interior continental regions, notably the American southwestern plains; severe drought was restricted to latitudes equatorward of 40°, and east coastal areas were normally or abnormally wet. Like the 1940s, the 1960s provided generous rainfall to the marginal interior continental regions of middle latitudes, but there were record dry years in many east coastal regions. The 1960s and early 1970s brought severe drought to the middle and lower subtropics, notably in southern Asia and central Africa.

To date the 1970s have witnessed only a very slight tendency to drought in middle latitudes — and that only

Patterns of atmospheric circulation on earth reflect cyclic changes in the sun. Studying such solar cycles, the author predicts a "little ice age" bringing extremes of cold by the year 2200. But the next age of widespread glaciation is still too distant to be seen.



in southern portions of the belt (our Mexican border states). Apparently there has been some dryness during the past two years in marginal Russian grain land, but the data necessary to put that occurrence into perspective are not readily available.

General circulation patterns during the past 50 years correlate with these temperature and rainfall records: strong high-latitude climatic stress patterns developed early in the 1930s. The 1940s were dominated by zonal westerlies at somewhat subnormal latitudes, and very strong climatic stresses marked the 1950s. Since then, the general circulation has been predominantly zonal, remarkably free of stress patterns.

Any prediction of future climatic change, including the possibility of a new ice age, must depend upon our understanding of these recent climatic fluctuations. At least two hypotheses are possible — one based primarily on man's pollution of the atmosphere, the other based wholly on natural variations of solar energy inputs. This paper will consider both and propose the latter as more consistent with data from the recent past.

The Atmospheric Pollution Hypothesis

During the past 50 years the outstanding trends of temperature are the sharp rise over much of the northern hemisphere, culminating in the higher latitudes about 1940, and the following cooling which reached its fullest in the higher and middle latitudes in the middle 1960s. If atmospheric pollution is hypothesized to explain changes of temperature at the earth's surface, it must especially help us to understand these trends.

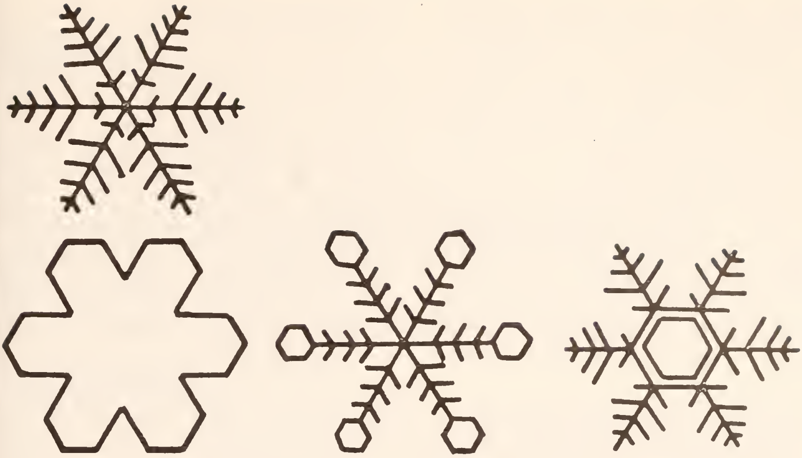
Since atmospheric carbon dioxide (CO^2) has continued to increase more than linearly throughout this period due primarily to the growing consumption of fossil fuels, Reid A. Bryson of the University of Wisconsin sensibly maintains that the hemispheric temperature should have continued to increase rapidly except as some other factor modified the effect of CO_2; he proposes that this factor is increasing dust and smoke in the atmosphere of volcanic or industrial origin.

Some analyses propose a different effect, suggesting that particulate matter in the atmosphere is much more absorptive of outgoing long-wave terrestrial radiation than of incoming short-wave solar radiation. This leads to a hypothesized "greenhouse effect" — more warming of the atmosphere in the high latitudes where outgoing terrestrial radiation exceeds incoming solar radiation than in the low latitudes, where the reverse is true; this "greenhouse effect" must tend to warm the atmosphere more at high latitudes than at low and thus weaken the general circulation and be counter-glacial in effect.

But if Professor Bryson is correct and the trends he projects continue as from 1940 to 1960 into the 21st century, the decrease of the mean temperature of the northern hemisphere must be expected to continue; this would lead, rather quickly and uniquely in the earth's history, to the advent of an ice-age climate and glacial conditions. It is this assumption that leads to pessimistic predictions of reduced food production and increased energy demand.

But the pollution hypothesis cannot properly be made to account for recent climatic fluctuations. Any estimate of the effects of atmospheric particulates is at best difficult to make and must be based on a number of assumptions; it is sensitive to the number, size, vertical distribution, and absorptive and radiative characteristics of the particulate matter, as well as to the wavelength and angle of all incident radiation. For this reason I believe it hopeless within the scope of present knowledge to reach a quantitative estimate of what particulate matter may be doing to the mean temperature of the hemisphere.

My own reading of the record convinces me that recent increases of atmospheric carbon dioxide have contributed much less than 5 per cent of the recent changes of atmospheric temperature and will contribute no more than that in the foreseeable future. If this is true, and the heating effect of CO_2 is considered negligible, then there is no need to invoke any cooling effect of particulate pollution to account for climatic fluctuations. Indeed, I believe that



man will pollute himself off the face of the earth long before he can pollute himself into an ice age.

The Solar-Climatic Hypothesis

Sunspot activity occurs in cycles which have been well studied and are widely recognized. Three of these cycles of solar activity are to be considered in relation to recent climatic fluctuations: the eleven-year sunspot cycle, the double sunspot cycle, and the longer secular cycle. Complete, quantitative explanations for the relationship between solar cycles and climate remain to be given, though some hypotheses can be suggested (*see page 50*) in the absence of the right kind of solar observational data and physical research. But a fair argument for the solar-climatic hypothesis of climatic fluctuation can be made, resting squarely on observed, historical relationships between solar and climatic cycles.

The Reversing Sunspot Cycles

The most widely recognized cycle of solar activity as it affects climate spans a period of about 22 years. The number of sunspots rises to a maximum, falls to a minimum, and returns to a maximum in an average of 11 years; but between each 11-year cycle there is a reversal in the direction of the sun's magnetic field. Thus each 11-year cycle has a polarity opposite to that of the preceding cycle, and conditions in fact repeat themselves only every 22 years.

The 11-year sunspot cycle (actually ranging from nine to 14 years) is of minor interest for climatic correlations; only in the equatorial belt is there any significant correlation between the 11-year cycle and the weather, notably temperature. At all higher latitudes the double (22-year) sunspot cycle completely obscures the single cycle in climatic significance, because alternate sunspot maxima have opposite effects on atmospheric circulation and weather. Accordingly, the following discussion takes no further account of the 11-year cycle except as the positive (major) or negative (minor) half of the 22-year cycle.

The Long Secular Solar-Climatic Cycle

The long solar-climatic cycle, based on both planetary configurations and sunspot and solar magnetic activity, is alternately of approximately 100 and 80 years' duration.

The following lists the broad features of the northern hemispheric (and probably also southern hemispheric) climatic patterns which tend to correlate with this long, secular cycle of solar activity:

The initial three or four quiet decades of each long cycle generally show strong zonal circulation patterns with maximum coldness in all except the equatorial and bordering subtropical latitudes, where low temperatures are probably delayed until the third and fourth decades; and wetness is likely in the middle, lower middle, and equatorial latitudes except in east coast continental areas in the middle latitudes. This climate of strong subtropical activity is favorable to glaciation.

The next two decades are marked by strong zonal circulation patterns shifting rapidly from low to high latitudes, temperatures rising to maximum in the polar and higher middle latitudes and to near normal in equatorial and subtropical latitudes, and increasing wetness poleward of 50° and in the subtropics. This is predominantly an interglacial climate.

For the 100-year cycles only, the three decades following high sunspot activity are a period of very active weather: high-latitude zonal circulation patterns break down sharply into climatic stress; extremes of temperature in the middle latitudes, with cooling first in the higher altitudes and some 15 years later in the lower-middle latitudes; and alternating drought and flood, first in the higher-middle and then in the lower-middle latitudes. It is a period of wetness, with many northeasters and hurricanes on continental east coasts.

Peak sunspot activity in the middle of the 80-year cycle is preceded in the middle latitudes by a sudden, brief rise of temperatures, then a quick return to low temperatures during and following the sunspot peak. There is a moderate upturn of temperature to a much lower peak

preceding the modest sunspot maximum late in the cycle.

During the final one (80-year) or two (100-year) decades of rapidly decreasing sunspot activity, there is a return towards the low-latitude zonal circulation patterns and weather of the initial quiet decades. A trend towards lower temperatures in all extra-tropical latitudes with peak warmth in the lower subtropics and equatorial latitudes continues, and the precipitation patterns of the initial quiet decades are repeated.

Two interesting facts stand out in the limited observational evidence relating temperatures to these secular solar-climatic cycles:

— By far the most significant temperature departures of the last secular cycle occur in the subtropics, where peak warmth of the warming trend occurs 20 years (or even more) later than it does at 50°N.

— The statistical significance of these temperature trends in the subtropics, and their clear tendency to follow the sun seasonally, suggest strongly that the secular cycles are caused by fluctuations in the effective radiation received from the sun.

Following the Cycles Through Flood and Drought

Precipitation trends are more complex and less well established than those of temperature, but a few broad correlations with prevailing circulation patterns of the last 100-year secular cycle may be noted:

The period of strongest low-latitude zonal circulation, from 1880 to 1910, was prevailingly wet across the United States in lower-middle latitudes (except on the east coast), and prevailingly dry across Canada in higher-middle latitudes; indeed, during the first two-thirds of this period western Canada experienced the most severe drought in its observational history, coincident with a very wet period across the southern United States. The only drought of consequence in the United States occurred in the Mexican border states in the 1890s.

Dry weather prevailed from 1910 to 1940 in the United States and southern Europe, and wet weather covered Canada and northern Europe.

The predominance of high-latitude zonal circulation ended during the early 1930s with the advent of strong weather systems in middle latitudes, and these persisted through the 1950s in lower-middle latitudes. The outstanding features of the 1935 to 1960 period as a whole are recurrent severe droughts in the midwest coincident with extreme wetness on the east coast (including northeasters in winter and spring and hurricanes in summer and autumn).

The Double Sunspot Cycle

Climatic aspects of the double (22-year) sunspot cycle come out more strongly during the latter, active half of the 100-year secular cycle. Accordingly, the following discussion of the double cycle is based entirely on the record of the 100-year secular cycle just ended, for which solar and climatic data are best known.

The basic solar-climatic feature of the 22-year sunspot cycle as observed during the period from 1870 to 1970 is a strongly contrasting change of the patterns of the general circulation during the period between one sunspot minimum and a following maximum with a *positive* solar magnetic field (Max^+), opposite in sense to that in the period between a sunspot minimum and a following maximum with a *negative* solar magnetic field (Max^-). Latitudinal changes of atmospheric pressure correlating with solar magnetic and sunspot cycles clearly indicate a tendency for the zonal circulation to weaken going into the positive half and to strengthen going into the negative half of the double sunspot cycle.

Strong weather patterns caused by polar highs in winter and by higher-latitude extensions of the lower-latitude oceanic high pressure cells in summer characterize the Max^+ phase of the double cycle. Absence of such patterns characterize the Max^- phases of the cycle.

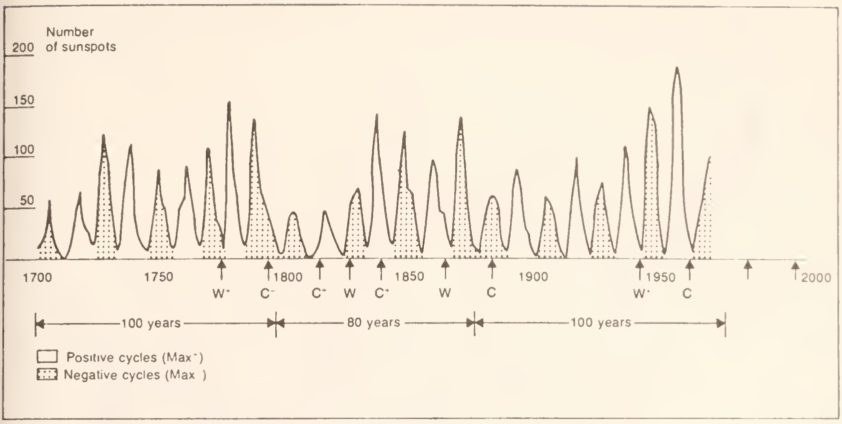
Solar Activity and Earth's Atmosphere

It is interesting to speculate on possible physical linkages between the solar and the climatic aspects of the secular and the double sunspot cycles. It was noted earlier that the temperature in subtropical latitudes during the summer season is the most significant manifestation of the secular cycles. This could result from either of two possible causes:

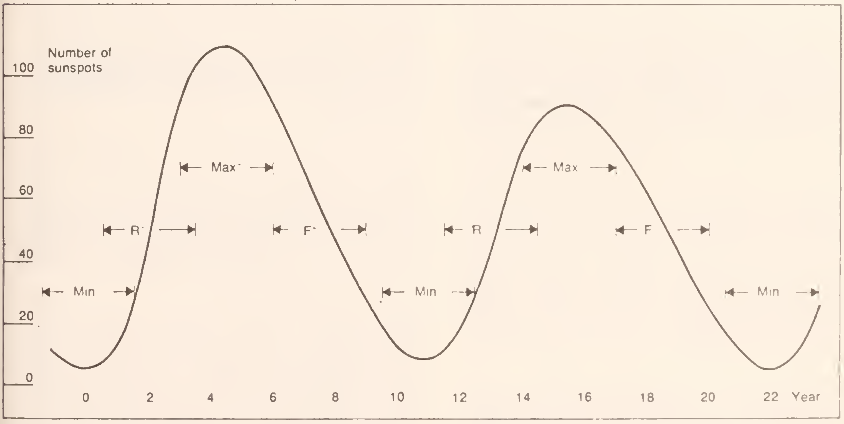
— A change in the direct heat of the sun (the solar constant).

— A change in the atmosphere of the earth to decrease its transmission of solar energy into the atmospheric systems; such a change might be caused either by a change in the photochemical equilibrium resulting in an increase in ozone or by the production of active condensation nuclei (cloudiness) in the upper atmosphere.

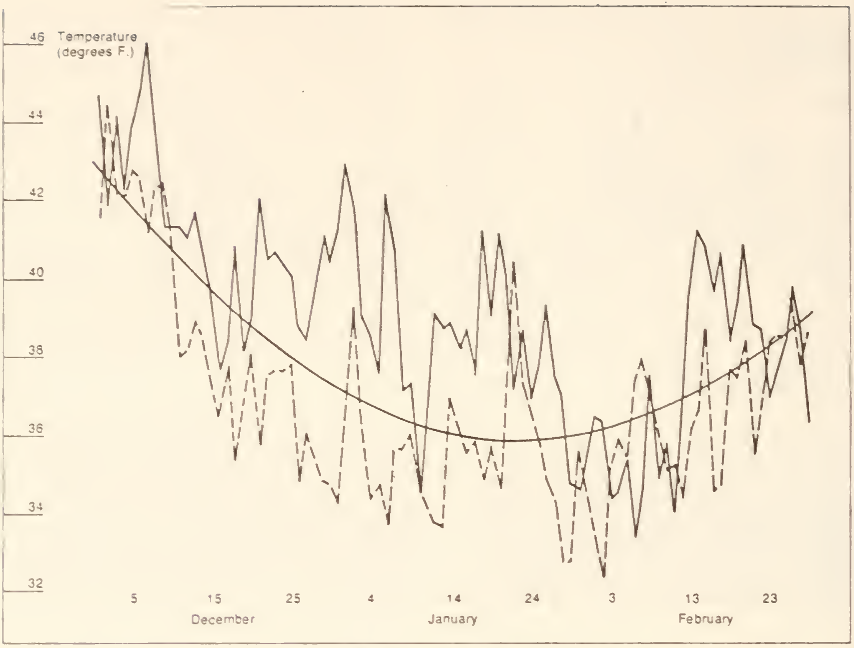
On the other hand, the most significant climatic manifestations of the double sunspot cycle are in the winter-season circulation in high latitudes, in the contrast between strong zonal circulation, and its breakdown into a climatic stress pattern. The one solar variable that meets this seasonal and latitudinal requirement is the solar wind, which could in turn affect the amount of ozone in



The long secular solar-climatic cycle, based on planetary configurations and sunspot and solar magnetic activity, alternates between 100 and 80 years, here are shown three such cycles on which are superimposed the 11-year solar cycles in which the solar magnetic field reverses polarity, stretching from 1700 to 1980. Low sunspot activity and wide spacing of the 11-year cycles of magnetic reversal characterize the first 30 years of each 100-year cycle; high sunspot activity and close spacing of sunspot extremes, the last half. The 80-year cycle is different: the most rapid sunspot changes occur in the middle of the period. Shaded 11-year cycles represent periods of negative solar magnetic field; note that at the end of 80- and 100-year cycles the solar magnetic field fails to reverse from negative to positive. The letters show probable years of maximum warm (W) and cold (C) temperatures, as analyzed from historical data. The author notes rapid rises of temperature during the period when sunspot activity is growing rapidly just after the half-way mark in each 100-year cycle. The peak temperatures came midway in the 80-year cycle, followed by a return to severe cold with falling sunspot activity Since we are now at the start of a new 80-year cycle, says the author, the period from 1800 to 1880 is of the most immediate predictive significance to us now.



This chart shows the average of the five double sunspot cycles during the last 100-year secular cycle, with climatic experiences superimposed In general, during these five cycles the climate became active while sunspots were at their minimum and growing rapidly — the positive half of the 11-year cycle — with solar magnetism changing from negative to positive (Min through R⁺), the weather was active, characterized by severe droughts in continental interiors During the next nine-year period the active climate persisted but drought gave way to wetness and heat to cold. Then came six years (R through Max) of more moderate weather cool and wet Finally, in six years from F to Min the zonal circulations shifted poleward and weakened bringing warmer weather to northern latitudes. Clearly, thinks the author these data established the connection of sunspot activity and solar magnetism with earth's climatic change



The hard, smooth curves of these charts are the average over 93 and 100 years, respectively, of Weather Bureau maximum winter temperatures in Boston (above) and maximum summer temperatures in Omaha (opposite). The jagged solid lines show the daily average temperatures during periods of declining sunspot activity with negative solar magnetism. The dashed lines show the same data for all dates which fell during periods of decreasing sunspot activity with positive solar magnetism. Strictly parallel results are obtained with minimum temperatures, but in all cases at somewhat lower levels of significance, a difference which, says the author, "is entirely consistent with the fact that maximum temperatures are more representative of undisturbed atmospheric and solar conditions than minimum temperatures." The correlation of sunspot and magnetic data with climate is strongly suggested.

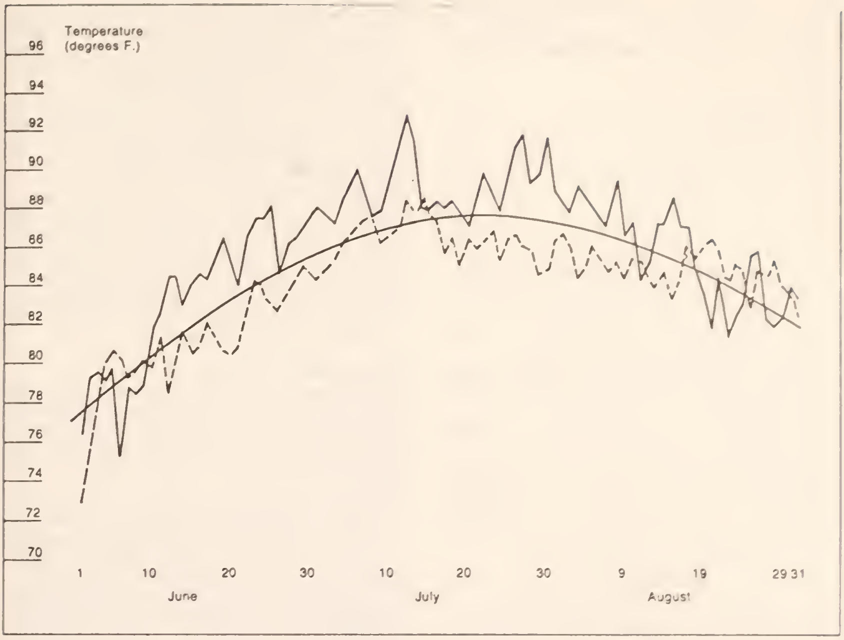
the upper atmosphere. In fact, the basic cause of all large-scale long-term fluctuation between zonal and more active circulation patterns, both winter and summer, in higher and lower latitudes, appears to lie in the strength of the major continental-maritime circulations. And the intensity of these depends in turn upon the relative radiational cooling of the continents in winter and their insolational heating in summer — that is, upon the transparency of the atmosphere.

