GLOBAL CLIMATE:

A Variable and Vulnerable
Natural Resource

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Executive Summary

We have become involved in a global climate experiment in which human activities (discharges of chemicals, deforestation, irrigation, etc.) act as agents of inadvertent global change. Potential consequences have serious implications for the well being of humankind, but any responses of climate to human activities will be at least partially obscured by the earth's own natural variability. This creates the need for a concentrated and comprehensive effort of monitoring the most important features of the global climate and for simulating its past behavior with models that can then be used to predict future changes.

Plans for such an effort have been formulated internationally as one of the three main streams of the World Climate Research Program, which addresses the heretofore somewhat neglected case of climatic phenomena lasting more than a few years, i.e., from decades to centuries, and the International Geosphere Biosphere Program, which addresses the complex interactions of the climate system with the geological and biological processes. Within the United States, an increasing emphasis is apparent, both in terms of ongoing efforts under the National Climate Program (e.g., the Department of Energy Carbon Dioxide Research Program) and recently proposed multi-agency efforts such as the Earth System Science Program.

The climate machine is driven mainly by solar heating at the surface of the Earth's oceans and the land. This heat is distributed globally to a large extent by ocean currents and injected into the atmosphere primarily through tropical rainfall. The complex nature of these and other processes arises from their internal linkages which make causes and effects difficult to separate or even identify. Existing models as yet cannot simulate all of these "feedbacks," and their ability to represent reality therefore needs to be established by success in reproducing the (imperfectly recorded) historical changes of climate.

Recent and continuing increases in atmospheric carbon dioxide (CO_2) due to burning of fossil fuels can be thought of as a global climate experiment. Such a change in the chemical composition of the atmosphere may lead to future climatic scenarios resembling those of the last major warm period ("interglacial") 125,000 years ago and of the "climatic optimum"

4000-6000 years ago. Other industrial gases with radiative properties resembling those of CO_2, as well as a variety of counteracting natural and man-made substances (e.g., volcanic and industrial particles), contribute to the complexity of the problem.

However, just as technology has engendered the ongoing global climate experiment, it also holds the promise of improved understanding and prediction of the outcome of the experiment through the use of modern computers and global observing systems. We are at a technical threshold from which progress can be proportional to the investment of effort. The potential threats as well as opportunities for predicting and managing our responses to global climatic change demand that such an effort be made now.

Global Climate: A Variable and Vulnerable Natural Resource

1. Climate and the Earth System

As our understanding of the physics, chemistry, and biology of the Earth has progressed, more and more evidence has accrued that the separate components of the planet are really not separate at all, but are interrelated in both obvious and complex ways. Ultimately, we cannot separate the geosphere (oceans, atmosphere, ice, and solid earth) from the biosphere (aquatic and terrestrial, including man), because events in one part of this Earth system are intimately related to happenings elsewhere. As a simple example of this linkage, consider rocks and rain reacting to form soils, while plants and animals through their mutual activities, in turn, influence the composition of both the soil and the atmosphere.

A key component of the Earth system is the global climate. Weather and climate are critical in determining the patterns of life on Earth. Extremes of temperature, winds, and precipitation can mean the demise of species and changes in ecosystems. Recent technological and theoretical advances have greatly improved our understanding of the climate system as well as our prospects for increasing our skill in predicting changes in climate. Given the historical importance of climate in human affairs and the potential impact of human activities on the climate system, we must make every effort to comprehend the global climate, and its relation with the rest of the Earth system.

2. The Global Experiment

During the past three decades we have become increasingly aware that human activity may be inadvertently and irreversibly influencing global climate. In recent years we recognized a series of complex environmental issues. To some of these we may have taken premature action, based on inadequate information. In other cases we delayed action while seeking additional information, and consequently incurred unnecessary economic and environmental losses.

Thus in the early 1970's, respected scientists were warning the President of possible rapid descent into an ice age. Global climate had been cooling for several decades, the present interglacial period had already lasted longer than previous ones, and sea ice extent was expanding. Before the decade ended, however, scientific attention had turned in the opposite direction to the "greenhouse warming" due to carbon dioxide released from burning fossil fuels.[1] Concern increased in the 1980's as it was realized that other gases such as chlorofluorocarbons (CFCs), nitrous oxide, and methane could collectively contribute about as much additional greenhouse warming as carbon dioxide.[2] Recognition that these trace gases introduced by human activities are increasing in concentration in the atmosphere led to estimates of increasing global temperatures. Suggested consequences include a drier climate for the U.S. corn belt and a substantial sea level rise caused by melting polar ice and by the warming and expansion of ocean waters.

However, beyond the direct effect of increasing global temperature, there is no general scientific concensus on the many secondary effets which carry most of the serious consequences for humans. The problem is that these secondary effects involve another complex array of interacting physical mechanisms, many of which are not well understood. Furthermore, certain important secondary effects can be expected to exhibit wide regional differences in magnitude and even in basic character.

The most recent concern is over an "ozone hole" in the stratosphere over Antarctica.[3] For the past several years, total ozone over a large area has decreased towards the end of the long polar night, with concentrations recovering again in the following few weeks (Fig. 1). That the decline became larger

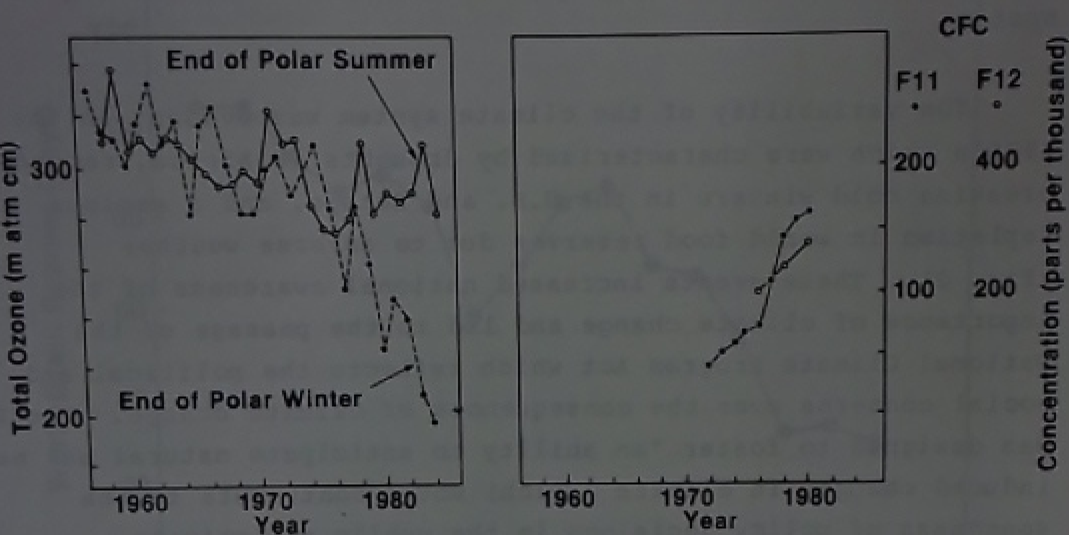


Fig. 1. Decreasing ozone and increasing chlorofluorocarbons (CFCs) above Halley Bay, Antarctica at the end of the polar winter and at the end of the polar summer between 1957 and 1984. (Adapted from Farman, J.C., Gardiner, B.G., Shanklin, J.O., 1985, Large Losses of Ozone in Antarctica Reveal Seasonal ClO_x/NO_x Interaction. Nature, 315, 207.)

each year has sparked discussion that this may be an early sign of a major global depletion of the ozone layer which protects life at the Earth's surface from harmful ultraviolet radiation from the sun. One hypothesis suggests CFCs are the culprit[4]; another attributes the phenomenon to solar influences[5]; a third links it to stratospheric clouds[6]. If the cause is natural, the phenomenon demonstrates a startling variability of the global atmosphere that was unsuspected until recently. If man-made, it reveals, in a very sobering way, the extreme vulnerability of the system.

The variability of the climate system was evident in the 1970's which were characterized by droughts in Africa, record-breaking cold winters in the U.S. and Europe, and a serious depletion in world food reserves due to adverse weather (Fig. 2). These events increased national awareness of the importance of climate change and led to the passage of the National Climate Program Act which reflects the political and social concerns over the consequences of climate change. The Act was designed to foster "an ability to anticipate natural and man-induced changes in climate (which) would contribute to the soundness of policy decisions in the public and private sector." This goal is especially relevant today.

Both the greenhouse warming due to carbon dioxide and trace gases (including CFCs) and the possible ozone depletion due to CFCs are examples of the way in which human activities may be inadvertently changing the global atmosphere and climate. Thus we are performing an experiment on a grand scale, the outcome of which is still in question, and the consequence of which may be far-reaching indeed.