Correlating Climatic Trends and Solar Cycles

Perhaps the most convincing argument for the acceptance of a hypothesis of climatic fluctuation is its success in prediction. The solar-climatic hypothesis has performed remarkably — indeed, without one serious error — in a number of long-term forecasts of climatic trend. These forecasts were all based on the approaching termination of one secular cycle and the lengthening of the double sunspot cycle with the advent of the new secular cycle.

In 1951 I proposed that "the temperature level over much of the world will fall significantly during the next 15 years, probably reaching a first minimum level between 1960 and 1965. This temperature fall probably will be sharpest where the anomalous warmth of the past 25 years has been most extreme." This prediction has verified almost perfectly.

In 1955 I reported that "the present (1950 to 1959) decade almost certainly is witnessing the peak of hurricane frequency in the Western Atlantic as opposed to the Gulf area, a peak which probably will begin to decline during the remainder of the decade and continue to decline sharply during the decade of the 1960s. The severity as well as the frequency of hurricanes in the North Atlantic coastal areas will decrease. At the same time there will be a slight, but not more than slight, increase in the frequency of West Gulf hurricanes, so that the total number of Atlantic zone hurricanes will decline, by the end of the 1960s, at least to the level of the period from 1900 to 1930. The period from 1960 to 1990 will probably find the overall frequency of Atlantic zone hurricanes at



an average level corresponding to 1870 to 1900, a level even lower than that of 1900 to 1930." To date this forecast has verified in every particular.

Another related forecast, which never received publication, was made to the State of Maine Department of Sea and Shore Fisheries in the mid-1950s, predicting cooling of the sea-surface temperatures of the middle and north Atlantic coast during the early and middle 1950s to subnormal levels during the 1960s and probably to even lower levels from the mid-1980s into the 1990s. By 1965, sea-surface temperatures off the Maine coast had fallen a full 5°F. to well below the long-term norm.

Forecasts for the Next Double Secular Cycle

These and other similar results give me courage to make a series of 180-year predictions, based on the assumption that the next two secular cycles of 80 and 100 years, respectively, will follow the solar chronology and related climatic pattern of the last two cycles. The double sunspot cycle is considered only in the detail of the next 30 years — and at that not with full certainty because of its imminent reversal of phase, its tendency to be less dominant during the first (relatively quiet) half of the long secular cycle, and our ignorance of its manifestations during the 19th century, when the last 80-year cycle should be analogous to the next 80 years.

In the next 25 years the temperatures in all latitudes will fall to significantly lower levels than those reached in the mid-1960s. Whether this decline starts immediately, leading to lowest levels in the 1980s, or starts in the 1980s with lowest levels reached in the 1990s, depends on whether the double sunspot cycle reverses phase.

No major, prolonged drought is foreseen in lower-middle latitudes except possibly along the subtropical margin — the Mexican border states of the United States. Whether this is centered in the first or second decade ahead also depends on whether the double sunspot cycle reverses phase. If it does not, the 1975-85 prediction stands.

In higher-middle and subtropical latitudes, the next two decades will be a predominantly dry period, particularly in Canada and northern Europe, with a severe drought possible across the Canadian plains. A similar ten-year period of severe drought is likely in southern Asia and subtropical Africa, but decadal timing is uncertain.

From 2000 to 2010 A.D., there will be an abrupt return to markedly warmer weather in the middle and higher latitudes, followed rather quickly by a return of temperatures to the low levels predicted for the next two decades. The warmth of the 2000-2010 decade will not approach that of the period from 1930 to 1960. The warm decade will tend to be wetter in higher-middle and in subtropical latitudes and thus will terminate the prospective drought conditions there. It will be drier in the lower-middle latitudes, but stress conditions of drought

Solar Cycles: Cold Winter Ahead

Beware.

Drawing on his research and experience correlating cycles of solar activity with weather and climate on earth, Hurd C. Willett, Professor of Meteorlogy Emeritus at M.I.T., thinks an abnormally cold winter with heavier-than-usual snowfall awaits the eastern U.S. It's a forecast with a "moderate confidence rating," he says — likely but not certain.

For the nation east of the Continental Divide, said Professor Willett in early November, "the current prolonged period of very warm weather should terminate before the end of November, to be followed by a prolonged spell of very cold weather, probably most severe during the mid-winter month of January, to give us a winter season markedly colder than normal.

"A moderating trend should set in late in the winter, followed by a comparatively mild early spring.

"Rather frequent rapidly eastward-moving active storms should result in above normal precipitation generally except in the far southwest, along the west Gulf Coast, and along the Canadian border.

"This storm activity, combined with a winter much colder than last, should result in snowfall and snow accumulation generally heavier than normal, and heavier than last winter, in most of the eastern part of the country except from the northern plains eastward across the upper Great Lakes into northernmost New England, where precipitation will be less than last year.

"Snowfall probably will be less, and melting earlier, than last year going into the spring season."

Although Professor Willett's forecast last year of a very cold winter was in error, his companion prediction of a heavy snow season across most of the northern half of the country was accurate. In addition, both the early fall (September-October) and spring (March and particularly April) were colder than usual.

Professor Willett said the same general conditions as last year — combining a strong westerly circulation with alternating periods of extreme warm and cold — are continuing in full force this year, as it should be at this phase of the double sunspot cycle.

He considers it likely that the same pattern of alternating extreme warm and cold periods will continue in the months ahead. However, their timing has been running out of phase with last year — the autumn has been very warm, in contrast to a year ago — and this heightens the chance of a cold winter and warm spring this year, he says. — *J.M.*

and coastal storminess will not approach those of the period from 1930 to 1960. The return to cooler conditions after 2010 should bring a return to relative wetness in the lower-middle latitudes and relative dryness in the higher middle and subtropical latitudes.

The last 25 years of the 80-year secular cycle (2030 to 2055) promise a modest warming trend in the middle and higher latitudes, with decreasing dryness in the higher-middle and subtropical latitudes. Temperatures and climatic stress will decrease dramatically.

The next period of extreme warmth followed by climatic stress comparable to that from 1930 to 1960 probably will occur in the years between 2110 and 2140. The warmth and climatic stress may be even more severe than that of the 30 years prior to 1960, including in the middle latitudes hot summers, cold winters, severe drought in interior continental areas, and severe weather with winter coastal storms and summer hurricanes in the United States and northern Europe.

Predictions Beyond 180 Years

If the next ice age is in fact foreseeable, it can come only after the year 2150. The following predictions bearing on its possible advent are based entirely on solar-climatic analogy with the past, disregarding, as in earlier conclusions, any possible human or volcanic pollution of the atmosphere.

Only two cycles are utilized in this discussion. The first is a 10,000- to 12,000-year cycle, for which no supporting solar information is available; rather, it is supported by geological evidence of two or three peaks of glaciation during each of the last two glacial periods; this cycle evidently passed through its extreme interglacial phase about 5,000 years ago and probably is approaching its extreme glacial phase. The other is a cycle of approximately 720 years (4 × 180 years) which has strong solar support.

There occurred in each of the 12th and 14th centuries a 25-year period of severe climatic stress. The first stress period terminated all communications between the Norse Vikings and their Greenland and Iceland colonies; the second one — the most severe period of climatic stress on record, most extreme between 1370 and 1390 — ravaged all of northern Europe with strong blizzards and extreme cold in winter (including record storm flooding of the Dutch lowlands) and heat and drought in summer. The consequences in famine and plague reduced the population of the British Isles by two-thirds. Old Chinese records indicate that this was a period of sunspot activity such as

has never been seen since. European observations suggest that the following three centuries was a period of extremely low sunspot activity. This was the period of the so-called Little Ice Age, in which there was rapid advance and finally slow retreat of glaciation.

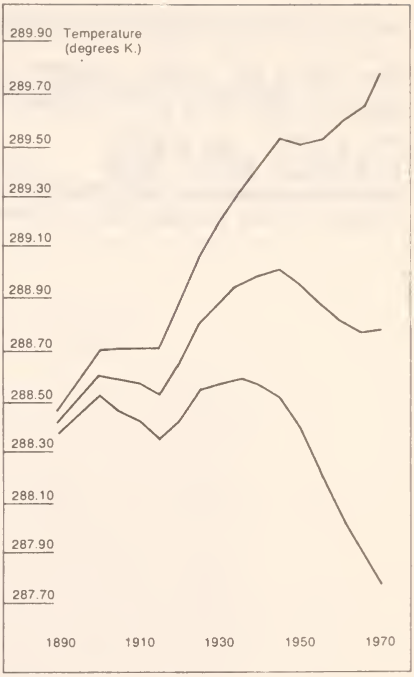
For the last 300 years, sunspot activity has followed a marked upward trend; on the basis of this observation and of the 700- and 10,000-year climatic and sunspot cycles, I offer the following predictions:

The climatic stress period from 2110 to 2140 will represent the peak of the current 720-year cycle; weather will be substantially more severe than that of 1930 to 1960, probably matching that of 1370 to 1400. The following "Little Ice Age," from 2200 to 2550, will be somewhat more severe than that from 1500 to 1850. It will probably mark the peak of glaciation of the current 10,000-year cycle, to be followed for the next 5,000 years by a cyclical progression towards a warmer interglacial period of the long cycle.

One final prediction remains. Was the climatic optimum of 2000 to 3000 B.C. the final interglacial stage in the major ice sheet sequence, or was it merely the first warm point in the long trend towards an extended interglacial climate? If the first alternative is true, then the next climatic optimum would be much less optimal, and by this phase in the next long cycle — some 10,000 years from now — we would be well into the next major glacial epoch. However, analogy with past glacial chronology makes it appear much more probable that there is a longer true interglacial period to come; hence it probably will be at least the year 30,000, or even longer, before we come into the next ice age.

If human pollution of the atmosphere is ruled out as an important contributor to recent climatic changes, and the evidence for that is strong, then the solar-climatic hypothesis best fits the observed climatic changes of the past 700 years. On that basis, by analogy with the past, the next ice age is unlikely for at least 10,000 years, even for more than 30,000 years, unless the sun takes off on a new tangent.

Hurd C. Willett first fulfilled his interests in the weather on his father's farm near Pittsburgh. Born in Providence, Rhode Island, he studied at Princeton (B.S. 1924) and George Washington University (Ph.D. 1929) before joining the M.I.T. Meteorology Department, in which he has spent almost his entire professional career. He has been honored for his central role in developing the polar front theory of weather forecasting, a natural outgrowth of his life-long interest in climatic fluctuations as influenced by variable solar processes.



The middle curve shows the average Northern Hemisphere temperature over 80 years since 1890; with what can its fluctuations be coordinated to understand their cause and make possible predictions for the future? Particulate matter in the atmosphere is proposed to absorb solar energy which would otherwise reach the earth's surface; but there is also the possibility that particulates have an opposite — the "greenhouse" — effect of increasing temperatures by trapping solar energy. Increasing atmospheric carbon dioxide due to fossil fuel combustion may also be a cause of increasing temperatures. The upper curve shows temperatures hypothesized in the absence of atmospheric particulates; the lower curve is one estimate of temperatures in the absence of any increase in CO_2. The author finds that neither can account for recent climatic trends.

UNITED STATES DEPARTMENT OF
COMMERCE NEWS
WASHINGTON, D.C. 20230
SCIENCE AND ENGINEERING NEWS FROM NOAA

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

March 1976--SEN-56

OUR IMPACT ON GLOBAL WEATHER AND CLIMATE; HARDLY PERCEPTIBLE

IN SHORT...Although not verifiable at present, the time may not be far off when human activities will result in measurable large-scale changes in weather and climate of more than passing significance to our well being. Inadvertently, we are already causing measurable variations on the local scale. The climate in and near large cities is warmer, the daily range of temperature is less, and annual precipitation is higher than if cities had never been built. The total mass of carbon dioxide in the atmosphere has increased 3 percent since 1958, and atmospheric dust loading has risen appreciably downwind of large cities in industrialized countries. Waste heat from our activities is now 0.02 percent of the average heat received by Earth from the Sun, and the stratospheric ozone layer may have been subtly changed. The worldwide effects on climate are not yet detectable against the background of natural variations; however, mathematical models of climatic change, still imperfect, predict significant global effects in the near future if the rates of growth of industry and population persist. Such changes would have far-reaching influences on the quality of our continued existence on the Earth, if not on that very existence itself.

Weather and climate have a greater, more prolonged impact on us and our activities than more localized natural catastrophes such as volcanic eruptions and earthquakes. On the other

hand, extreme fluctuations in the long-term atmospheric state have caused drastic alterations in animal and plant populations. Even in historical times far-reaching social consequences of relatively small, documented climatic changes have been noted. As an example, the westward migration across the Atlantic Ocean was delayed no doubt by the "little ice age," from about 1300 to 1700 A.D.; but for this the Western Hemisphere would probably have been settled several centuries earlier.

Until recently, the primitive state of scientific development precluded our intentionally affecting the weather and climate. Advances in knowledge of the chemistry and physics of the atmosphere in the past 30 years have indicated the possibility of modifying weather measurably. Nuclear explosions liberating high energies have caused local, short-term changes in weather and intentional cloud seeding may cause highly localized patterns and amounts of precipitation. But the inertia of the global atmosphere-ocean system has been found to be too tremendous to be perturbed seriously by such sudden, high, relatively isolated energy releases. Rather, the slow, insidious effects of human activities are more important, and are being studied to determine how they influence the climate.

The first serious large-scale scientific study of a possible manmade influence on climate resulted from the

inclusion of a program to measure carbon dioxide (CO_2) during the International Geophysical Year, 1957-58. Subsequently, programs to measure CO_2 and solar radiation were started in the Antarctic and at the Mauna Loa Observatory in Hawaii--the latter is a benchmark station for climatic change monitoring. Working groups of governmental, university, and industrial scientists met to identify possible global environmental hazards and make recommendations concerning monitoring programs, and pollution abatement. One such meeting held by American scientists in 1970 was the Study of Critical Environmental Problems (SCEP). Climatic problem areas identified by SCEP were: CO_2 and other trace gases that may affect climate, particulate matter in the atmosphere as turbidity and cloud modifiers, waste heat (thermal pollution), land-use changes, radioactivity in the atmosphere, and jet aircraft pollution of the high troposphere and stratosphere.

A subsequent international meeting concerning inadvertent climate modifications was the Study of Man's Impact on Climate (SMIC), with representatives from 14 countries. The major areas treated by SMIC were: previous climatic changes, man's activities influencing climate, theory and models of climatic change, climatic effects of manmade surface change, modification of the troposphere, and modification of the stratosphere. Worldwide programs of monitoring and research have been established at strategic locations, and the resulting studies have shown that human activities are capable of

influencing weather and climate on both regional and global scales, but the degree of global influence is as yet too small to be detected in the "noise" of natural climatic fluctuations. The on-going programs should make it possible to separate the information from the noise and refine the prognostic mathematical models of climatic change.

Scientist Earl W. Barrett of the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), has recently synthesized the results* of an intensive study involving all the reports published during the past 25 years in the scientific and popular literature relating to inadvertent weather modification. Working in NOAA's Atmospheric Physics and Chemistry Laboratory at Boulder, Colo., Barrett has reviewed 23 articles and referenced 363 others. He concludes that man has not made any noticeable impact on climate except in and near metropolitan areas, but potential change on a global scale does exist when present rates of growth of certain of his activities are extrapolated into the future.

Climate is defined as the ensemble of pertinent weather elements (means, extremes, and measures of dispersion and skewness) taken over a suitably long period of time. A climatic epoch is taken to be 30 years, and the main elements are temperature, wind, precipitation, evaporation,

*Barrett, Earl W., "Inadvertent Weather and Climate Modification", Critical Reviews of Environmental Control, Vol. 6, No. 1, December 1975, pp. 15-90.

solar radiation received, humidity, and pressures and winds at many atmospheric levels. Elements that may affect man are depleted oxygen and increased carbon dioxide. To determine manmade climatic effects, a measure of the degree of variability of these elements must be had. Also, it must be established whether fluctuations in their observed intensity and duration would have occurred naturally; a short-term trend in a climatic element following a change in man's activities does not necessarily imply a cause-and-effect relationship. Furthermore, since all climatic elements strongly interact with one another, there is the probability of multiple feedback, both positive and negative, that may give paradoxical results. However, the development of larger and faster computers makes possible quantitative rather than verbal relationships, and a start has been made in developing models to predict more accurately any possible long-term climatic changes.

Models are either diagnostic (describe the steady-state condition of a system) or prognostic (involve the time coordinate explicitly), and are used to predict the future state of a system, given initial conditions. They require accurate, long-term observational data to minimize errors and increase forecast reliability. Since the advent of the computer, many models have been developed and have given often contradictory results. The author has examined the output of models and arrived at what he believes to be a consensus of the findings

concerning the principal elements involved in predicting climatic changes.

CO_2, as a product of fossil fuel combustion, was early thought to play an important part in modifying the heat balance of the atmosphere, and thus weather and climate. To maintain an overall heat balance, the Earth's surface must lose to space the same amount of solar energy it receives. CO_2 acts as a radiative resistance to energy leaving the surface, and the surface temperature is thus higher than if no CO_2 were present. This is commonly referred to as the "greenhouse effect". For many years the difficulties involved in measuring CO_2 precluded the attainment of unbiased data that could lead to the determination of accurate trends in CO_2 content and resulting climatic changes. The development and adoption of a new infrared analysis technique and 17 years of continuous sampling at the Mauna Loa observatory (1958 to date) greatly reduced the scatter among the data and provided material that lead to reliable conclusions; the data from several programs show a consistent pattern, and the annual trends of CO_2 content can be compared with data taken at other stations in both hemispheres. The agreement between different data sets indicates an increase of atmospheric CO_2 since 1958, and the results of several mathematical models agree fairly well with the measurements.

Models to predict the effects of increased CO_2 on climate have also been developed, and the subsequent conclusions indicate that: (a) human combustion of fossil fuels is raising the CO_2 content by about 0.2 percent per year; (b) extrapolation of combustion rates and absorption by the seas should result in 350 to 400 ppmv (parts per million by volume) by the year 2000; and (c) warming due to combustion CO_2 alone will be 0.06°C per decade and be detectable in about 100 years in the climatological records. These findings indicate that CO_2 monitoring must be continued at least a similar length of time and be correlated with temperature records at selected climatological stations throughout the world to guard against the possibility that positive feedback mechanisms will amplify strongly the weak climatic effect.

The total supply of oxygen (O_2) in the atmosphere is 10^{21}grams (10^{15} metric tons). Fossil fuel combustion (which adds CO_2) removes a proportional amount of free oxygen, but burning the entire world resources of fossil carbon would deplete the O_2 supply by only about 0.8 percent (the O_2 content at 73 meters above sea level). Since 1910, a consistent value of 20.946 percent by volume of O_2 has been measured. Thus, while not considered to be a problem, the present rate of O_2 consumption is probably very close to that of its production by photosynthesis. It is possible that a positive feedback runaway mechanism might cause O_2 production to be less than losses from oxidation.

However, if all plants on Earth were to die suddenly (photosynthesis stopped) it would require 6,385 years to reduce the O_2 content to 60 percent of its present value. A decrease to a marginal level for humans would take 8,333 years, and everyone would have starved long before breathing became a problem.

Climatic effects of the pollution by nuclear weapons and tests involve several possible factors: worldwide changes in the pH (acid-base ratio) of rainwater, nucleating effects on clouds from bomb-raised dust, effects on the electrical parameters of the atmosphere, and pollution by oxides of nitrogen formed in the fireball. Although measurable effects on the electrical parameters have been detected, of these, only the last has been found to merit concern; nitrogen oxides, which are delivered in part to the stratosphere, can affect the photochemical equilibria that govern the ozone (O_3) concentration and reduce it, but evidence of that effect is inconclusive. Therefore, it is concluded that releases of nuclear energy have little effect on climate, especially if compared to the direct ecological effect of the radioactivity itself.

Concern over possible global effects of manmade particulate matter did not arise until 1954 during nuclear weapons testing, although local effects in urban areas had been considered. CO_2 is a stable, homogeneous, and mostly a well-mixed gaseous constituent of the atmosphere; however, particles are heterogeneous in chemical composition, size

76-572 O - 76 - 23

shape, and optical properties, their sources are much more variable, and sampling and measuring is more difficult than for CO_2. Modeling their effects on the radiation budget, and other studies of particles are thus much more difficult to perform than for gases.

Natural particles in the atmosphere arise from seven sources: wind-raised soil mineral particles, evaporated sea spray, volcanoes, forest fires, meteorites, oxidation of gases such as sulfur dioxide (SO_2), and oxidation of organic vapors from living and decaying vegetation. Turbidity in the troposphere can be measured by such methods as the electrical conductivity, lidar (laser radar), and direct sampling. The measurements show that manmade atmospheric turbidity is increasing downwind of large cities and, more regionally, downwind from highly industrialized nations, but with no appreciable increases in other regions, especially in the relatively nonindustrialized Southern Hemisphere, or in the atmosphere as a whole. Man's production of aerosols is estimated to be between 10 and 90 megatons annually (16 - 19 percent of the total), and most return to the surface within a few days to a few weeks. This short residence time in the air would seem to preclude any appreciable climatic effects except downwind from large cities.

To maintain a constant global mean temperature, Earth must lose to space the same amount of heat it receives from that source. Burning fossil fuels (solar energy formerly

received but held as potential energy for many millions of years) increases the mean global temperature. The solar input averaged over the globe and over the year is about 100 watts per square meter. The human contribution was computed (1970) to be about 0.0157 percent of the solar, or an elevation of only 0.01°C as a result of heat released by man's activities (recently computed to be growing at a rate of 5.7 percent per year). This contribution will rise to a maximum as more fossil fuels are burned, then begin to decrease as the world supply (estimated to be 3×10^6 megatons) is exhausted. At the estimated 1970 usage rate of 7.5×10^3 megatons per year, and at the growth rate as given above, this would be in the year 2032. At that time the energy release would be 0.54 percent of solar input and the temperature excess would be 0.39°C averaged globally, not considered to be a serious climatic factor. Unless a nearly limitless energy source such as hydrogen fusion becomes available, thermal pollution will not become a serious threat for some 75 years; the fossil fuel supply will be exhausted before the global mean temperature rise becomes climatically dangerous.

Pollution of the stratosphere can be serious because its relative stability results in long residence times for particulate matter therein which may affect both the atmosphere's physical state and its chemical composition. Aircraft flying at such high altitudes emit a variety of

combustion products, and gaseous effluents may be converted to particles by chemical and photochemical processes. The possible depletion of the fragile ozone (O_3) layer, which protects the surface (and man) from an excess of ultraviolet (uv) radiation, is an important consideration because more uv is related to more severe sunburn and possible increased incidence of skin cancer.

Increasing certain oxides of nitrogen (NO_x) from nuclear explosions, supersonic aircraft, and chlorine from refrigerants and aerosol spray propellants should tend to reduce the O_3 content in the stratosphere, if indeed they ever reach there. Models have been developed which indicate that O_3 could be substantially depleted should such be the case. However, measurements show that O_3 has been increasing on a global scale for the past 10 to 15 years, although a downward trend has set in for the past 3 years or so. It appears that long-term natural variations in global ozone are of about the same magnitude as are the suggested effects of pollution in decreasing it.

Large industrialized urban areas are the principal sources of air pollutants including waste heat, and the long-recognized differences between urban and rural climates downwind of them are understandable. These are examples of inadvertent local climatic changes that now may be relatively insignificant to man, but should the present exponential growth rates of energy release continue, long-term climatic effects may well be serious.

The role of urban smokes as fog and cloud condensation nuclei has been recognized for many years. Above-normal rainfall, snow, and hail have been observed and recorded downwind of many large cities and industrial concentrations in the United States. Of particular interest is the La Porte, Ind. anomaly where, during the years 1925-68, this small city was in an area which had 31 percent more precipitation, 38 percent more thunderstorms, and 246 percent more hail days than other stations some 30 km distant. Warm season precipitation for the period 1925-65 was highly correlated with annual steel production at mills upwind and with smoke/haze days at Chicago.

Results to date from a comprehensive experiment at St. Louis, Mo. (1971-75) show that total rainfall, lightning, and hail are maximum 15 to 25 km downwind of the urban area. The snow shower plumes that are downwind from Buffalo, Toronto, and Oshawa are further evidence of the inadvertent influences of urban industries on local weather and climate.

On the other hand, rainfall appears to be reduced where large amounts of cloud condensation nuclei from forest fires. agricultural burns, and volcanoes occur, probably in part because the increased turbidity of the atmosphere reduces solar heating and therefore the energy available to produce convective clouds.

The addition of water vapor to the atmosphere by human activities is trivial compared to the total water content of

the Earth-atmosphere system. However, altering the mean cloudiness might result in inadvertent modification. Under some atmospheric conditions, subsonic aircraft engine exhausts add moisture, and the resulting contrails may develop into extensive cloud systems. These could attenuate incoming solar radiation, and the surface temperature could be lowered appreciably. But such conditions are sporadic and are local or regional, probably manifested by slight surface cooling, a reduction in convective clouds and thunderstorms in summer, and a possible slight increase in winter precipitation.

Agricultural and industrial activities that extensively change the character of the Earth's surface can modify the microclimate over such areas. Factors include alteration of surface evaporation, albedo, roughness, amount of wind-raised particles, and water retention, any combination of which may result in climatic change. The local microclimate controls plant growth so that climatological data should be given great consideration before any extensive land use change is implemented. The extent to which global climate may be affected will be more or less proportional to the area of land involved.

The construction of mathematical models to incorporate in great detail the mechanics, physics, and chemistry of the air-ocean-land surface system in three dimensions and time is an essential goal to be reached if reliable advance warning of climatic change (natural or man-induced) is to be possible. The ultimate in climate models would have to include transport, radiative transfer, chemistry, air-sea interactions, topography

and albedo of land surfaces, the hydrologic cycle and clouds, and aerosols as turbidity and as nuclei, and be capable of predicting for hundreds or thousands of model years in a few hours of computer time. The effects of man's activities could then be compared with the statistical range of natural variability of climate, but much remains to be done before this will come about.

A summary of the more general finds of the literature survey show the following:

A gradual increase in CO_2 at about a 0.2 percent rate per year has been observed, but no parallel climatic trend is detectable.

The removal of oxygen (irreversible) by combustion should remain insignificantly small unless the supply of fossil fuel is vastly larger than now is known.

Manmade aerosols are undetectable globally, but are measurable on a local and regional scale. Reductions in the diurnal march of temperature locally is a result.

Hygroscopic nuclei such as sulfuric acid droplets are active as cloud condensation nuclei and cause longer lasting, more severe fog conditions locally.

The total of nonsolar heat is so slight as to elevate the global mean temperature by only 0.01°C. Released mainly over large cities, the frequency and duration of convective showers are increased in midlatitudes in the immediate area as a result.

Aircraft combustion products may cause artificial cloudiness, but appreciable loss of solar energy due to attenuation has not been noted.

Aircraft exhaust products such as oxides of nitrogen (NO_x) can reduce ozone, but those introduced by nuclear weapons testing have not significantly disturbed the ozone layer.

Refrigerants and spray can propellants can reduce ozone more effectively than NO_x, but records over the past 15 years do not indicate any appreciable decreases except during the past 3 years.

The effects of testing nuclear weapons are almost totally in the area of firing and a short distance downwind; they have not affected climate globally.

Land-use changes can cause variations in the evaporation from the surface, the albedo, the roughness, the amount of wind-raised particles, and the water retention, but they have the potential for modifying climate only on a scale comparable to the area involved in the change.

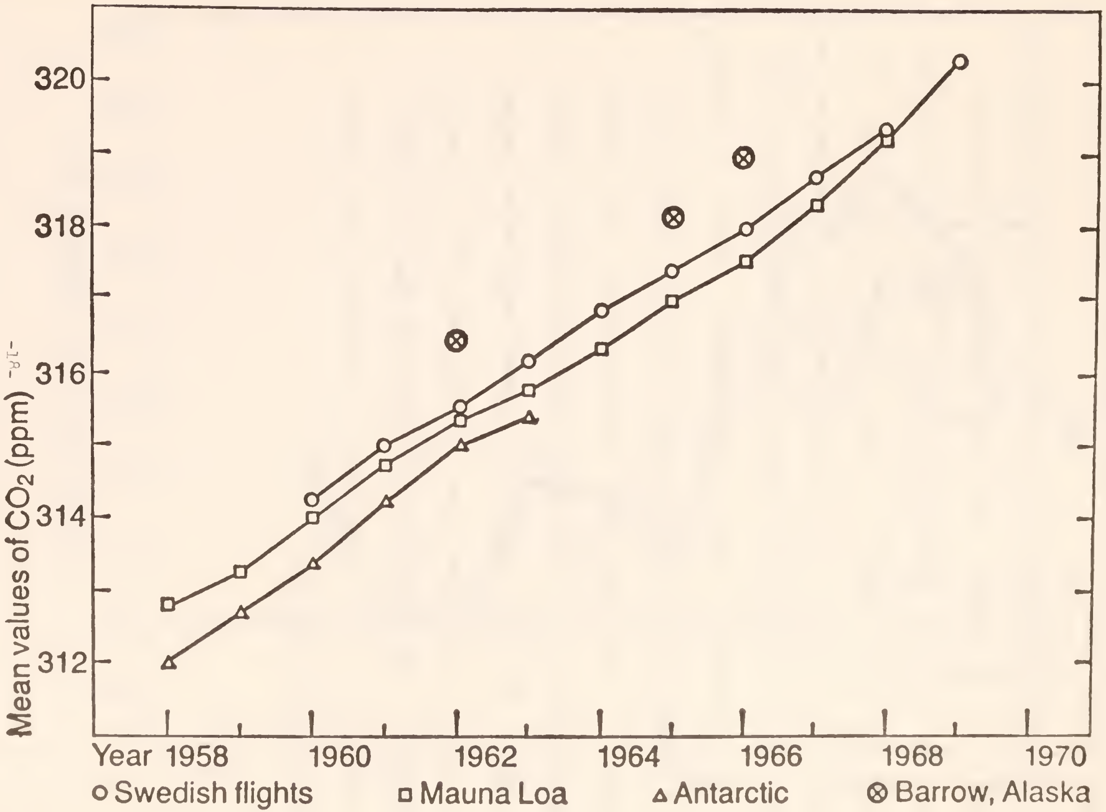
The global influences of all the pollutant effects noted herein are submerged in the "noise" of natural fluctuations, as yet unexplained.

Only the inhabitants of large urban areas in highly industrialized countries, and for short distances downwind, are feeling the relatively mild climatic effects of pollution as evidenced by higher temperatures, precipitation, and frequency of fog, than in the surrounding countrysides. Excepting chlorine-ozone interaction and land-use changes, all climatic

modifications are linked to combustion pollutants. A good forecast of future energy use will be the key to any successful forecast of the human impact on global climate. But monitoring programs and modeling research in climatic change should be expanded so the knowledge for possible counter measures will be available when the next global climatic oscillation occurs.

Caption for figure 1

Pollutants added to the atmosphere in industrialized areas cause measurable changes in the weather and climate in the immediate vicinity and for considerable distances downwind, but up until now it has not been possible to separate weather and climatic trends on a global scale from changes which are occurring naturally. However, one of the pollutants, carbon dioxide (CO_2), added as a result of the combustion of fossil fuels, has increased steadily in the past 15-20 years, and mean temperatures in the areas of its concentration have increased by several degrees celsius. Computerized models show that if the present rate of increase in the atmosphere's CO_2 load continues, global climatic changes will become detectable in about a century. The figure illustrates the trends in increased atmospheric CO_2 content measured at four widely separated locations for the period 1958-69. Although differing slightly in absolute values, the trends are highly similar for all sets. Mean values are in ppm (parts per million).



320
318
316
314
312
Mean values of CO_2 (ppm)
Year 1958
1960
1962
1964
1966
1968
1970
○ Swedish flights
□ Mauna Loa
△ Antarctic
⊗ Barrow, Alaska

Figure 1

Caption for figure 2

Growing industrialization adds to the air ever-increasing amounts of pollutants, including carbon dioxide, moisture, aerosols, heat, and particulate matter. Some of these pollutants may cause measurable change in weather and climate both where they originate and in areas downwind. Yet evidence that they have caused global climatic changes is submerged in the "noise" of natural climatic fluctuations. However, increases in the amount of carbon dioxide in the air by fossil fuel burning if continued at the present rate may cause surface temperatures to rise and cause significant global climatic changes. The figure shows annual mean temperature changes in degrees celsius for three latitude belts for the period 1870-1967. The horizontal bar gives the mean of temperature changes in the latitude belt 0°-80°N for the climatological epoch 1931-60.

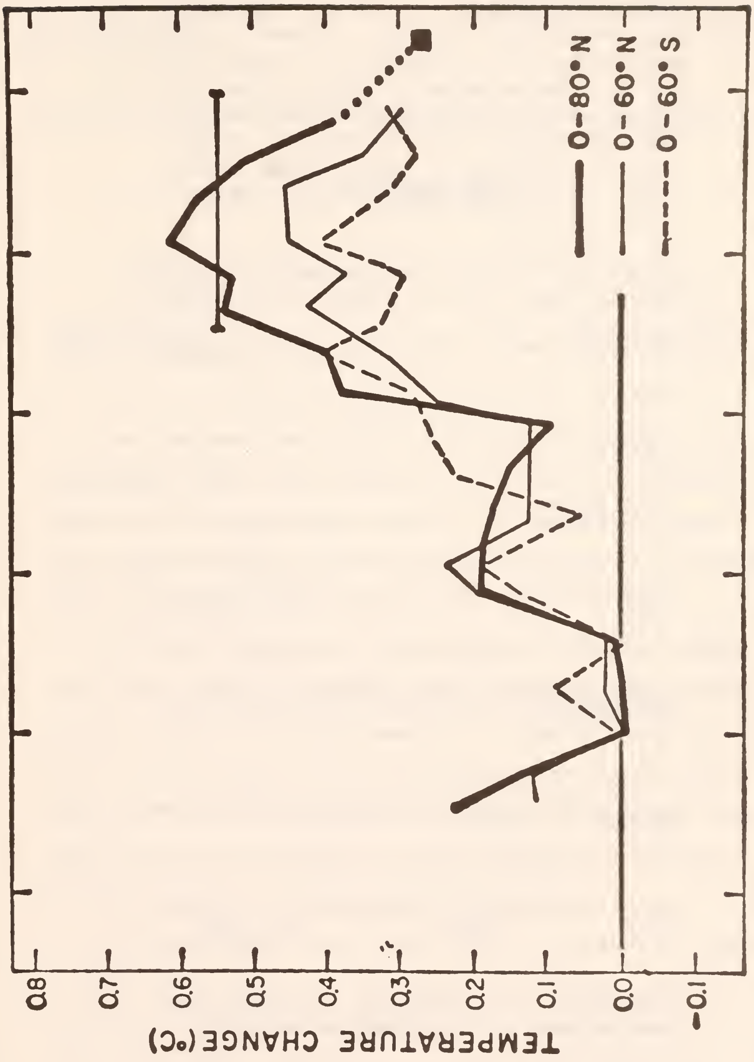

0-80° N
0-60° N
0-60° S
1860
1880
1900
1920
1940
1960
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
TEMPERATURE CHANGE (°C)

Figure 2

NOTE TO EDITOR: For further information concerning this release, or when copies are requested by the public, please address: Environmental Science Information Center, D83, Environmental Data Service, National Oceanic and Atmospheric Administration, Washington, D.C. 20235, Attention: William E. Hardy. Telephone is (202) 634-7336.

Prints of figures or illustrations of this SEN, if used, will be supplied on request.

Encircle number of the figure/s desired:

Figure 1 2 3 4 5 6 7 8 9

SEN-56

Send prints to:

____
Name

____
Periodical

____
Street

____
City State Zip Code

When any of this material is used, tear sheets from your publication would be appreciated.

Council on Environmental Quality
722 Jackson Place, N W
Washington, D C 20006

Federal Council for Science and Technology
1800 G Street, N W
Washington, D C 20550

INTERAGENCY TASK FORCE ON INADVERTENT MODIFICATION OF THE STRATOSPHERE (IMOS)

news

March 30, 1976

Warren R. Muir
(202) 382-6854

Carroll Leslie Pegler
(202) 632-7447

The Interagency Task Force on Inadvertent Modification of the Stratosphere (IMOS) today released a report, soon to be published, prepared by the Interdepartmental Committee for Atmospheric Sciences (ICAS), that assesses presently postulated man-made modifiers of the stratosphere other than fluorocarbons.

The report considers six classes of possible hazards: nitrogen fertilizers, brominated compounds, other chlorinated compounds, particles, the space shuttle, and carbon monoxide. The report concludes that "in each case there appears to be no immediate serious problem either because the concern is highly speculative or because it is based upon compounds that are not as yet released to the upper atmosphere in quantities believed sufficient to produce a hazardous effect."

During the study, a very large number of substances were considered and only those that at this time appear most potentially harmful are identified. The report also points out that the additive effects from several substances might become significant in the future, even if the effect from any individual substance is relatively small. The report

also cautions that there may well be materials yet to be invented or discovered that are serious candidates for concern, and urges agencies that deal in commerce, agriculture and with regulation and oversight of products and materials to be alert to all possible means of preventing inadvertent modification of the stratosphere now and in the future. The importance of increased research into the various postulated modifiers of the stratosphere is stressed.

IMOS was established in January 1975 by the Council on Environmental Quality, headed by Dr. Russell W. Peterson, and the Federal Council for Science and Technology, with Dr. H. Guyford Stever as Chairman. IMOS will continue its consideration of the possible hazards from these compounds and any related socio-economic and policy issues as part of its overall concern with the effects of man's activities on the stratosphere.

Copies of the printed report "Potential Modifiers of the Stratosphere Other than Fluorocarbons," will be available through the Government Printing Office and the National Technical Information Service. In the interim a limited supply of copies is available from Warren Muir, Council on Environmental Quality, 722 Jackson Place, N.W., Washington, D.C. 20006.

INTERAGENCY TASK FORCE ON INADVERTENT MODIFICATION OF THE STRATOSPHERE
IMOS

Council on Environmental Quality
722 Jackson Place N.W.
Washington D.C. 20006

Federal Council for Science and Technology
1800 G Street N.W.
Washington D.C. 20550

March 1976

In January 1975 Dr. Russell W. Peterson, Chairman of the Council on Environmental Quality and Dr. H. Guyford Stever, Chairman of the Federal Council for Science and Technology, formed an Interagency Task Force on Inadvertent Modification of the Stratosphere (IMOS) consisting of representatives of 13 Federal agencies and one interagency committee (the Interdepartmental Committee for Atmospheric Sciences). The first effort of IMOS was an assessment of the possible effects of fluorocarbons upon stratospheric ozone. This assessment and recommended Federal actions, Fluorocarbons and the Environment (GPO #038-000-0026-1), was published in June 1975.

An assessment of the possible impacts of other non-fluorocarbon modifiers of the stratosphere was deferred until the study on fluorocarbons could be completed. This report prepared by the Interdepartmental Committee for Atmospheric Sciences (ICAS), constitutes the findings of a group of experts brought together to discuss all presently postulated man-made modifiers from other than aircraft emissions or nuclear detonations -- although others may be as yet undiscovered.

The findings of the group point to the need for further research. Fortunately, in each case there appears to be no immediate serious problem, either because the concern is highly speculative or because it is based upon compounds that are not as yet released to the upper atmosphere in quantities believed sufficient

to produce a hazardous effect. IMOS will continue its consideration of the possible hazards from these compounds and any related socio-economic and policy issues as part of its overall concern with the effect of man's activities on the stratosphere.

We hope that this report will be of value not only to the scientific community but to the public as well.

Warren R. Muir
Co-chairman (for Council on Environmental Quality

Carroll Leslie Pegler
Co-chairman (for Federal Council on Science and Technology

POTENTIAL MODIFIERS OF THE STRATOSPHERE OTHER THAN FLUOROCARBONS

At the request of the IMOS, the ICAS has undertaken the task of identifying and assessing substances, other than Fluorocarbons 11 and 12, (F-11, -12) that could potentially prove harmful to the stratospheric ozone layer. To accomplish this work the ICAS obtained the advice of persons having knowledge of appropriate subjects bearing on the ozone chemistry and related issues. (The names of the contributors are listed in an appendix to this report.) The group met on September 24, 1975, in the National Science Foundation.

GENERAL COMMENTS

1. There are a large number of man-made substances that are potentially capable of damaging the ozone layer. Most of these, however, are produced and released to the atmosphere or hydrosphere in too small amounts to be individually threatening. Nonetheless, in the aggregate these materials might be as dangerous, or more so, than the relatively few that are produced in large amounts.

2. Chemical technology and techniques involving the use of chemicals are continually changing. Potentially harmful substances that are now produced in small amounts may in a few years be released in much larger amounts; substances that are unknown today may emerge and become threats.