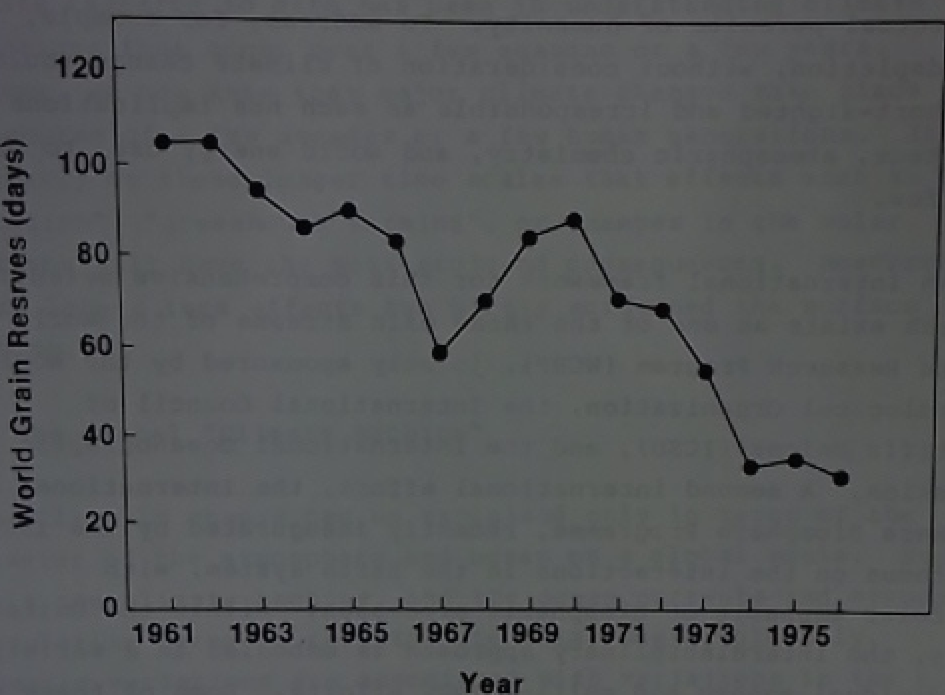


Fig. 2. Depletion of world food reserves due to adverse weather in the early 1970's. (Adapted from Brown, L.E., 1975, The World Food Prospect. Science, 190, 1053.)

A coherent, international, problem-solving campaign is required to understand the global processes that influence climate variability. Fragmented efforts to understand the global environment are certain to be inefficient and ineffective. It is crucial that we treat various environmental problems as connected, one to another, by the interactions among the geosphere, the biosphere, and the complex social, economic, and intellectual pursuits of humanity. To address, for example, ozone depletion, without consideration of climate change would be both short-sighted and irresponsible as each has implications for ecosystems, atmospheric chemistry, and world energy use, to name but a few.

An international framework for this comprehensive scientific approach exists as one of the three main streams of the World Climate Research Program (WCRP), jointly sponsored by the World Meteorological Organization, the International Council of Scientific Unions (ICSU), and the International Oceanographic Commission. A second international effort, the International Geosphere Biosphere Programme, recently inaugurated by the ISCU, will focus on the interactions in the Earth system, with particular emphasis on biospheric processes. Within the United States, the interdisciplinary approach is embodied in a variety of individual agency and multi-agency efforts. Some of these are ongoing programs that may be part of the National Climate Program, such as the Carbon Dioxide Research Program in the Department of Energy. The Environmental Protection Agency has an onoing program concerning global mean sea level rise related to greenhouse warming. Other efforts not presently part of the National Climate Program, but addressing global change concerns, recently have been proposed or are just getting underway.

Within the National Aeronautics and Space Administraton (NASA), the new emphasis is exemplified by the proposed "Earth Observing System." Within the National Science Foundation (NSF) there is a major new thrust in "Global Geosciences," and within the National Oceanic and Atmospheric Administration (NOAA) there is a growing stress on "Predicting Global Change." Most recently, the interdisciplinary approach has been emphasized in the "Earth System Science" program, jointly announced by NASA, NOAA, and NSF.

These plans acknowledge that most of the progress made in climate research to date has been in understanding climate variations that occur over a few seasons or a few years. However, we now know that major climate changes take place over the course of a few decades or a few human generations. It is precisely on these longer time scales that effects such as "ozone depletion", "greenhouse warming", or changes in the solar constant will have the most profound consequences. Research on these longer term effects has barely scratched the surface of the problem.