3. Many of the materials that might be harmful to the ozone layer could also produce other insults to the environment, e. g. the recent postulation that F-11 and F-12 can produce a "greenhouse effect" and thus, like CO_2, change the global temperature in the atmosphere. These possibilities ought to be considered in any regulatory actions that are contemplated.

4. An "acceptable level" of ozone depletion has not been established; it is not likely that such a level can be specified. If such a standard were defined, how could "shares" of the "acceptable level" of depletion be "rationed" among compounds that are subsequently proven to be harmful? How could such "rationing" be accomplished among nations? Are there mechanisms for international control of harmful substances?

5. It is strongly argued that atmospheric chemistry has too long been neglected and that an adequate program could provide the data so evidently lacking in our ability to assess possible threats to the stratospheric ozone layer. Such a program must be a continuing one, rather than simply responding to the current questions.

6. Considering the imperfect understanding of such things as stratospheric chemistry, atmospheric transport processes, and other physical information, the ICAS emphasizes, in the strongest possible way, the highly speculative nature of the predictions of ozone depletion.

EXCLUSIONS

Because they have been dealt with explicitly elsewhere, F-11, F-12, No_x from supersonic and subsonic aircraft, and nuclear testing and warfare are excluded from consideration.

SPECIFIC POTENTIAL THREAT MATERIALS

1. Fertilizer

Why: N_2O released to the air during the nitrogen cycle from both land and sea is capable of being transported into the stratosphere. After photochemical conversion to NO_x, it can cause catalytic destruction of ozone. There have been estimates by the industry that fertilizer production will have increased five-fold by about 1995. In addition other possible man-caused disturbances of the biosphere, such as acidification of the soil, might significantly enhance the amount of N_2O released to the atmosphere. Dr. McElroy's computations suggest a very large ozone depletion (30%) from such a large increase in fertilizer usage. Crutzen, on the other hand, estimates a maximum depletion of under 2% by the year 2000 AD.

Conclusions:

There is insufficient information, particularly concerning the amount, if any, and the time (it might take centuries or longer), of N_2O increase from denitrification due to increased world usage of fertilizers. But more particularly, the ICAS stresses that the potential ozone reduction is but one, perhaps even a minor part of the overall consequence of large increases in fertilizer application to grow more food. For example, new techniques of fertilizer applioations to reduce fertilizer requirements may be vital for both future energy and natural resource conservation. Denitrification is a poorly understood process that depends in complex ways upon a number of factors, such as soil acidity, soil bacteria, and soil moisture; research that is needed in order to understand it and thus resolve the main uncertainty associated with the effects of fertilizer on ozone, will be difficult and interdisciplinary, and will require many years, perhaps decades, to complete. Even if it turns out that there is no threat to the ozone layer from fertilizer, the results of this research will be very valuable for other purposes.

There is considerable uncertainty concerning the apportioning of the sources of N_2O in the atmosphere. One group (McElroy) argues that 80% comes from the land surface and 20% from the sea; another group (under Junge in Germany) says the opposite, 20% coming from land and 80% from the sea.

Measurements of N_2O fluxes from land and sea and long-term monitoring of the atmospheric content of N_2O, to determine whether or not it is increasing, must be a part of the program.

Evaluation:

A provisional analysis suggests that decades rather than years are available before a significant ozone reduction may take place. This is fortunate since the research to assess the threat could take decades, as just noted.

---

*Concern about a possible finite tropospheric residence time of N_2O (perhaps tens of years) raises questions about our understanding of the natural chemical destruction of ozone in the stratosphere. This concern emphasizes the need to initiate prompt research on N_2O and ozone.

2. Brominated compounds

Why: Gaseous bromine acts catalytically to destroy ozone in a manner that is similar to chlorine. The loss of Br to HBr, however, is thought to be less effective than the loss of Cl to HC. Thus bromine is potentially more effective than chlorine in ozone reduction on a molecule for molecule basis. Man-made brominated compounds used as fumigants, as brominated fluorocarbon fire retardants, and as components of automobile exhaust may increase in the future.

Conclusions:

The assessment of the harm to the ozone layer from a given amount of stratospheric bromine cannot now be made with sufficient confidence due to the absence of vital chemical rate constant information. Further, the natural and the man-made sources of bromine and its chemical nature are not well known. It is felt that this information could be determined in a matter of a few years and at a relatively low cost.

Evaluation:

No sense of immediate urgency is noted, but there is need to resolve the uncertainties in order to assess this potential threat with confidence.

3. Other Chlorinated compounds

Why: Only a small part of the industrial chlorine manufactured is used for the production of F-11 and F-12; many other chlorinated compounds could potentially provide a source of stratospheric chlorine. The assessment of such additional sources of stratospheric chlorine is hampered by the lack of measurements of many of the candidate compounds, particularly in the stratosphere, and by an incomplete knowledge of tropospheric residence times. Information on emission of these substances to the atmosphere may be reasonably valid.

Conclusions:

The main new emphasis regarding other chlorinated compounds lies in the need to consider the potential threat of secondary chlorinated products, other than the fluorocarbons, that are emitted to the atmosphere. Tropospheric and stratospheric measurements and determination of the atmospheric residence times of the substances listed in the accompanying

figures and table should be obtained. Other reaction products involving chlorine should also be investigated, e. g. chlorinated substances produced in the processes involved in bleaching of paper products with chlorine.

Evaluation:
Since the ongoing emissions might possibly be significant now or in the future and because new candidate halocarbocarbons may be under consideration, as substitutes for F-11, F-12, and others, this aspect of the program deserves prompt action.

4. Particles

Why: Although it is considered to be unlikely, particles in the stratosphere might act as a sink for ozone through heterogeneous chemical reactions. Further, particles in the stratosphere play a role in the radiation balance of the atmosphere. There is a suggestion by Crutzen that the sulfate particles in the Junge layer lying above the tropopause may be formed from the photodissociation of carbonyl sulfide (COS). It is possible that the source of COS may be increased due to a growing use of sulfur-bearing coal as an energy source.

Conclusions:
The destruction by particles does not appear to be a likely important sink of stratospheric ozone. However, the growth of carbonyl sulfide in the atmosphere deserves attention.

Evaluation:
No sense of immediate urgency is noted but the growth and role of COS in the air should be followed.

5. Space Shuttle

Why: The propellants planned for the space shuttle will emit HCl into the stratosphere which, when converted to ClO will destroy ozone molecules. Although the emission amounts are small compared to say, the fluorocarbons, the injection takes place directly into the stratosphere.

Conclusions:
Provisional analysis indicates very small ozone decreases. The space shuttle flights are not to start until about 1980. This suggests that IMOS await the review of a report on the subject by NASA expected in the Spring of 1976 before the issue is treated by IMOS.

Evaluation:
No action is deemed necessary until the NASA report noted above is available and analyzed.

6. Carbon-Monoxide

Why: Chemical kinetics indicate that the tropospheric concentration of the OH radical is in part controlled by the concentration of CO. One analysis indicates that about half the northern hemisphere lower tropospheric content of CO is man-made and can therefore increase with time. Should the increase occur with a concommitant reduction in OH, the expected

destruction of many chlorinated compounds in the troposphere might be reduced allowing more to enter into the stratospehre.

Conclusions:

No conclusion is drawn from this scenario, but the scientific community should watch for any significant growth in the release of CO (mainly from automobiles). Observations of CO concentrations in uncontaminated air should provide the required data.

Evaluation:

No sense of urgency is assigned to this potential, indirect threat.

The lack of immediate urgency associated with most of the threats treated in the foregoing paragraphs is drawn from the best available evidence as to the point in time when each of the materials discussed might produce a significant reduction in the stratospheric ozone layer; at present most of the threats are predicted not to constitute a serious hazard for a decade or more. This fact, however, should not be interpreted as implying that there can be a delay in commencing the required research efforts because:

(a) The predictions may be in error in such a way that the ozone depletion might occur sooner and that it might be more marked than now expected.

(b) The research needed to determine the validity and extent of the threats to the stratospheric ozone layer may take an extended period of time; this possibility is especially important in the case of fertilizers.

Thus there exists an urgent need for resolving each of the postulated threats irrespective of the time scale associated with the postulated effects. Research to resolve each of the threats should begin at the earliest possible time.

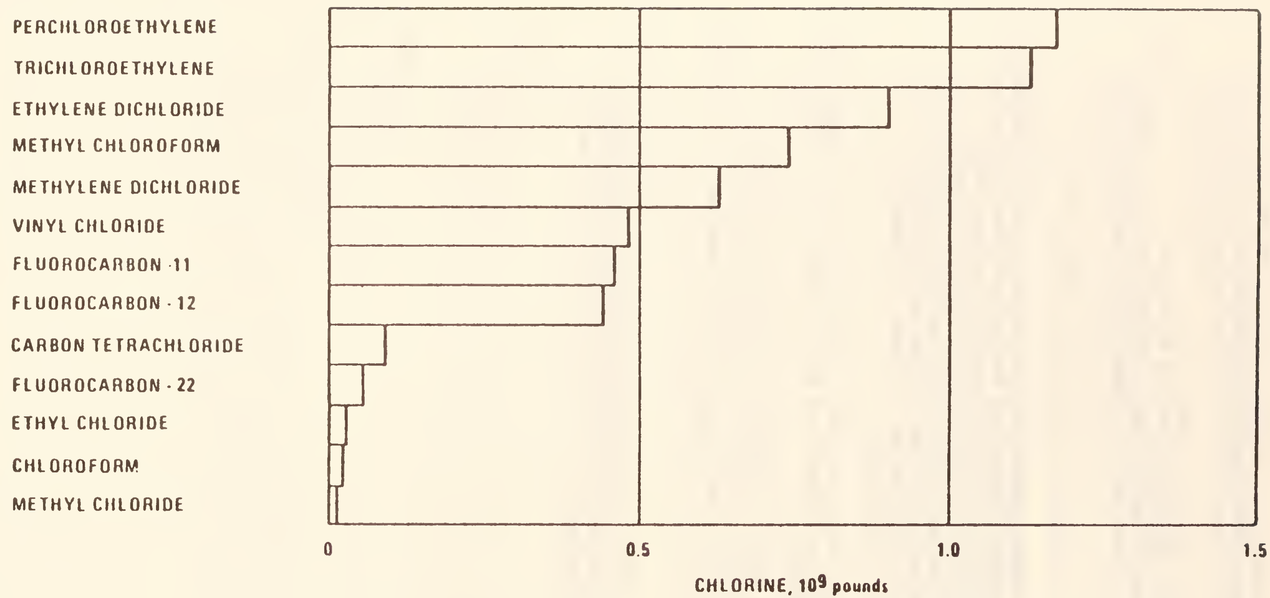


Figure 1. World-wide chlorine content of major man-made chlorinated pollutants - 1973.

This figure was constructed from data contained in a draft report Preliminary Economic Impact Assessment of Possible Regulatory Action to Control Atmospheric Emissions of Selected Halocarbons prepared for U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, N.C. 27711, by Arthur D. Little Inc., Acorn Park, Cambridge, Mass. 02140, July 1975.

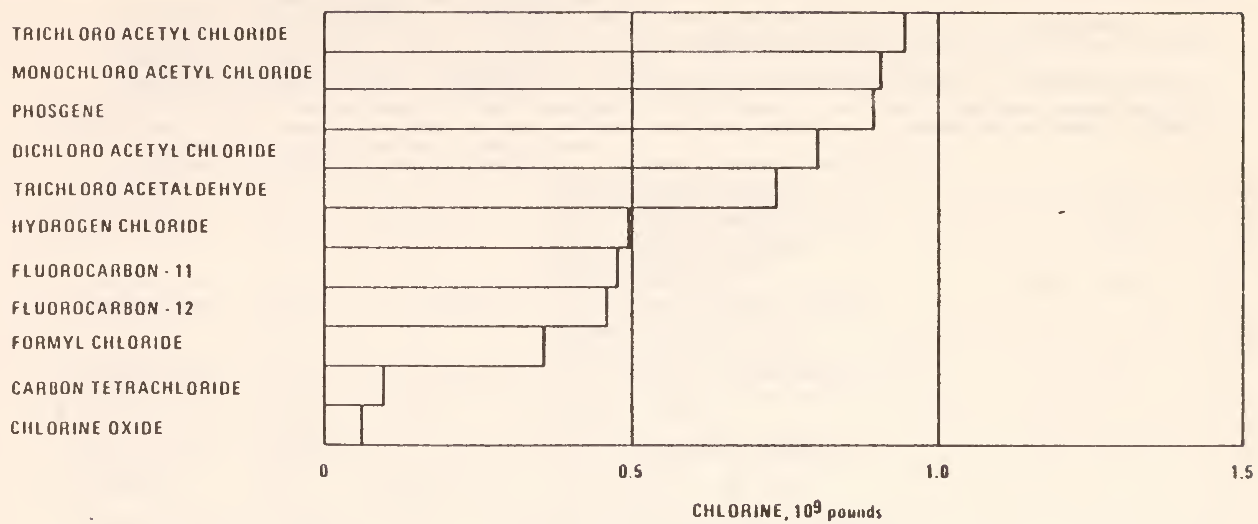


Figure 2. World wide amounts of chlorine in halogenated compounds after photo-oxidation in troposphere and lower stratosphere - 1973.

The above Figure was constructed by adding together the estimated amounts of products of photooxidation of all the pollutants in Figure 1. These are the first products formed; many of them will be further transformed before removal.

SELECTED PERTINENT DATA ON CHLORINATED COMPOUNDS

NAME	FORMULA	1973 Release[1] 10^9 lbs	Residence Time, yrs[2]	Reaction Products, Assumed percent chlorine content, and assumed chlorine amount, 10^9 lbs
F-22	$CHClF_2$	0.050	0.3-10	Chlorine monoxide, 100%,0.050
Carbon tetrachloride	CCl_4	0,084	100+	Carbontetrachloride, 100%, 0.084
Chloroform	$CHCl_3$	0,011	0.2-0.3	Phosgene 67%-0.008 Chlorine monoxide 335-0.003
Ethyl Chloride	C_2H_5Cl	0.015	0.3	Formyl chloride,100%-0.015
Ethylene dichloride	$C_2H_4Cl_2$	0.90	0.3	Monochloroacetyl chloride, 100%-0.90
Methyl Chloride	CH_3Cl	0.007	0.37-0.9	Formyl chloride, 100%-0.007
Methyl chloroform	$C_2H_3Cl_3$	0.74	1.1-3	Trichloroacetaldehyde, 100%-0.74
Methylene chloride	CH_2Cl_2	0.63	0.3	Phosgene, 100%-0.63
Perchloroethylene	C_2Cl_4	1.17	0.01-0.3	Trichloroacetyl chloride,80%-0.93 Phosgene,10%-0.12 Hydrogen chloride,10%-0.12
Trichloroethylene	C_2HCl_3	1.12	0.001-0.01	Dichloroacetyl chloride, 70%-0.79 Phosgene,12%-0.13 Formyl chloride, 8%-0.09 Hydrogen chloride, 10%-0.11
Vinyl chloride	$C_2H_3Cl_3$	0.48	0.001	Formyl chloride, 50%-0.24 Hydrogen chloride, 50%-0.24

1. Estimated world-wide release of chlorine to the air, in billions of pounds
2. Estimated tropospheric residence time in years.

NOTES -Higher priority should be assigned to those compounds with large releases to the atmosphere and longer tropospheric residence times. When information on the tropospheric residence times of the reaction products becomes available those substances should also be considered.

-There may be other chlorinated compounds, other than those noted in this table,that merit consideration, such as byproducts resulting from the bleaching of paper products.

-If there are to be large increases in the release to the atmosphere of the above listed or other chlorinated compoundsresulting from new industrial activity or uses as substitutes for existing compounds (e.g.F-31)those subject to increased release must then receive careful attention.

-There is, unfortunately, very little information on the tropospheric residence times of the reaction products from which to derive possible threats to the stratosphere.

Compound Name and Formula	1973 Estimated World-Wide Chlorine Release to the Air, 10^9 lbs.	Estimated Tropospheric Residence Time Years	Reaction Products and Their Assumed Chlorine Percentages and Amounts in 10^9 lbs.	
Perchloro-ethylene, C_2Cl_4	1.17	0.01	Trichloro acetyl chloride (80%)	0.93
Trichloro-ethylene, C_2HCl_3	1.12	0.001	Dichloro acetyl chloride (70%)	
			Phosgene - 12%	0.13
			Formyle chloride - 8%	0.09
			Hydrogen chloride - 10%	0.11
Ethylene di-chloride $C_2H_4Cl_2$	0.90	0.3	Monochloro Acetyl chloride - 100%	0.90
Methyl chloro-form, CH_3CCl_3	0.74	1.1	Trichloro acetaldehyde (100%)	0.74
Methylene chloride CH_2Cl_2	0.63	0.3	Phosgene - 100%	0.63
Vinyl chloride C_2H_3Cl	0.48	0.001	Formyl chloride - 50%	0.24
			Hydrogen chloride -50%	0.24
Fluorocarbon-12 CCl_2F_2	0.44	100.	Fluorocarbon-12 - 100%	0.44
Fluorocarbon-11	0.46	100	Fluorocarbon 11 - 100%	0.46
Fluorocarbon-22 $CHClF_2$	0.050	0.3	Chlorine monoxide - 100%	0.050
Carbon tetra-chloride, CCl_4	0.084	100	Carbon tetrachloride - 100%	0.084

Compound Name and Formula	1973 Estimated World-Wide Chlorine Release to the Air, 10^9 lbs.	Estimated Tropospheric Residence Time Years	Reaction Products and Their Assumed Chlorine Percentages and Amounts in 10^9 lbs.	
Ethyl chloride C_2H_5Cl	0.015	0.3	Formyl chloride - 100%	0.015
Chloroform $CHCl_3$	0.011	0.2	Chlorine monoxide - 33%	0.003
Methyl chloride CH_3Cl	0.011	0.4	Formyl chloride - 100%	0.007

Discussion Group Members

Anthony Broderick	Department of Transportation Transportation Systems Center Cambridge, Mass.
Frank Eden	National Science Foundation
Philip L. Hanst	Environmental Protection Agency Research Triangle Park, Raleigh, North Carolina
Lester Machta	NOAA, Silver Spring Md.
George Stanford	USDA, Agricultural Research Service Beltsville, Maryland
Gene Adams	National Science Foundation
James King	NASA
Robert Watson	University of Maryland
S. C. Wofsy	Harvard University
Hugh Albers	ICAS, Executive Secretary
James P. Friend	Drexel University

NATIONAL SCIENCE FOUNDATION

news

Ralph Kazarian
(202) 632-5728
Home: (703) 451-0681

FOR RELEASE:
April 12, 1976
NSF PR76-33

STUDIES SHOW GLOBAL WEATHER MAY BE WARMING, NOT COOLING, ENVIRONMENTAL SCIENTISTS REPORT

Contrary to some reports of world-wide cooling, a warming trend in the southern hemisphere may be more than offsetting the observed cooling that is confined to the high northern portions of the globe, according to environmental scientists at two universities.

The scientists came to their conclusion after analyses of data gathered at 67 southern hemisphere stations, including six in Antarctica.

The scientists reported that, except for regional fluctuations, their analyses of the data from the 67 stations show no significant changes from the equator to 45 degrees south latitude. Nevertheless, their studies confirmed a warming trend in Australia and New Zealand and "strongly suggest" a marked warming trend at higher southern latitudes which, they said, may exceed in magnitude a high northern latitude cooling trend.

The researchers are Dr. Paul E. Damon, professor geosciences at the University of Arizona, and Steven M. Kunen, senior environmental chemist at the University of Utah Research Institute. Their research was funded by the Division of Earth Sciences of the National Science Foundation (NSF).

The scientists said that global cooling observed since the early 1940's has been limited largely to the northern hemisphere and, perhaps, sub-equatorial Africa.

"We are confident that large regions of the northern and southern hemispheres have experienced opposite changes in surface temperature during the last three decades," the scientists said. "However, there are insufficient data to precisely and confidently specify the trend in global climate as a whole."

The scientists pointed out that carbon dioxide and particulate matter are the two main pollutants that may be affecting current climate trends. The principal source of the man-made portion of these pollutants is the highly populated and industrialized northern hemisphere. It has been shown that the difference between carbon dioxide concentration in both hemispheres will be small because of the relatively fast mixing rates in the atmosphere. On the other hand, they said, they feel particulate pollution doesn't become as thoroughly mixed throughout the global atmosphere as carbon dioxide molecules because many of the particulates fall out or are cleansed out by rain.

As a result, the climatic effect of carbon dioxide will be almost equal in both hemispheres, while the effect of particulate matter will be more intense in the highly industrialized northern hemisphere, they reported.

There seems to be general agreement that the effect of the increasing burden of atmospheric carbon dioxide will be global warming, the greenhouse effect, the researchers said. The greenhouse effect is the result of solar radiation absorbed by the earth being converted into longer wavelengths and thus being prevented by carbon dioxide from being lost to space. This results in a gradual increase in the temperature of the atmosphere. There also is general agreement that climatic trends are amplified at high latitudes in both hemispheres. Dr. Damon attributes this to the snow and ice cover at the extreme north and south affecting the solar reflectivity.

If the greenhouse effect causes a global warming, it probably will become apparent first in Antarctica, the scientists said. A warming trend was observed at five out of six Antarctic weather stations used in their study.

"Is this the first indication of an imminent global warming?" the scientists asked in a paper reporting on their research.

They said a coordinated international effort is needed to monitor factors affecting global climate and to check world-wide climate trends. The monitoring recommended by the investigators would include not only an increased number of surface and upper air weather stations, but also increased observations of all factors affecting the albedo or reflectivity of earth--such

as cloud, ice and snow coverage. It also should include a definitive study of solar energy variations during several 11-year solar cycles, the scientists said.

Dr. Damon and Kunen first presented their research results in a paper at an Antarctic symposium at Victoria University in Wellington, New Zealand.

In another research effort, sponsored by the NSF's Office of Polar Programs, Dr. Robert H. Thomas, a research associate at the University of Nebraska-Lincoln, has reported finding a "fairly consistent" temperature increase of one degree centigrade on the eastern part of the Ross Ice Shelf in Antarctica. This observation substantiates the analyis by Dr. Damon and Kunen.

The ice temperature at 10-meter depths in the ice shelf is approximately equal to the average annual air temperature at the surface. Dr. Thomas took measurements of 10-meter temperatures at 47 stations in the eastern part of the ice shelf from 1973 to 1975 and compared these to measurements made in 1958 at 25 stations in the same area. The comparison revealed the temperature increase.

"During the same period," Dr. Thomas said, "in the northern hemisphere at mid and high latitudes, average temperatures decreased, and there appears to have been an anti-phase relationship between the northern and southern hemispheres."

The Ross Ice Shelf where Dr. Thomas made his measurements is the largest floating ice sheet in the world. It has an area about equal to that of Texas and the ice thickness ranges from about 300 to 900 meters (990 to 2,970 feet).

While one degree centigrade does not seem like much of a change, Dr. Damon pointed out that the "Little Ice Age"--from about the 16th century through the 18th century--was the result of just such a change in temperature. The Little Ice Age had a marked effect on human history since it had, among other things, a big effect on agriculture, he said.

21 May 1976, Volume 192, Number 4241 **SCIENCE**

Solar Structure and Terrestrial Weather

After more than a century of controversy this subject may be moving toward scientific respectability.

John M. Wilcox

Claims for a connection between the variable sun and the earth's weather can be found in a literature of well over 1000 published papers during the past century. The subject has been discussed by such illustrious authors as Herschel, Gauss, Sabine, Faraday, Wolf, Stewart, Schuster, and Airy. Nevertheless, the subject has tended to remain on the fringes of respectable science.

Observations of the changing sun are not now employed in routine weather forecasting. Many scientists are reluctant to admit the possibility of such an influence. Perhaps the main stumbling block involves energy considerations. The variation of the amount of energy received at the earth in connection with the variable sun is rather small compared to the energy in the general circulation of the earth's atmosphere. By the variable sun I mean any changes on a time scale of a few days in the sun as viewed from the earth. Lacking a knowledge of the physical mechanism(s) that may be involved, I cannot be more specific.

Such concern with energy is undoubtedly valid, but may not be conclusive. It may be instructive to consider the situation at the turn of the century. It had been noted that geomagnetic activity often increased after a large solar flare. Furthermore, days with enhanced geomagnetic activity sometimes recurred at intervals of 27 days, the solar rotation period. This led to suggestions that geomagnetic activity was caused by the sun.

In his famous presidential address in 1892 to the Royal Society, Lord Kelvin (*1*) made a stiff dismissal of such claims. He calculated the energy associated with 8 hours of a not very severe geomagnetic disturbance, and concluded that in order to supply this energy to the geomagnetic field "as much work must have been done by the Sun in sending magnetic waves out in all directions through space as he actually does in four months of his regular heat and light." Lord Kelvin's calculations were quite correct within the framework of his knowledge. He did not know about the solar wind, which extends the solar magnetic field away from the sun in all directions and completely changes the energetic considerations. We may wonder if an unknown process comparable in importance to the solar wind may be part of a causal chain between the variable sun and the earth's weather.

It seems possible that sun-weather investigations are finally beginning to move to a position of scientific respectability. The most firm conclusion that I would draw is not related to any specific claim, but rather is that this subject has reached a state in which it merits the consideration of serious scientists (*2*). Such consideration is indeed increasing as witnessed by several symposia on the subject, the most recent of which was held in 1975 at the 16th General Assembly of the International Union of Geodesy and Geophysics in Grenoble. It is encouraging that such symposia have been attended by solar physicists and meteorologists, who are thus beginning to bridge the interdisciplinary gap.

Some Recent Work

I will now describe some recent work involving the cooperative efforts of several scientists at several institutions. For a decade or more W. O. Roberts at the National Center for Atmospheric Research and the University of Colorado in Boulder has been a leading American worker on the subject of sun-weather interactions. Some recent work by Roberts and Olson (*3*) studied days on which geomagnetic activity had a sizable increase, which was assumed to have a solar cause. They also studied the history of low-pressure troughs (cyclones) from the Gulf of Alaska as they moved across the continental United States, and found that troughs associated with geomagnetic activity were significantly larger on the average than troughs associated with intervals of quiet geomagnetic conditions. The vorticity area index, a measure of the size of low-pressure troughs devised by Roberts and Olson, has been used in several subsequent investigations.

A low-pressure trough is a large rotary wind system, having a diameter of a few thousand kilometers, that is usually associated with clouds, rain, or snow. Although the formation and structure of low-pressure troughs have been studied in some detail, it is not possible in general to predict the time and place at which a trough will form. This is one reason why the skill in short-range weather prediction becomes small (that is, little better than a prediction of average properties) within 2 or 3 days (*4*). The vorticity area index devised by Roberts and Olson can be computed from maps of the height of constant-pressure (300-mbar) surfaces by using the geostrophic wind approximation. These maps are prepared twice a day, at 0 and at 12 universal time (U.T.), by the National Weather Service. The circulation of the air mass in a trough is defined as the line integral of the velocity of the air around a closed path. Vorticity is defined as the circulation per unit area. In our use of the vorticity area index, it is computed for the portion of the Northern Hemisphere north of 20°N. The index is

The author is an adjunct professor at the Institute for Plasma Research, Stanford University, Stanford, California 94305.

now defined as the sum of all areas in which the vorticity exceeds a certain threshold, which is chosen so that all well-formed troughs are included. Once the threshold level (20×10^{-5} sec^{-1} in our work) has been chosen, the computation of the vorticity area index is completely objective.

The results of the investigations to be described in this article will be presented in terms of graphs in which the meteorological input to the investigation is plotted on the ordinate and the solar input is plotted on the abscissa. The meteorological input is the vorticity area index just described. Now we must consider what the solar input will be.

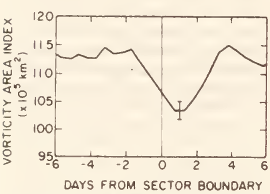
Roberts and Olson (*3*) assumed that the increases in geomagnetic activity used in their analysis were caused by the changing sun. This assumption was challenged by Hines (*5*), who suggested that some geomagnetic activity may be caused by current systems induced by motions of the lower atmosphere. To the extent that this assumption is correct, the assumed chain "sun → geomagnetic increase → weather change" would be replaced by a closed circle "weather change → geomagnetic activity → weather change." In my opinion such an influence on the investigations of Roberts and Olson (*3*) can probably be neglected. Nevertheless, it is clearly an advantage in this situation if a structure that is clearly of solar origin can be used for the solar input in the investigation.

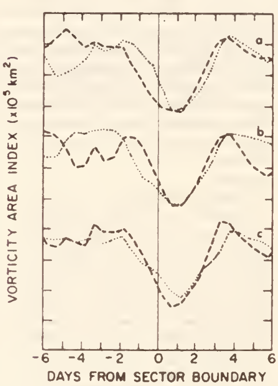
For this purpose we consider the solar sector structure, which is a fundamental large-scale property of the sun. A description of several solar, interplanetary, and terrestrial properties of this structure is available (*6*). The structure is readily perceived in observations by spacecraft magnetometers of the interplanetary magnetic field that is swept past the earth by the solar wind. For several consecutive days this interplanetary field will be observed to have a polarity directed away from the sun. For the next several days it will be observed to have a polarity directed toward the sun. These two sectors are separated by a thin boundary that typically is swept past the earth during an interval measured in tens of minutes.

In the investigations described here, the time at which a sector boundary is observed to sweep past the earth is used as a zero phase reference. This sharply defined time is very convenient for the analysis, but it must be emphasized that the sector boundary itself is probably not an important influence on the weather. Furthermore, the large-scale sector pattern of the interplanetary magnetic field (and associated structures in the solar wind) is not necessarily a physical influence on the weather. The solar influence (if there is one) described in this article could be related to variations in the solar ultraviolet emission, in the solar "constant," in some manifestation of the changing solar magnetic field such as energetic particle emission, in an influence of the extended solar magnetic field on galactic cosmic rays incident at the earth, or in some other unknown factor. In any event, the extended solar sector structure as observed with spacecraft in the interplanetary magnetic field near the earth is clearly a solar structure that is not influenced by terrestrial weather. We now consider further the possibility that some aspect of the solar structure may influence the weather.

Extension of Earlier Investigations

Our group at Stanford joined forces with Roberts and Olson to extend their original investigations. The first results (*7*) of this collaboration are shown in Fig. 1, where the average change in the vorticity area index is plotted against days from sector boundary as the sector structure is swept past the earth by the solar wind. Day zero represents the time at which a sector boundary passed the earth. We see in Fig. 1 that on the average the vorticity area index reaches a minimum approximately 1 day after the boundary passage. The amplitude of the effect from the minimum to the adjacent





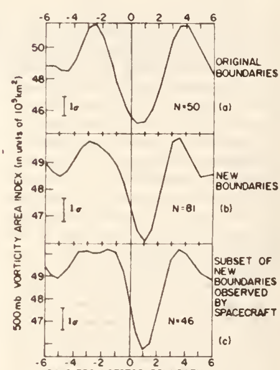
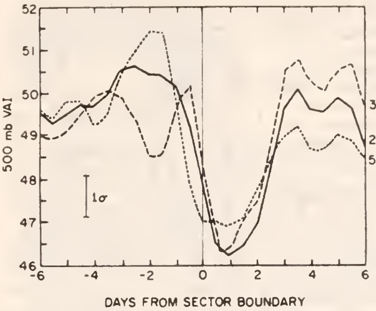


Fig. 1 (left). Average response of the vorticity area index (the area of all the low-pressure troughs in the Northern Hemisphere) about times when solar magnetic sector boundaries were carried past the earth by the solar wind. Sector boundaries were carried past the earth on day 0. The analysis includes 53 boundaries during the winter months November to March in the years 1964 to 1970. The standard error of the mean (error bar) was calculated after subtracting a 27-day mean centered on each sector boundary, to remove long-term trends. The deviations corresponding to the individual boundaries are consistent with a normal distribution about the mean. Fig. 2 (middle). Same format as Fig. 1. The list of boundaries used in Fig. 1 was divided into two parts according to (a) the magnetic polarity change at the boundary, (b) the first or last half of the winter, and (c) the yearly intervals 1964 to 1966 and 1967 to 1970. (a) The dotted curve represents 24 boundaries in which the interplanetary magnetic field polarity changed from toward the sun to away from the sun, and the dashed curve 29 boundaries in which the polarity changed from away to toward. (b) The dotted curve represents 31 boundaries in the interval 1 November to 15 January, and the dashed curve 22 boundaries in the interval 16 January to 31 March. (c) The dotted curve represents 26 boundaries in the interval 1964 to 1966, and the dashed curve 27 boundaries in the interval 1967 to 1970. The curves have been arbitrarily displaced in the vertical direction, but the scale of the ordinate is the same as in Fig. 1; that is, each interval is 5×10^{5} km^2. Fig. 3 (right). Same format as Fig. 1 for (a) 50 of the boundaries used in the original work, (b) 81 new boundary passages not included in the original analysis, and (c) a subset of (b) in which the times of 46 boundary passages were determined from spacecraft observations.



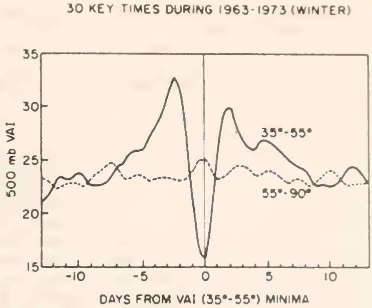


Fig. 4 (left). Similar to Fig. 3, except that the results are shown separately for the latitude zones 35°N to 55°N and 55°N to 90°N, and for the entire Northern Hemisphere north of 20°N. The form of the minimum at 1 day after the boundary passage is rather similar in all of these latitude zones. Fig. 5 (right). Same as Fig. 4, except that the key days are 30 minima in the latitude zone 35°N to 55°N that are not near sector boundaries (see text). The solid curve shows the results for the zone 35°N to 55°N, and the dashed curve shows the results for the zone 55°N to 90°N. The deep minimum in the lower zone does not appear in the upper zone. Abbreviation: *VAI*, vorticity area index.

maxima is about 10 percent. When we consider that weather usually consists of relatively small changes about climate (the average properties), this represents a sizable and important change. I repeat the warning that the sector boundary passage, although very convenient as a precise timing mark, almost surely does not have an important physical influence on the weather. The large-scale sector structure in the interplanetary magnetic field also may not have a direct causal influence on the weather, but may merely delineate some solar structure that does. Figure 1 is computed for 300 mbar, but similar results are found for 200, 500, and 700 mbar.

The result shown in Fig. 1 is prominent only during the winter months (*8*). This may be related to the fact that this is the season in which the equator-to-pole temperature differences are the largest, producing the largest stresses on the earth's atmospheric circulation.

In view of the checkered history of sun-weather influences, the new claim shown in Fig. 1 must be subjected to the most careful scrutiny. The first test is to compute the standard error of the mean, which is shown by the error bar in Fig. 1. This is satisfyingly small, and on formal grounds one might conclude that the minimum near the sector boundary in Fig. 1 is significant. However, the textbook instructions for computing an error bar are always subject to assumptions and boundary conditions that are never completely fulfilled in any analysis of real observations. We therefore proceed to further tests. Figure 2 is in the same format as Fig. 1, but in this case the list of times of boundary passages has been divided into two parts, and the same analysis has been performed on each half separately. The extent to which the analysis of parts of the data is similar to the analysis of the entire data set is a further test of significance. In Fig. 2 the data have been divided into two parts in three different ways, as explained in detail in the figure legend. We see that the effect persists in all of these divisions of the data set.

A further test of significance is to inquire if the effect persists in new observations (*9*). Figure 3a shows our original analysis, while Fig. 3b shows the same analysis performed with a list of 81 new boundary passage times, none of which are included in the analysis of Fig. 3a. The new boundary passage times used in Fig. 3b were obtained by increasing the interval examined to 1963 to 1973, and by supplementing spacecraft observations of the interplanetary magnetic field polarity with inferred polarities of the interplanetary field obtained from analysis of polar geomagnetic variations (*10*). In response to the suggestion (*5*) that some geomagnetic activity could be caused by variations in the weather, we performed the analysis shown in Fig. 3c, using a subset of 46 of the 81 boundary passage times used in Fig. 3b. In the analysis of Fig. 3c we used only boundary passages in which the time was fixed by spacecraft observations. It can be seen from Fig. 3 that the effect clearly persists in the new observations.

The last test of significance (9) to be described in this article is shown in Figs. 4 and 5. Figure 4 shows the same analysis performed in the latitude zones 35°N to 55°N, 55°N to 90°N, and 20°N to 90°N. We see that the effect is quite similar in these three zones. The possibility might still remain that due to conventional meteorological processes, whenever the vorticity area index has a minimum in the zone 35°N to 55°N it also has a similar minimum in the zone 55°N to 90°N. This possibility has been investigated in the following way. From a plot of the vorticity area index in the zone 35°N to 55°N during the time interval of interest, all those times not near a sector boundary passage at which the index had a minimum resembling the average minimum in Fig. 3 were tabulated. Figure 5 shows the same analysis performed with the resulting list. The result for the zone 35°N to 55°N shows a deep minimum, since each individual case was selected to have such a minimum. By contrast the result for the zone 55°N to 90°N is essentially a null result. No trace of a corresponding minimum is to be seen. It thus appears that at times that are not near sector boundary passages, minima in the two latitude zones occur independently, whereas some solar influence causes both zones to show similar minima 1 day after the passage of a sector boundary. If we accept the reality of this result, we can turn the argument around and say that the unknown solar influence causes similar results in the two latitude zones.

The most important test of the significance of the results claimed in Fig. 1 was made by Hines and Halevy (*11*), who stated, "Reports of short-term Sun-weather correlations have been greeted with skepticism by many." They subjected the data used in preparing Fig. 1 to a variety of statistical tests and requested the analysis of new data shown in Fig. 3. They concluded that "We find ourselves obliged, however, to accept the

validity of the claim by Wilcox *et al.*, and to seek a physical explanation."

What does one conclude from all of the above? The results of the past century suggest that a certain caution would be very appropriate. The one statement that I would make with complete conviction is that this appears to be an interesting subject that should be vigorously pursued.

Summary

If there is indeed an effect of the variable sun on the weather, the physical cause for it remains quite elusive (*12*). We should keep in mind the possibility that there may be several causes and several effects. The situation may change through the 11-year sunspot cycle and the 22-year solar magnetic cycle, as well as on longer time scales.

Work is proceeding at a lively pace at the institutions mentioned in this article and at many others around the world. The Soviet Union has long had considerably more workers interested in this field than has any other country. A bilateral agreement between the Soviet Union and the United States has considerably increased the interactions between workers interested in this subject, including an exchange of extended visits between the two countries.

A detailed knowledge of solar causes of geomagnetic activity is only now beginning to emerge after many years of scientific efforts. This suggests that a possible successful solution to the sun-weather problem will require a similar magnitude of effort. We look forward with interest and optimism to the results of the next few years.

References and Notes

1. Lord Kelvin, *Nature (London)* **47**, 106 (1892).
2. For recent reviews on this subject see J. M. Wilcox, *J. Atmos. Terr. Phys.* **37**, 237 (1975); L. Svalgaard, in *Correlated Interplanetary and Magnetospheric Observations*, D. E. Page, Ed. (Reidel, Dordrecht, 1974), pp. 627–639; J. W. King, *Astronaut. Aeronaut* **13**, 10 (1975). "Proceedings of the symposium on possible relationships between solar activity and meteorological phenomena, NASA Goddard Space Flight Center, Greenbelt, Md., 7 to 8 November 1973," *NASA Spec. Publ.*, in press.
3. W. O. Roberts and R. H. Olson, *J. Atmos. Sci.* **30**, 135 (1973); *Rev. Geophys. Space Phys.* **11**, 731 (1973).
4. C. E. Leith, *Rev. Geophys. Space Phys.* **13**, 681 (1975).
5. C. O. Hines, *J. Atmos. Sci.* **30**, 739 (1973).
6. J. M. Wilcox, *Space Sci. Rev.* **8**, 258 (1968).
7. ———, P. H. Scherrer, L. Svalgaard, W. O. Roberts, R. H. Olson, *Science* **180**, 185 (1973); ———, R. L. Jenne, *J. Atmos. Sci.* **31**, 581 (1974).
8. J. M. Wilcox, L. Svalgaard, P. H. Scherrer, *Nature (London)* **255**, 539 (1975).
9. ———, *J. Atmos. Sci.*, in press.
10. L. Svalgaard, *J. Geophys. Res.* **77**, 4027 (1972); *ibid.* **78**, 2064 (1973); *ibid.* **80**, 2717 (1975); J. M. Wilcox, *Rev. Geophys. Space Phys.* **10**, 1003 (1972).
11. C. O. Hines and I. Halevy, *Nature (London)* **258**, 313 (1975).
12. A. J. Dessler, in "Proceedings of the symposium on possible relationships between solar activity and meteorological phenomena, NASA Goddard Space Flight Center, Greenbelt, Md., 7 to 8 November 1973," *NASA Spec. Publ.*, in press.
13. This work was supported in part by the National Aeronautics and Space Administration under grants NSG 5024 and NGR 05-020-559, by the Atmospheric Sciences Section of the National Science Foundation under grants ATM74-19007 and DES75-15664, and by the Office of Naval Research under contract N00014-76-C-0207.

Ideas and trends

By James P. Lodge

A risky road from hypothesis to fact

An unproven hypothesis can trigger a panic reaction without any assessment of risks and costs

It is in the nature of science that scientists are wrong a large fraction of the time. However, paradoxical as it may sound, this is the way that science makes progress. A scientist formulates a hypothesis, either to explain something he has observed or to extrapolate from current knowledge. He then makes the best efforts of which he is capable to prove himself wrong. If he is unsuccessful, the hypothesis makes an official transition into the status of a theory, and it is provisionally accepted until such time as it fails to explain something it should have explained. Then it is replaced by a new theory, grown from a hypothesis like the last.

Today the presentation of preliminary hypotheses carries substantial risk to the scientist and to the society in which he works. The scientific journals that have served as his conduit to his peers throughout the world are no longer limited in audience. These, along with scientific symposia, are routinely covered by the mass media. Too often, what began as appropriate—indeed necessary—scientific questioning is assumed to be scientific fact. The attendant publicity tends to be in direct proportion to the extent that the original question carries "doomsday" implications. (Why is the continuation of the world so much less welcome news than the end of the world? Are our consciences troubling us?)

All too often a scientist's statement that "under highly unrealistic laboratory conditions, I have a small amount of evidence to suggest that lifetime exposure to elephant hide could, with 5% probability, cause cancer" becomes "Scientist says elephants cause cancer." A few conscientious reporters will add an ellipsis to indicate omitted words or will carry a brief amplification several pages back from the elephant-damning headline.

Lest it be thought that the media are unilaterally responsible, I must add that there are certain scientists who, either spontaneously or under pressure from institutional public information offices, make similar claims in their own names. There are undoubtedly occasions when the gravity of the situation justifies this approach, although probably not as many as are claimed. However, there is some reason to think that premature public disclosure is at least occasionally motivated by a perception of positive benefit in the current scramble for scarce research funds.

The effects are far-reaching.

Scientific responsibility. A formerly cooperative effort, in which the developer of the hypothesis solicits help from his peers in determining whether his methodology and preliminary conclusions are flawed in any way, becomes an adversary situation. Since funding agencies are only marginally aware of the positive value of fallibility in science and are vulnerable to pressure from a public that has still less understanding, the affected scientist must defend his position to protect his future support.

In areas that concern public health and consumer products, the risks are compounded. An easily frightened public reacts to publicity, and pressure for government action grows.

The costly death of cyclamates is one example of premature acceptance of hypothesis as fact. Recently it has come to light that some women had abortions because spray adhesives, since shown to be harmless, were suspected of causing birth defects. As a scientist, I find that kind of reaction chilling. I know I do not deserve that sort of life-and-death power.

But what of the opposite situation, such as the thalidomide scandal? Certainly that case illustrates the need for new areas of pharmaceutical testing. I doubt if any drug now reaches the market that has not been tested for *in utero* effects on the fetuses of experimental animals. However, I submit that we are ultimately faced with only two alternatives: a retreat from even present levels of technology, or the acceptance of an occasional tragedy of that magnitude. The reason is simple: There is always some probability that any finite series of studies will miss a unique impact.

Still under public and scientific scrutiny is the question of whether the chlorofluorocarbons, widely used as refrigerants and aerosol propellants, are damaging the ozone layer. The question involves a long chain of interlocking hypotheses and theories, few of which have been tested in the real world. Yet every minor measurement in the least pertinent to the subject is trumpeted in the press as "proving" the hypothesis, despite the fact that a number of these have, when dispassionately examined, tended to cast doubt on it. The National Academy of Sciences now has two committees studying the subject, and they have recently announced a postponement of their reports because so much additional information is becoming available. Nevertheless, every jurisdiction in the land, of whatever size, seems filled with legislators rushing to be the first to ban underarm deodorants.

Weighing the risks. My intimate involvement in this particular controversy has forced me to examine the way such matters are, and should be, handled. I should therefore like to suggest a modification of the present approach to questions of this sort. I suggest that we approach each case by making an initial assessment of the risks and the costs involved.

The urgency of action in any particular case must be determined by some sort of product of the probability that the hypothesis is correct and the size of the population at risk if it is. But the calculation of this product should be realistic. It does not follow from our concern with the size of the population that even a fairly improb-

Dr. James P. Lodge is a consultant in atmospheric chemistry based in Boulder, Col. He is science adviser to the Council on Atmospheric Sciences, an organization of the fluorocarbon-related industries.

Drawing by James Humphrey—BW

Ideas and trends

Continued

One of the key questions is who pays for research to prove or disprove safety

able hypothesis must be acted on at once when it affects something as global as the worldwide ozone layer.

In this case, the entire population of the world is involved, but a much smaller number are actually at risk. Nonwhites are almost totally immune to skin cancer, and swarthy whites are only slightly susceptible. Moreover, the cost of delaying action while we determine the validity of the hypothesis is small. A delay of two or three years in banning aerosol products in the United States would, if the theory is completely correct, cause an increase in ozone depletion of no more than 0.1%. Hence, while a final somber appraisal of observational fact may ultimately lead to the end of the present halocarbons, there is no reason for a panicky instant response.

A similar argument can probably be made for the entire class of suspected carcinogens of low potency that now seem to occupy so much of our attention. If—but only if—we can assume the validity of the data, it is probably expedient to remove chloroform from cough medicines. However, such long exposure to weak carcinogens of this sort is necessary before cancer actually results that the instant removal of present stocks of these medicines from the market will have a trivial effect. Once again, it is necessary to weigh not only the probability of harm and the size of the population at risk but also the cost of increasing the state of knowledge or decreasing the cost of action by less precipitate regulation.

Possible answers. As with most social as well as scientific problems, there are no easy or quick answers to the problem of public investment of preliminary hypotheses as revealed scientific truth. One cannot enhance scientific freedom at the expense of freedom of the press. One can try to enlist the media in helping the public understand the difference between a hypothesis, a theory, and a law of science. One can perhaps also ask the media to report more accurately the full context of scientific announcements. Scientists must simultaneously realize the risk and responsibility that they undertake when they initiate release of frightening but unproven hypotheses. They also bear a responsibility to assist in public education, precisely in the area I have called the "value of fallibility."

Beyond this point, which requires a period of education of the media, the public, and the scientists, there are shorter-range questions. One of the key items of discussion at the moment appears to be responsibility for costs—first for research to prove or disprove safety for both life and the environment, and then for compensation of those affected. The latter problem is perhaps easier to solve.

The thalidomide case has provided a precedent. Clearly, in a case of this sort, the responsible industry must pay the affected individuals for the damage inflicted. Where the damage is more diffuse, as in the case of broad environmental impact, the solution is correspondingly more diffuse. Nevertheless, there seems to be adequate legal precedent for the concept, and reasonable legislation could be enacted to charge responsible industry for its equitable share of environmental degradation of whatever sort.

Conceivably the same legislation that made industry liable for damages could create an insurance pool to compensate it for losses caused by abrupt changes in regulations. In view of its role as the chief regulator, the federal government might reasonably undertake to reimburse the pool for any payments it has to make to the producers of improperly suppressed products.

The costs of research. The question of financing research is still more complex. A friend recently put it in a nutshell: "Why should I as a taxpayer pay for research to prove whether or not some big company's fluorocarbons are destroying the ozone?"

I pointed out that the manufacturing industry is now committed to some $5 million of research support, the recipients being universities, research institutes, and research corporations. And I added that a substantially larger amount is being devoted to internal studies of possible replacement chemicals. However, the question set me thinking about the reasonable allocation of such costs.

Despite some problems, the present national toxic substances legislation has one helpful philosophical concept: It makes the development of test protocols the responsibility of the Environmental Protection Agency, while their execution for individual substances is the responsibility of the manufacturer. The difficulty with the halocarbon question, and many similar ones, is that the basic research to define the necessary conditions for acceptance and rejection has not been done. Accordingly, the external research supported by the industry is almost totally devoted to fundamental studies leading to the possibility of setting criteria for acceptable materials. To this extent the industry is responding far beyond the standards of responsibility established by the Toxic Substances Act. The nation as a whole has been seriously remiss in failing to support research on the structure of our atmosphere that would permit reasonable answers to the halocarbon/ozone questions.

Whatever approach we take to these problems, there is an obvious need to accept the clear fact that no institutional structure can provide a life completely free of risk. After all, it has been pointed out that the removal of the smog of Los Angeles would, according to present theory, lead to a doubling of the present rate of skin cancer in the affected area—just because of the added sunlight it would let in.

Drawing by Joseph S. Pecsenke

6 August 1976, Volume 193, Number 4252 SCIENCE

Global Cooling?

No, Southern Hemisphere warming trends may indicate the onset of the CO_2 "greenhouse" effect.

Paul E. Damon and Steven M. Kunen

According to Mitchell (*1, 2*), there has been a systematic fluctuation in global climate during this century characterized by a net worldwide warming of about 0.6°C between the 1880's and the early 1940's followed by a net cooling of 0.2° to 0.3°C by 1970. A recent press account (*3*) has suggested a somewhat greater cooling of 0.35°C and has impressed on the public consciousness the potential adverse economic consequences of a continuation of this trend.

Damon (*4*) has pointed out that global cooling since the early 1940's is not in accord with the well-known studies by Abbot (*5*) and co-workers from the Smithsonian Astrophysical Observatory or with data from recent balloon investigations in the Soviet Union and the United States (*6*) which indicate a relationship between solar energy (*S*) and solar activity as measured by the sunspot or Wolf number (*N*). These studies suggest that *S* increases by 2 to 2.5 percent as *N* increases, reaching a maximum at $N \sim 80$ to 100, after which it decreases to an intermediate value at the highest values of *N*.

More recently, Schneider and Mass (*7*) have combined the hypothesized solar energy effect with the effect of volcanic dust and CO_2 in a climate model. Global surface temperatures computed from this model rise from the early 1880's through the early 1940's in agreement with Mitchell's global temperature curve, but the computed warming trend persists to the early 1950's, followed by temporary cooling through the early 1960's and renewed warming from then until the present. Thus, the model of Schneider and Mass does not predict Mitchell's global cooling since the early 1940's, although it is in accord with the prior warming trend. Schneider and Mass would be the first to admit uncertainties in the model, but we have also been led to question the concept of global cooling.

We became aware of the current warming trend in New Zealand during the late spring of 1974 (*8*) and began a study of Southern Hemisphere temperature trends. Since then, the data of the New Zealand Meteorological Service have been published by Salinger and Gunn (*9*). Temperature trends in New Zealand, perhaps fortuitously, are in striking accord with the trend of calculated global surface temperatures for the 20th century by Schneider and Mass. Salinger and Gunn suggest that the current warming trend in New Zealand is common to a wider range of latitudes in the Southern Hemisphere. For example, they point out evidence for a warming trend since the 1940's for seven of eight Australian urban centers, Scott Base in Antarctica, and Orcadas Island at latitude 64°43'S near South America. The warming trend in Australia has been corroborated by Tucker (*10*), who observed that a large part of the Australian continent experienced an increase in excess of 1°C during the 7-year period from 1967 to 1973. Coughlan (*11*) showed that two-thirds (24 of 35) of the Australian weather stations indicate rising average annual maximum temperatures during the last 30 years, but he pointed out that a recent reversal of the trend over large areas is probably a result of the heavier rainfall in 1973 and 1974, which affected 95 percent of the Australian continent.

The purpose of this article is to report the results of an analysis of 67 weather stations in the Southern Hemisphere (see Table 1 and Fig. 1). Except for Australia and New Zealand, we find no evidence for significant climate change from the equator to 45°S latitude. Our analysis confirms the warming trend in Australia and New Zealand and strongly suggests a marked warming trend at higher southern latitudes, which may exceed in magnitude the cooling trend in high northern latitudes. Although confidence in the analysis is limited by the sparsity of weather stations, the level of confidence has been analyzed statistically.

Data Base

Currie (*12*), using the maximum entropy method, has demonstrated a variation of surface air temperature during the solar cycle for 226 weather stations (78 from North America) whose records span 60 years or more. The amplitude of the temperature variation is 0.05° to 0.2°C. A variation of this magnitude represents a significant fraction of the global cooling postulated by Mitchell and, if not taken into consideration, it could seriously affect arbitrarily chosen pentad or decade averages. For this reason, we decided to take averages centered around the last three solar cycles. The 23rd solar cycle extends from mid-1943 to mid-1953, the 24th solar cycle from mid-1953 to mid-1963 and, for the purpose of this article, we have taken the 25th cycle to extend from mid-1963 to mid-1974. With this in mind, the following criteria and approximations were initially used in handling the temperature data, which were taken from the *World Weather Records* (*13*) and *Monthly Climate Data for the World* (*14*).

1) Stations must include surface air temperature data from 1943 through 1974.

Paul E. Damon is professor in the Department of Geosciences and chief scientist of the Laboratory of Isotope Geochemistry, College of Earth Sciences, University of Arizona, Tucson 85721, and Steven M. Kunen is senior environmental chemist, Environmental Studies Laboratory, University of Utah Research Institute, Salt Lake City 84108

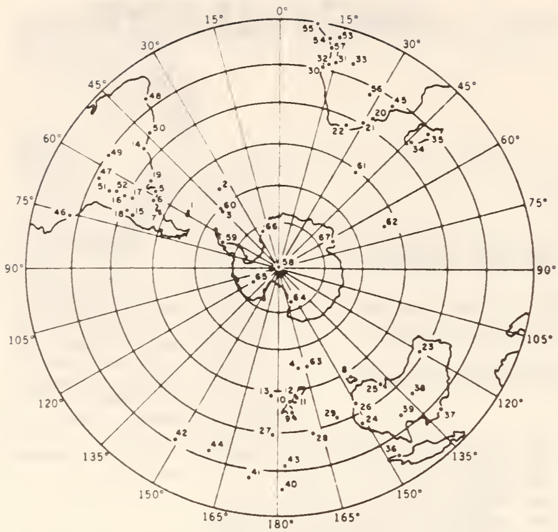


Fig. 1. Locations of Southern Hemisphere weather stations used in this study.

2) All stations that had more than minimal site changes were discarded

3) All stations were discarded for which more than 10 percent of the annual data were missing.

4) For stations meeting the above criteria, a missing year was interpolated by using the average of the five preceding and the five following years (10-year average).

5) If three or less months were missing for a particular year, data for the month in question for the 5 years before and after were averaged (10-year average). If a year was missing more than 3 months' observations, the year itself was determined as in item 4 above.

6) In averaging for any classification of stations, the average was carried out to an additional significant figure, such as 20.57°C, even though the measurements for any single station were accurate only to 0.1°C.

Only 57 Southern Hemisphere stations met criteria 1 to 3. These 57 stations were used in the initial analysis. Later, the first criterion was relaxed to add ten additional stations for latitudes 45° to 90°S, where data were available for the four pentads from 1955 to 1974. This al-

Table 1. Weather stations and temperature data used in study.

Station	Location	Temperature (°C)						
		Solar cycles			Pentads			
		23rd	24th	25th	1955–1959	1960–1964	1965–1969	1970–1974
1 Stanley, Falkland Islands	51°42'S, 57°52'W	6.0	5.7	5.6	5.8	5.8	5.6	5.6
2. Grytviken, South Georgia Islands	54°16'S, 36°30'W	1.7	2.0	2.1	2.1	1.8	2.2	2.2
3. Islas Orcadas (Laurie Island), South Orkney Islands	60°43'S, 44°43'W	−4.6	−3.5	−3.8	−3.5	−3.4	−3.5	−3.7
4 Campbell Island	52°33'S, 169°07'E	6.7	6.3	7.1	6.9	7.1	7.1	7.0
5. Mar del Plata, Argentina	38°08'S, 56°58'W	13.6	13.6	13.8				
6 Bahía Blanca, Argentina	38°44'S, 62°11'W	15.1	14.7	14.9				
7 Trelew, Argentina	43°14'S, 65°18'W	13.8	13.3	13.4				
8 Hobart, Tasmania	42°53'S, 147°30'E	12.1	12.3	12.4				
9 Auckland, New Zealand	36°51'S, 174°46'E	15.3	15.8	15.2				
10. Wellington, New Zealand	41°17'S, 174°46'E	12.3	12.8	12.4				
11. Hokitika, New Zealand	42°43'S, 170°57'E	11.3	11.4	11.5				
12. Christchurch, New Zealand	43°32'S, 172°37'E	11.4	11.9	11.5				
13. Chatham Island, New Zealand	43°58'S, 176°33'W	11.0	11.4	11.2				
14. Curitiba, Brazil	25°25'S, 49°17'W	16.2	16.7	16.4				
15. Santiago, Chile	33°27'S, 70°42'W	14.6	14.6	14.1				
16. San Miguel de Tucumán, Argentina	26°48'S, 65°12'W	19.2	18.8	19.8				
17. Córdoba, Argentina	31°24'S, 64°11'W	17.8	17.2	17.4				
18. San Juan, Argentina	31°37'S, 68°32'W	17.6	17.4	17.6				
19. Montevideo, Uruguay	34°58'S, 56°12'W	16.6	16.7	17.4				
20. Lourenço Marques, Mozambique	25°58'S, 32°36'E	22.3	22.6	22.3				
21. Durban, South Africa	29°50'S, 31°02'E	20.5	20.2	20.3				
22. Port Elizabeth, South Africa	33°57'S, 25°37'E	17.7	17.0	17.3				
23. Kalgoorlie, Australia	30°45'S, 121°30'E	18.4	18.3	18.4				
24. Eagle Farm, Brisbane, Australia	27°28'S, 153°02'E	20.3	20.6	20.7				
25. Adelaide, Australia	34°56'S, 138°35'E	16.5	16.8	16.3				
26. Sydney, Australia	33°52'S, 151°12'E	17.6	17.8	17.9				
27. Raoul Isle, Kermadec Islands	29°15'S, 177°55'W	18.9	19.0	18.7				
28. Norfolk Island	29°03'S, 167°56'E	18.6	18.9	18.8				
29. Lord Howe Island	31°31'S, 159°51'E	19.2	19.1	19.3				
30. Moçâmedes, Angola	15°12'S, 12°09'E	21.0	20.3	20.2				
31. Nova Lisboa, Angola	12°46'S, 15°44'E	18.7	18.7	18.6				
32. Sá da Bandeira, Angola	14°55'S, 13°29'E	17.9	18.5	18.5				
33. Luso, Angola	11°47'S, 19°55'E	20.5	20.4	20.3				

lowed us to strengthen the evidence, suggested from the initial analysis, for a warming trend at high southerly latitudes.

Analysis of the Data

For an average temperature change between solar cycles or pentads to be considered significant, it seemed to us that the following two conditions were reasonable.

1) The temperature change between any two solar cycles or pentads must be $\geq 0.1°C$.

2) There must be at least a four-fifths chance (> 80 percent confidence) that the difference is significant, as determined by the standard t-test, where

$$t = \frac{\bar{x}(n-1)^{1/2}}{s}$$

$\bar{x}$ is the mean difference in temperature for the set of n stations, $(n - 1)$ is the number of degrees of freedom, and s is the standard deviation of the mean ($\bar{x}$) for the set of n stations. From the value of t, the confidence level can be determined from standard tables.

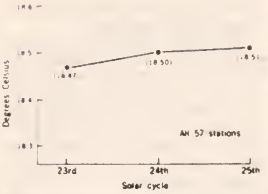


Fig. 2. Mean temperatures for the 23rd to 25th solar cycles for all 57 stations.

For example, data from all 57 stations that meet the criteria given above are plotted in Fig. 2. The increase in temperature between the 23rd and 25th solar cycles is only 0.04°C and the confidence level is only 70 percent. Thus, if the above criteria are accepted, no significant change in temperature since 1943 is indicated by the 57 Southern Hemisphere stations.

There remains the possibility that the set of 57 stations has been affected by artificial heating of urban centers, as demonstrated by Dronia (*15*) and Mitchell (*16*). Figure 3 shows that artificial heating has affected Southern Hemisphere cities with populations greater than 750,000. These cities show a steady warming trend, where the difference between the 23rd and 25th solar cycles is approximately 0.2°C and is significant at the 85 percent confidence level. Two of the three cities with populations between 500,000 and 750,000 (stations 14, 17, and 21) do not contribute to the warming trend, and so we conclude that in this analysis the urban effect is negligible for cities with populations below 750,000. Subtracting the urban centers from the original set of 57 stations does not affect our conclusion that the data show no significant trend in temperature for Southern Hemisphere weather stations since 1943.

This conclusion does not obviate significant regional temperature trends, and Fig. 4 demonstrates that there have been significant changes on a continental scale. The stations for subequatorial Africa show a pronounced cooling trend of 0.16°C between the 23rd and 24th solar cycles, significant at the 95 percent confidence level. This is followed by a leveling off between the 24th and 25th solar cycles. The Australian stations show the warming trend (significant at the 95 per-

Table 1 (continued).

Station	Location	Temperature (°C)						
		Solar cycles			Pentads			
		23rd	24th	25th	1955–1959	1960–1964	1965–1969	1970–1974
34. Fort-Dauphin, Malagasy	25°02'S, 46°49'E	22.7	23.0	22.9				
35. Tananarive Observatory, Malagasy	18°55'S, 47°33'E	18.7	18.2	18.2				
36. Port Moresby, New Guinea	09°26'S, 147°13'E	26.8	27.0	26.7				
37. Darwin, Australia	12°28'S, 130°51'E	27.3	27.4	27.6				
38. Alice Springs, Australia	23°38'S, 133°52'E	20.3	21.3	21.1				
39. Cloncurry, Australia	20°43'S, 146°30'E	25.1	25.3	25.8				
40. Funafuti, Ellice Islands	08°31'S, 179°12'E	28.0	28.0	27.8				
41. Apia, Samoa	13°48'S, 171°46'W	26.6	26.6	26.4				
42. Tahiti, Society Islands	17°32'S, 149°34'W	26.1	25.8	25.7				
43. Lauthala Bay (Suva), Fiji	18°09'S, 178°28'E	25.0	25.1	24.9				
44. Rarotonga, Cook Islands	21°12'S, 159°46'W	23.8	23.7	23.9				
45. Beira, Mozambique	19°50'S, 34°51'E	24.3	24.3	24.4				
46. Lima, Peru	12°06'S, 77°02'W	18.4	18.2	18.1				
47. Santa Cruz, Bolivia	17°47'S, 63°10'W	23.8	24.4	24.8				
48. Salvador, Brazil	13°00'S, 38°31'W	24.7	25.1	25.3				
49. Cuiabá, Brazil	15°36'S, 56°06'W	25.6	26.1	25.6				
50. Rio de Janeiro, Brazil	22°54'S, 43°10'W	23.3	23.4	23.7				
51. La Quiaca, Argentina	22°06'S, 65°36'W	9.4	9.2	9.4				
52. Salta, Argentina	24°51'S, 65°29'W	17.2	16.3	16.3				
53. Brazzaville, Republic of Congo	04°15'S, 15°15'E	24.8	24.9	25.1				
54. Pointe Noire, Republic of Congo	04°49'S, 11°54'E	25.2	24.8	24.7				
55. Port Gentil, Gabon	00°42'S, 08°45'E	26.3	25.8	25.7				
56. Bulawayo, Southern Rhodesia	20°09'S, 28°37'E	19.2	19.0	18.9				
57. Luanda, Angola	08°51'S, 13°14'E	24.5	24.3	24.2				
58. Amundsen-Scott Base	90°00'S				−49.0	−49.3	−49.8	−49.2
59. Argentine Island	65°15'S, 64°16'W				−5.2	−4.6	−4.5	−2.7
60. Signy Island	60°43'S, 45°36'W				−2.9	−2.7	−3.3	−3.7
61. Marion Island, South Africa	46°53'S, 37°52'E				5.1	5.2	5.0	5.4
62. Port aux Français, Kerguelen	49°20'S, 70°13'E				4.6	4.1	4.3	4.3
63. Macquarie Island	54°30'S, 158°57'E				4.7	4.6	4.6	4.7
64. McMurdo Station	77°50'S, 166°36'E				−18.0	−18.1	−16.9	−16.0
65. Byrd Station	80°00'S, 120°00'W				−28.2	−28.2	−27.6	−26.4
66. Halley Bay	75°31'S, 26°36'W				−18.6	−19.4	−18.0	−19.0
67. Mawson	67°36'S, 62°53'E				−10.7	−11.3	−12.0	−11.7

cent confidence level) previously noted by Salinger and Gunn (*9*), Tucker (*10*), and Coughlan (*11*). The South American stations show no overall trend between the 23rd and 25th solar cycles, but, a significant cooling did occur in the 24th solar cycle, followed by a return to the temperatures prevalent in the 23rd solar cycle. These regionally averaged temperature trends are probably associated with circulation changes on the scale of long waves, as recently demonstrated for the Northern Hemisphere by Van Loon and Williams (*17*).

The data were also classified into categories representing (i) all continental stations (36 stations) compared to all oceanic stations (21 stations); (ii) coastal continental stations (19 stations) compared to inland continental stations (17 stations); and (iii) large islands (9 stations) compared to small islands (12 stations). No significant temperature trends were observed for these categories between the 23rd and 25th solar cycles.

Figure 5 shows that there is no consistent latitudinal variation at latitudes below 45°S. However, the four stations (stations 1 to 4) at latitudes above 45°S (51° to 61°S) show a pronounced warming trend of 0.3°C, but the number of stations is insufficient to establish confidence that the trend is representative of the entire zonal area.

To ascertain whether the indication of a high-latitude warming trend is statistically significant, we decided to analyze high-latitude data for the last four pentads (1955 to 1974). In this way, by relaxing criterion 1 above, we increased the number of stations from 4 to 14 (stations 1 to 4 and 58 to 67) at latitudes above 45°S (Fig. 6). The set of 14 stations shows a 0.12°C decrease from the 1955–1959 pentad to the 1960–1964 pentad, followed by an increase of 0.37°C to the 1970–1974 pentad, significant at the 90 percent confidence level. The same trend is observed for the eight stations at latitudes above 60°S and the six stations at latitudes above 65°S, but the warming trend is much more pronounced for the stations at higher latitudes. The warming between the 1960–1964 and 1970–1974 pentads is significant at the 90 percent confidence level for the stations above 60°S and at the 95 percent confidence level for the stations above 65°S. The increase above 65°S is approximately 1.0°C. Five of the six stations above 65°S show a warming trend (stations 58, 59, 64, 65, and 66). Only Mawson station (station 67), Antarctica, shows a cooling trend which continues to the 1965–1969 pentad, followed by warming during the 1970–1974 pentad. The warming trend is dominated by Argentine Island (station 59, 1.9°C), McMurdo (station 64, 2.1°C), Byrd Station (station 65, 1.8°C), and Halley Bay (station 66, 0.4°C). It occurred to us that these four stations might be biasing the data for the entire set of 14 stations. However, excluding these stations, the six stations between 45° and 60°S also show a warming trend of 0.12°C, which in itself is significant at the 85 percent confidence level.

Although 14 stations are obviously inadequate to cover the entire portion of the globe between 45° and 90°S, the regional distribution is fairly good. Three stations, besides Mawson, show a cooling trend since the 1960–1964 pentad. One of these is in the Falkland Islands (station 1, −0.2°C) and the other two are from the South Orkneys (station 60, −1.0°C, and station 3, −0.3°C). It is these two stations from the South Orkneys which depress the curve for 60° to 90°S below that for 65° to 90°S in Fig. 6.

Summarizing, the following generalizations are warranted by the data.

1) The set of 57 weather stations meeting our initial criteria show no significant trend in surface air temperature from 1943 to 1974. Since 53 of the 57 stations are between 0° and 45°S, the data provide no evidence for a consistent, overall trend of surface air temperature for that part of the Southern Hemisphere below 45°S.

2) However, sectors of the Southern Hemisphere below 45°S do show significant temperature trends, which are balanced by opposite changes in other sectors. For example, a cooling trend in subequatorial Africa is offset by a warming trend in Australia and New Zealand.

3) There is an urban artificial heating effect of approximately 0.2°C for cities above 750,000 inhabitants; however, this has been taken into consideration and

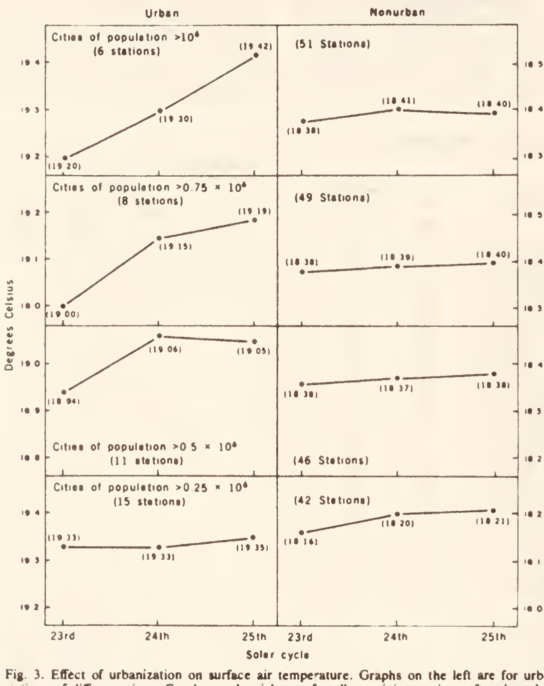


Fig. 3. Effect of urbanization on surface air temperature. Graphs on the left are for urban stations of different sizes. Graphs on the right are for all remaining stations after the urban stations on the left are subtracted. Numbers in parentheses are the mean surface air temperatures for the corresponding solar cycles. The warming trend is significant for cities with more than 750,000 inhabitants at the 95 percent confidence level.

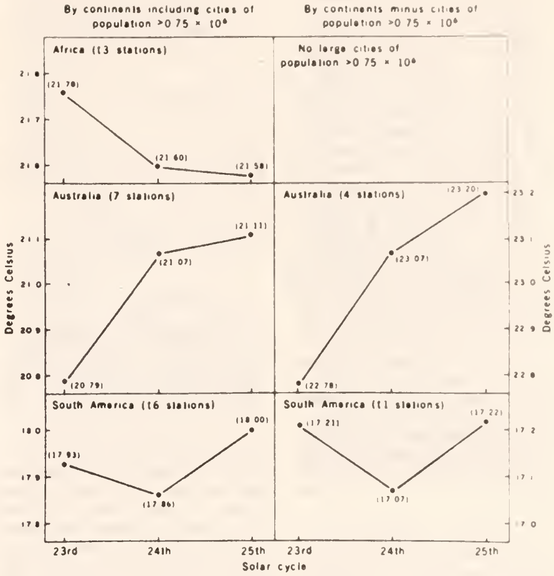
does not affect the statements above.

4) Fourteen stations between 45° and 90°S for which surface air temperature data for the four pentads from 1955 to 1974 were available show a mean decrease of 0.12°C from the 1955–1959 pentad to the 1960–1964 pentad, followed by an increase of 0.37°C to the 1970–1974 pentad. This apparent warming trend appears to be amplified at higher latitudes.

5) At least one sector at high latitudes, the sector including the South Orkney Islands and Falkland Islands, shows a cooling trend in opposition to the apparent warming trend for the Southern Hemisphere as a whole at latitudes above 45°S.

Discussion of Results

According to Mitchell, "meteorological data reveal a systematic fluctuation of global climate in the past century . . . [which] is presumed to reflect a systematic change of the overall heat budget" (*2*, pp. 440–441). We must conclude that this statement is not necessarily valid for the "global" heat budget during the period from 1943 to 1974. Cooling since the early 1940's is not necessarily global in extent; rather, it seems to be largely limited to part of the Northern Hemisphere (*17*) and some Southern Hemisphere sectors such as subequatorial Africa. Cooling is most evident at high northern latitudes. The data for 60° to 80°N account for "about one-half the net secular trend of that hemisphere, despite the small geographical area represented by the added data" (*18*). Thus, cooling at high northern latitudes seems to be balanced by warming at high southern latitudes since the 1955–1959 pentad. The



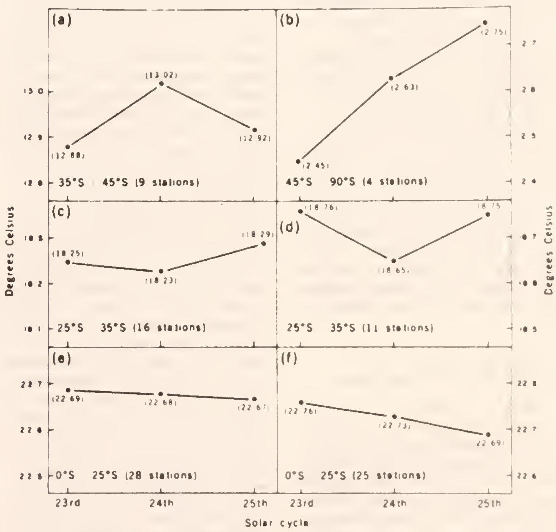


Fig. 4 (top). Variations in continental surface air temperature. Graphs on the left include urban centers with populations > 0.75 × 10⁶ and graphs on the right exclude them. The African cooling trend and the Australian warming trend are significant at the 95 percent confidence level. South American stations also show a significant warming trend between the 24th and 25th solar cycles, following cooling from the 23rd to the 24th solar cycle. The numbers in parentheses are the mean surface air temperatures for the corresponding solar cycles. Fig. 5 (bottom). Surface air temperatures for different latitudes: (a) all stations between 35° and 45°S; (b) all stations between 45° and 90°S; (c) all stations between 25° and 35°S; (d) all stations between 25° and 35°S except those with populations > 0.75 × 10⁶ inhabitants; (e) all stations between 0° and 25°S; and (f) all stations between 0° and 25°S except for those with populations greater than 0.75 × 10⁶. Numbers in parentheses are mean surface air temperatures for the corresponding solar cycles.

data do not permit a conclusion concerning the overall global heat budget.

Making allowance for the expected amplification at high latitudes (*19*), the curves in Fig. 6 are compatible with the climate model of Schneider and Mass (*7*) in which the temperature rise is approximately equally divided between the CO_2 atmospheric ("greenhouse") effect and an increment due to increased solar energy during the last solar cycle. If the correspondence between theory and observation is not coincidental, then some other phenomena must be depressing temperatures in the Northern Hemisphere. Reitan (*20*) and Hirschboeck (*21*) have suggested volcanism as a significant contributing factor. Bryson and Wendland (*22*) have attributed the cooling to the rapid rise of atmospheric turbidity as a by-product of human activity. Particulate matter entering the atmosphere has a short residence time (*2*) and would largely be restricted to the highly populated Northern Hemisphere. The effect of particulate matter is complex (*23*), but the addition of condensation nuclei by pollution leading to an increased hemispheric albedo (*24*) may be the dominant effect.

Assuming that the data, based on 67 weather stations, adequately demonstrate opposite trends in surface air temperature at high latitudes in the two hemispheres, an assumption that might be contested because of the limited areal coverage, two working hypotheses occur to us as reasonable explanations.

1) The observations represent natural fluctuations on a regional scale in an atmospheric system which has been negligibly affected by human activity.

2) The expected increase in temperature due to an increase in solar energy coupled with the CO_2 greenhouse effect since the 1960–1964 pentad is observed in the Southern Hemisphere. It is overwhelmed in the Northern Hemisphere by cooling due to an increased effective albedo caused by man-made particulate pollution with, possibly, a significant contribution due to different intensities of volcanism in the two hemispheres (*21*).

Conclusions and Recommendations

We are certain that large regions of the Northern and Southern Hemispheres have experienced opposite changes in surface air temperature during the last three decades. Salinger has suggested that "divergence between Northern Hemisphere and Southern Hemisphere temperatures may be a phenomenon of the past 50 yr" (*25*, p. 311). However,

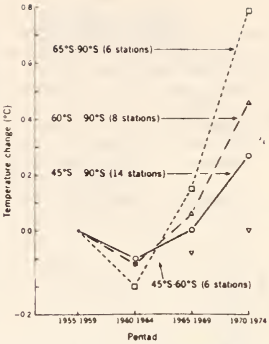


Fig. 6. Mean surface air temperatures for the last four pentads as a function of latitude. Confidence levels for significance of the warming trend from the 1960–1964 pentad to the 1970–1974 pentad are: 45° to 60°S, 85 percent; 45° to 90°S, 90 percent; 60° to 90°S, 90 percent; and 65° to 90°S, 95 percent.

the data are insufficient to precisely and confidently specify the trend in global climate as a whole. According to the climate model of Schneider and Mass (*7*), human activity may already have contributed significantly to the trend of global surface air temperatures, and Broecker (*26*) has predicted that the current cooling trend at high northern latitudes will soon give way to a warming trend due to the CO_2 greenhouse effect coupled with one of the more or less periodic temperature fluctuations observed in the Greenland ice core oxygen isotope record (*27*). Considering the complexity of weather phenomena and the sparsity of data, it is not yet certain that current trends in global climate are significantly influenced by human activity.

Carbon dioxide and particulate matter are the two major pollutants that may be affecting current climate trends. The major source of both of these pollutants is the highly populated and industrialized Northern Hemisphere. Hoffert (*28*) has demonstrated that the difference in CO_2 concentration between the Northern and Southern Hemispheres will be small because of the relatively fast latitudinal mixing rates of CO_2 in the atmosphere. On the other hand, Mitchell (*2*) has pointed out that, because of the short atmospheric residence time of particulate matter, particulate pollutants are unlikely to become thoroughly mixed throughout the global atmosphere like CO_2 molecules. Consequently, the climatic effect of CO_2 will manifest itself almost equally in both hemispheres, whereas the effect of particulate matter pollution will be most intense in the Northern Hemisphere. There seems to be general agreement that the effect of the increasing burden of atmospheric CO_2 will be global warming, although the exact magnitude of the effect is still debated (*29*). However, the direct effect of particulate matter pollution can be either cooling or warming, depending on the size and distribution of the particles. It may well be that the indirect effect of particulate pollution discussed by Twomey (*24*) will be dominant—that is, increasing cloud coverage and increasing planetary albedo with consequent cooling. There seems also to be general agreement that climatic trends will be amplified at high latitudes in both hemispheres.

This trend of thought leads us to the final conclusion and recommendation of this article, which is the urgent need for a more intensive and coordinated international world weather watch. It is of utmost importance to human welfare that factors affecting climate and reflecting trends in climate be continuously and adequately monitored. This includes all factors affecting planetary albedo, such as cloud, ice, and snow coverage. It should also include a definitive study of solar energy variations during an entire 11-year solar cycle. Retrospective monitoring, such as isotopic and thermal studies of ice, could help establish trends. Of utmost importance is the observation of climatic trends at high latitudes (> 60°) in both hemispheres. If the CO_2 greenhouse effect causes a global warming trend, it will most probably become apparent first in Antarctica. A warming trend was observed at five of six Antarctic weather stations used in this study. Is this the first indication of an imminent global warming? If so, what will be its effects on agriculture, the stability of the polar ice masses, and sea level?

Summary

The world's inhabitants, including scientists, live primarily in the Northern Hemisphere. It is quite natural to be concerned about events that occur close to home and neglect faraway events. Hence, it is not surprising that so little attention has been given to the Southern Hemisphere. Evidence for global cooling has been based, in large part, on a severe cooling trend at high northern latitudes. This article points out that the Northern Hemisphere cooling trend appears to be out of phase with a warming trend at high latitudes in the Southern Hemisphere. The data are scanty. We cannot be sure that these temperature fluctuations are not the result of natural causes. How-

ever, it seems most likely that human activity has already significantly perturbed the atmospheric weather system. The effect of particulate matter pollution should be most severe in the highly populated and industrialized Northern Hemisphere. Because of the rapid diffusion of CO_2 molecules within the atmosphere, both hemispheres will be subject to warming due to the atmospheric (greenhouse) effect as the CO_2 content of the atmosphere builds up from the combustion of fossil fuels. Because of the differential effects of the two major sources of atmospheric pollution, the CO_2 greenhouse effect warming trend should first become evident in the Southern Hemisphere. The socioeconomic and political consequences of climate change are profound. We need an early warning system such as would be provided by a more intensive international world weather watch, particularly at high northern and southern latitudes.

References and Notes

1. J. M. Mitchell, Jr., in *Global Effects of Environmental Pollution*, S. F. Singer, Ed. (Springer-Verlag, New York, 1970), p. 139.
2. ———, *Quat. Res. (N.Y.)* 2, 436 (1972).
3. P. Gwynne, *Newsweek*, 28 April 1975, p. 64.
4. P. E. Damon, paper presented at the Symposium on Quaternary Dynamics of the Geological Society of America, Miami Beach, Fla., 19 November 1974, lecture at the National Center for Atmospheric Research, Boulder, Colo., 11 February 1975, lecture at the Instituto Venezolano de Investigaciones Científicas, Caracas, 4 November 1975.
5. C. G. Abbot, *Smithson. Misc. Collect.* **448**, 7 (1966).
6. K. Ya. Kondratyev, G. A. Nikolsky, D. G. Murcray, J. J. Kosters, P. R. Gast, *Space Res.* 11, 695 (1971).
7. S. H. Schneider and C. Mass, *Science* **190**, 741 (1975).
8. During a conversation concerning global cooling and solar energy at the Dry Valley Drilling Project symposium in Seattle during June 1974, A. T. Wilson of the University of Waikato, New Zealand, pointed out that there has been a marked warming in New Zealand during the time of supposed global cooling. Later, he sent a graph prepared by workers of the New Zealand Meteorological Service, which dramatically illustrated the New Zealand warming trend.
9. M. J. Salinger and J. M. Gunn, *Nature (London)* **256**, 396 (1975).
10. G. B. Tucker, *Search* 6, 323 (1975).
11. M. J. Coughlan, Bureau of Meteorology, Australian Department of Science and Consumer Affairs, Melbourne, paper presented at the Australian Conference on Climate and Climatic Change, Monash University, Victoria (1975); available as preprint.
12. R. G. Currie, *J. Geophys. Res.* **79**, 5657 (1974).
13. U.S. Weather Bureau, *World Weather Records, 1941–1950* (Department of Commerce, Washington, D.C., 1959); *World Weather Records, 1951–1960* (Department of Commerce, Washington, D.C., 1965).
14. World Meteorological Organization and U.S. Weather Bureau, *Monthly Climatic Data for the World* (Department of Commerce, Washington, D.C., 1960 to 1974), vols. 13 to 27.
15. H. Dronia, *Meteorol. Abh. Inst. Meteorol. Geophys. Berl.* 74 (No. 4) (1967).
16. J. M. Mitchell, Jr., *J. Meteorol.* **10**, 244 (1953).
17. H. Van Loon and J. Williams, *Mon. Weather Rev.* **104**, 365 (1976).
18. J. M. Mitchell, Jr., *Ann. N.Y. Acad. Sci.* 95, 238 (1961).
19. W. D. Sellers, *J. Appl. Meteorol.* 13, 831 (1974); S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **32**, 3 (1975).
20. C. H. Reitan, *Quat. Res. (N.Y.)* 4, 25 (1974).
21. K. K. Hirschboeck, paper presented at the annual meeting of the Southwestern and Rocky Mountain Division, American Association for the Advancement of Science, and the Arizona Academy of Science, Tucson, 28 April to 1 May 1976; *J. Ariz. Acad. Sci.* 11, 96 (1976).
22. R. A. Bryson and W. M. Wendland, in *Global Effects of Atmospheric Pollution*, S. F. Singer, Ed. (Springer-Verlag, New York, 1970), p. 130.
23. For a review of the particulate pollution problem see S. H. Schneider, *Quat. Res. (N.Y.)* 2, 425 (1972). See also R. A. Reck, *Science* **186**, 1034 (1974); *ibid.* **188**, 728 (1975); R. W. Welch and W. Zdunkowski, in preparation.
24. S. Twomey, *Atmos. Environ.* **8**, 1251 (1974).
25. M. J. Salinger, *Nature (London)* **260**, 310 (1976).
26. W. S. Broecker, *Science* **189**, 460 (1975).
27. W. Dansgaard, S. J. Johnsen, H. B. Clausen, C. C. Langway, Jr., in *Late Cenozoic Glacial Ages*, K. K. Turekian, Ed. (Yale Univ. Press, New Haven, Conn., 1971), p. 37; W. Dansgaard, S. J. Johnsen, H. B. Clausen, N. Gunderstrup, *Medd. Groenl.* **197** (No. 2), 1 (1973).
28. M. I. Hoffert, *Atmos. Environ.* **8**, 1225 (1974).
29. S. H. Schneider, *J. Atmos. Sci.* **32**, 2060 (1975).

30. We have benefited from discussions with S. H. Schneider, W. D. Sellers, H. Van Loon, and A. T. Wilson. We are grateful to J. C. Lerman, J. Salinger, and S. H. Schneider for critical reviews of the preliminary manuscript. Supported by grant DES74-13362 from the National Science Foundation and by the state of Arizona. University of Arizona, Department of Geosciences, Publication No. 712.

****

APPENDIX B

SELECTED BIBLIOGRAPHY

****

SELECTED BIBLIOGRAPHY

Alexander, Tom. Ominous changes in the world's weather. Fortune, v. 89, February 1974: 90-95, 142, 146, 150, 152.

Bernard, Harold W., Jr. A mini ice age could begin in a decade. Globe [Boston Globe], Nov. 2, 1975: 6-8, 10, 12-13, 30, 32-35.

Broecker, Wallace S. Climatic change: are we on the brink of a pronounced global warming? Science, v. 189, Aug. 3, 1975: 460-463.

Brown, Lester R. The world food prospect. Science, V. 190, Dec. 12, 1975: 1053-1059.

Bryson, Reid A. A perspective on climatic change. Science, v. 184, May 17, 1974: 753-759.

----- Drought in Sahelia: who or what is to blame? Ecologist, v. 3, October 1973: 366-371.

----- Statement from hearings of the Foreign Agricultural Policy Subcommittee. In the world food conference; a print of the Committee on Agriculture and Forestry; U.S. Senate. Washington, U.S. Govt. Print. Off., 1974. 377 p.

----- The lessons of climatic history. Environmental Conservation v. 2, autumn, 1975: 164-170.

Climate: how large an unknown in the food equation? Mosaic, v. 6, May/June 1975: 36-41.

Cook, Ann K. GATE to understanding. N O A A, v. 3, January 1973: 14-17.

Cressman, George P. Freakish weather -- what winter will bring. U.S. news and world report, v. 75, October 29, 1973: 49-51, 54-55.

Decker, Wayne L. Unsettled and variable climate -- uncertain food supply. Industrial research, v. 16, Nov. 15, 1974: 51-56.

Devine, Samuel L. Ozone layer. Remarks in the House. Congressional record (daily ed.) v. 122, February 5, 1976: H 781.

Do cities change the weather? Mosaic, v. 5, summer 1974: 28-34.

Dresch, Jean. Drought over Africa. Unesco courier, v. 26, August-September 1973: 44-47.

Dry times in Mauritania. Swiss review of world affairs, v. 22, Jaunary 1973: 15-17.

Fluorocarbon file. New scientist, October 2, 1975: 7-18.

Formula for world famine? Energy gap + population explosion + droughts. U.S. news and world report, v. 76, January 28, 1974: 50-52.

Fowler, W.B. and J.D. Helvey. Effect of large-scale irrigation on climate in the Columbia [River] Basin. Science, v. 184, April 12, 1974: 121-127.

Franda, Marcus F. India: "an unprecedented national crisis." [Hanover, N.H.] American Universities Field Staff, 1973. 13 p. (American Universities Field Staff. Field staff reports. South Asia series, v. 17, no. 5)

Frazier, Kendrick. Earth's cooling climate. Science news, v. 96, November 15, 1969: 458-459.

Gilman, Donald L. Recent weather anomalies in the perspective of meteorological records. Paper presented at the 140th meeting of the American Association for the Advancement of Science in San Francisco, February 27, 1974.

Goldwater, Barry. The stratosphere, ozone, and emotion. Remarks in the Senate. Congressional record (daily ed.) v. 122, Mar. 17, 1976: S3567-S3570.

Gough, Douglas. Ice ages and the mixed-up sun. New scientist, v. 56, December 7, 1972: 562-564.

Grehan, Farrell. Future is famine for ten million south of Sahara. Smithsonian, v. 4, April 1974: 73-78.

Hammond, Allen L. Long-range weather forecasting: sea temperature anomalies. Scicnce, v. 184, June 7, 1974: 1064-1065.

Hannah, A.E. Land and food: an appraisal. Journal of soil and water conservation, v. 30, Nov.-Dec. 1975: 264-267.

Hays, James D. The ice age cometh. Saturday review of the sciences, v. 1, March 24, 1973: 29-32.

Herbert, John P. Model finds ozone depletion not as fast as thought. In Remarks of David F. Emery. Congressional record (daily ed.) v. 122, March 25, 1976: E1542.

Hirst, Eric. Food-related energy requirements. Science, v. 184, April 12, 1974: 134-138.

Hobbs, P.V., H. Harrison, and E. Robinson. Atmospheric effects of pollutants. Science, v. 183, March 8, 1974: 909-915.

Holmquist, Carl O. Long-range weather prediction. United States Naval Institute proceedings, v. 99, November 1973: 45-50.

Imbrie, John. Lessons from the geologic and historic climate records. Paper presented at the 140th meeting of the American Association for the Advancement of Science in San Francisco, February 27, 1974.

Kellogg, W.W. and S.H. Schneider. Climate stabilization: for better or for worse? Science, v. 186, Dec. 27, 1974: 1163-1171.

Keilhorn, William V. The inseparable couple -- air and sea. Naval research reviews, v. 24, October 1973: 11-24.

Klein, Frederick C. St. Louis study indicates people are doing more about the weather than talking about it. The wall street journal, Aug. 19, 1975: 34.

Kukla, George J. and Helena J. Kukla. Increased surface albedo in the northern hemisphere. Science, v. 183, February 22, 1974: 709-714.

LaMarche, Valmore C., Jr. Paleoclimatic inferences from long tree-ring records. Science, v. 183, March 15, 1974: 1043-1048.

Lamb, H.H. Climatic change and foresight in agriculture: the possibilities of long-term weather advice. Outlook on agriculture, v. 7, no. 5, 1973: 203-210.

----- Is the Earth's climate changing? Unesco courier, v. 26, August-September 1973: 17-20.

----- Whither climate now? Nature, v. 224, August 17, 1973: 395-397.

Langlo, Kaare. Unlocking the secrets of tomorrow's weather. Unesco courier, v. 26, August-September 1973: 4-16.

Lansford, Henry. Climate outlook: variable and possibly cooler. In Remarks of Hubert Humphrey. Congressional record [daily ed.] v. 121, Nov. 13, 1975: S19910-S19912.

----- We're changing the weather by accident. Science digest, v. 74, December 1973: 18-23.

Laur, Timothy M. The world food problem and the role of climate. EOS Trans. Amrican Geophysical Union, v. 57, Apr. 1976: 189-195.

Living with climatic change. Proceedings of a conference/workshop held in Toronto Nov. 17-22, 1975. Ottawa, Science Council of Canada, 1976. 105 p.

Lubkin, Gloria B. Fluorocarbons and the stratosphere. Physics today, Oct. 1975: 34-39.

MacDonald, Gordon J.F. The modification of planet Earth by man. Technology review, v. 72, October-November 1969: 26-35.

Massachusetts Institute of Technology. Inadvertent climate modification; report of the study of man's impact on climate (SMIC). Cambridge, MIT Press [1971] 308 p.

Mitchell, J. Murray, Jr. and Edwin P. Weigel. World climate: major changes under way? NOAA [National Oceanic and Atmospheric Administration] magazine, Apr. 1975: 16-23.

Namias, Jerome. Collaboration of ocean and atmosphere in weather and climate. Marine industries: problems and opportunities. Proceedings of the Marine Technology Society 9th Annual Conference. Washington, 1973. p. 163-178.

----- Long-range forecasting of drought and floods. Unesco courier, v. 26, August-September 1973: 48-51.

National Oceanic and Atmospheric Administration. The influence of weather and climate on United States grain yields: bumper crops or droughts; report. Washington, NOAA, 1973. 30 p.

National Research Council. Board on Agriculture and Renewable Resources. World food and nutrition study: enhancement of food production for the United States; report. Washington, National Academy of Sciences, 1975. 174 p.

National Research Council. Committee on Atmospheric Sciences. The atmospheric sciences and man's needs; priorities for the future. Washington, National Academy of Sciences, 1971. 88 p.

----- Weather and climate modification. Washington, National Academy of Sciences, 1973. 258 p.

National Research Council. U.S. Committee for the Global Atmospheric Research Program. Understanding climatic change: a program for action. Washington, National Academy of Sciences, 1975. 239 p.

Newell, Reginald E. The Earth's climatic history. Technology review, Dec., 1974: 31-45.

----- The global circulation of atmospheric pollutants. Scientific American, v. 224, January 1971: 32-42.

Newman, James E. and Robert C. Pickett. World climates and food supply variations. Science, v. 186, Dec. 6, 1974: 874-881.

Nice weather we're having. The economist, September 1, 1973: 56-57.

One place where drought is taking its toll. U.S. news and world report, v. 76, March 18, 1974: 40.

Parker, Eugene N. On the solar wind, magnetic fields, and Earth weather. Bulletin of the atomic scientists, v. 24, May 1973: 25-30.

Peterson, James T. Energy and the weather. Environment, v. 15, October 1973: 4-9.

Pollution causes climatic changes. Mines magazine, v. 60, August 1970: 11-13.

Posey, Carl A. Global climate and man. NOAA, v. 4, January 1974: 24-29.

Purrett, Louise. Weather and the limits of prediction. NOAA magazine, v. 6, Apr. 1976: 16-17.

Ramanathan, V. Greenhouse effect due to chlorofluorocarbons: climatic implications. Science, v. 190, Oct. 3, 1975: 50-51.

Return of the dust bowl? U.S. news and world report, v. 70, May 3, 1971: 22-24.

Roberts, Walter Orr. Hurricanes, aeroplanes, climate, and smog. Mosaic, v. 2, winter 1971: 26-33.

----- Walter Orr Roberts on the atmosphere, global pollution and weather modification. Bulletin of the atomic scientists, v. 29, March 1973: 42-46.

Ross, John E. and Reid A. Bryson. The technical front: food, man and weather. War on hunger, v. 8, February 1974: 13-18.

Schneider, Stephen H. A new world climate norm? implications for future world food needs. In Remarks of Hubert Humphrey. Congressional record, v. 120, Dec. 20, 1974: S22577-S22580.

----- The genesis strategy. New York, Plenum Press [1976] 419 p.

Scientists link aerosols and global temperatures. NOAA week, v. 5, June 7, 1974: 1, 6.

Singh, Khushwant. Waiting for the monsoon. New York times magazine, August 26, 1973: 30-32, 34, 36, 38, 40, 46, 48.

The Southwest fears another year of drought. U.S. news and world report, v. 72, May 22, 1972: 68-69.

Steinberg, Robert. Role of commercial aircraft in global monitoring systems. Science, v. 180, April 27, 1973: 375-380.

Steinhart, J.S. and C.E. Steinhart. Energy use in the U.S. food system. Science, v. 184, April 19, 1974: 307-316.

Sullivan, Walter. Scientists ponder why world's climate is changing. In Remarks of Hubert Humphrey. Congressional record [daily ed.] v. 121, June 4, 1975: S9558-9560.

Tarbeev, Yuri V. Operation "GATE". Unesco courier, v. 26, August-September 1973: 21-23.

The Institute of Ecology. Impact of climatic fluctuations on food production; preliminary report. Washington, The Institute of Ecology, 1976. 6 p.

The Rockefeller Foundation. Climate change, food production and interstate conflict; working papers for Bellagio conference. New York, The Rockefeller Foundation, 1976. 69 p.

Thompson, Louis M. Weather variability, climatic change and grain production. Science, v. 188, May 9, 1975: 535-541.

----- World weather patterns and food supply. Journal of soil and water conservation, v. 30, Jan.-Feb. 1975: 44-47.

U.S. Central Intelligence Agency. Potential implications of trends in world population, food production, and climate; report. Washington, Central Intelligence Agency, 1974. 42 p. [OPR-401]

U.S. Congress. House. Committee on Foreign Affairs. Subcommittee on Africa. The drought crisis in the African Sahel. Hearing, 93d Congress, 1st session. July 16, 1973. Washington, U.S. Govt. Print. Off., 1973. 224 p.

U.S. Congress. Senate. Committee on Agriculture and Forestry. Subcommittee on Foreign Agricultural Policy. U.S. and world food situation. Joint hearings before the Subcommittee on Foreign Agricultural Policy and the Subcommittee on Agricultural Production, Marketing, and Stabilization of Prices, United States Senate 93d Congress, 1st session. October 17, 18, 1973. Washington, U.S. Govt. Print. Off., 1974. 202 p.

U.S. Congress. Senate. Committee on Foreign Relations. Subcommittee on African Affairs. Drought and famine in West Africa. Hearing, 93d Congress, 1st session. June 15, 1973. Washington, U.S. Govt. Print. Off., 1973. 52 p.

U.S. Department of Agriculture. Economic Research Service. The world food situation and prospects to 1985; report. Washington, U.S. Department of Agriculture, 1974. 90 p. [Foreign Agricultural Economic Report No. 98]

U.S. Domestic Council. Environmental Resources Committee. Subcommittee on Climate Change. A United States climate program. [Washington] 1974. 39 p.

U.S. Federal Council for Science and Technology. Interdepartmental Committee for Atmospheric Sciences. National atmospheric sciences program, fiscal year 1976. Washington, National Science Founation, 1975. 82 p. (ICAS 19-FY 76)

----- Interdepartmental Committee for Atmospheric Sciences. The possible impact of fluorocarbons and halocarbons on ozone. Washington, National Science Foundation, 1975. 75 p. (ICAS 18a-FY 75)

----- Interdepartmental Committee for Atmospheric Sciences. Report of the Ad Hoc Panel on the Present Interglacial. Washington, National Science Foundation, 1974. 22 p. (ICAS 18b-FY 75)

U.S. Office of Federal Coordinator for Meteorological Services and Supporting Research. The Federal plan for meteorological services and supporting research; fiscal year 1976. Washington, U.S. National Oceanic and Atmospheric Administration, 1975. 80 p.

University of Missouri-Columbia. Atmospheric Science Department. Economic impacts of weather variability. James D. McQuigg, principal investigator. Columbia, 1975. 256 p.

Walker, Martin. Drought. The New York times magazine, June 9, 1974: 11-13, 42-46.

Wick, Gerald. Where Poseidon courts Aeolus. New scientist, v. 57, January 18, 1973: 123-126.

Will widespread drought hit the country soon? . U.S. news and world report, v. 76, March 18, 1974: 41-44.

Willett, Hurd C. The sun as a maker of weather and climate. Technology review, Jan. 1976: 47-55.

World's "crazy" weather: is a major change under way? U.S. news and world report, v. 75, September 3, 1973: 43.

****

APPENDIX C

LIST OF SELECTED ACRONYMS

****

SELECTED ACRONYMS

AMS	American Meteorological Society
AMTEX	Air-Mass Transformation Experiment (GARP)
BOMEX	Barbados Oceanographic and Meteorological Experiment (GARP)
CAS	Committee on Atmospheric Sciences (National Academy of Sciences)
CCEA	Center for Climatic and Environmental Assessment (U.S. National Oceanic and Atmospheric Administration)
EARTHWATCH	A global environmental assessment program; part of the U.N. Environment Program
FGGE	First GARP Global Experiment
FAO	Food and Agriculture Organization (U.N.)
GARP	Global Atmospheric Research Program
GATE	GARP Atlantic Tropical Experiment
GFDL	Geophysical Fluid Dynamics Laboratory (U.S. National Oceanic and Atmospheric Administration)
GIST	GARP International Sea Trials
GOCC	GATE Operations Control Center
GOES	Geostationary Operational Environmental Satellite
GOS	Global Observing System
GTS	Global Telecommunications System
ICAS	Interdepartmental Committee for Atmospheric Sciences
ICSU	International Council of Scientific Unions
IDOE	International Decade of Ocean Exploration

IGOSS	Integrated Global Ocean Station System (IOC/WMO)
INDEX	Indian Ocean Experiment
IOC	Intergovernmental Oceanographic Commission
ISOS	International Southern Oceans Studies
ITCZ	Intertropical Convergence Zone
ITOS	Improved TIROS Operational Satellite
JOC	Joint Organizing Committee (WMO/ICSU)
MONEX	Monsoon Experiment (GARP)
NACOA	National Advisory Committee on Oceans and Atmosphere
NAOS	North Atlantic Ocean Station
NAS	National Academy of Sciences
NCAR	National Center for Atmospheric Research
NCP	National Climatological Program (U.S. National Oceanic and Atmospheric Administration)
NGTG	NCAR GARP Task Group
NMC	National Meteorological Center
NOAA	National Oceanic and Atmospheric Administration
NORPAX	North Pacific Experiment
POLEX	Polar Experiment (GARP)
RMC	Regional Meteorological Center
SEASAT	Sea Satellite
SMS	Synchronous Meteorological Satellite
TEB	Tropical Experiment Board (WMO/ICSU)
TEC	Tropical Experiment Council (WMO/ICSU)
TWERLE	Tropical Wind, Energy Conversion, and Reference Level Experiment

UNEP	United Nations Environment Program
USC-GARP	U.S. Committee for GARP (National Academy of Sciences)
WDC	World Data Center
WHO	World Health Organization (U.N.)
WMC	World Meteorological Center
WMO	World Meteorological Organization (U.N.)
WWW	World Weather Watch

O