3. The Global "Climate Machine"

Climatic change can be explained only in terms of the behavior of the atmosphere and ocean on a global scale. Sunlight fuels the climate machine, and the ocean currents and atmospheric circulation serve to redistribute solar energy globally. Climatic variations are associated with variations in the vigor of the whole global circulation, but an adequate understanding of the relationships between these phenomena is lacking. The fundamental problem in the study of climatic change is the development of a quantitative understanding of the general circulation of the atmosphere. Moreover, since three-quarters of the Earth's surface is covered by ocean, most of the heat energy which is the source of atmospheric motion comes by way of the ocean surface. Therefore, a quantitative understanding of oceanic heat transport and atmosphere/ocean energy exchange is especially vital (Fig. 3).

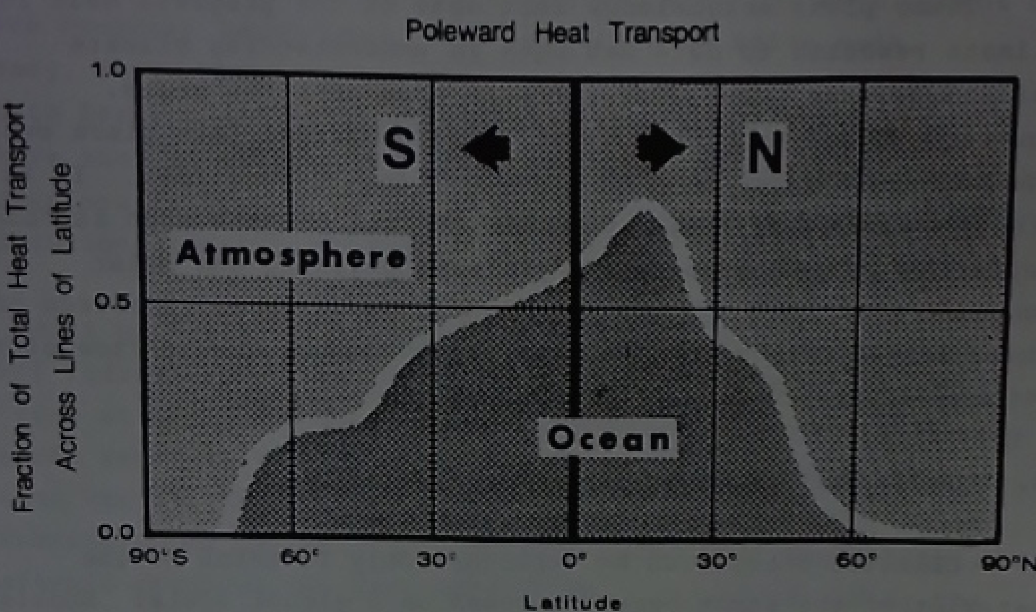


Fig. 3. How the atmosphere and oceans contribute to global heat transport. (Source: Ocean Heat Transport and Storage: A Program/Plan for Investigating the Ocean's Role in Climate Variability. NOAA, 1979)

Fundamental physical laws should enable us to predict the global distribution of temperature, pressure, motion, water vapour, clouds, and precipitation, together with resulting moisture and heat transports (Fig. 4). In practice, because the various parts of the climate system interact in innumerable ways on scales ranging from the microscopic to the global, this presents enormous difficulties. However, with the development of modern computer technology, rapid progress is being made. Already, it is becoming possible to mathematically simulate certain large scale processes in more detail than we can now observe them in nature. In order to firmly ground such computer simulations in reality, a comprehensive data base of physical observations is also required.

Most pathways for inadvertent climate modification involve direct influences on the planetary heat balance which regulates the flow of energy in the "climate machine." The most promising research strategy for understanding both natural and manmade climate variations and atmospheric dynamics is to gain a better understanding of the processes of the atmospheric heat budget. Remarkable progress has been made to date in understanding the roles of particular physical variables in influencing climate. Some of these are discussed in the next section.

3.1 Factors Involved in Climate Change

The only external forces acting on the global climate are solar radiation, the gravitational fields due to the sun, moon, and earth, and the forces related to the planet's rotation and orbital motion. Much attention has been devoted to variations in these truly fundamental causes of climate change which seem to account satisfactorily for the sequence of ice ages and warm "interglacials" of the last million years. On the shorter time scales of most concern to human beings (decades to centuries), however, we are concerned more with various internal interacting components of the system, such as the composition of the

COMPONENTS OF THE ATMOSPHERE-OCEAN-ICE-LAND SURFACE-BIOMASS CLIMATIC SYSTEM

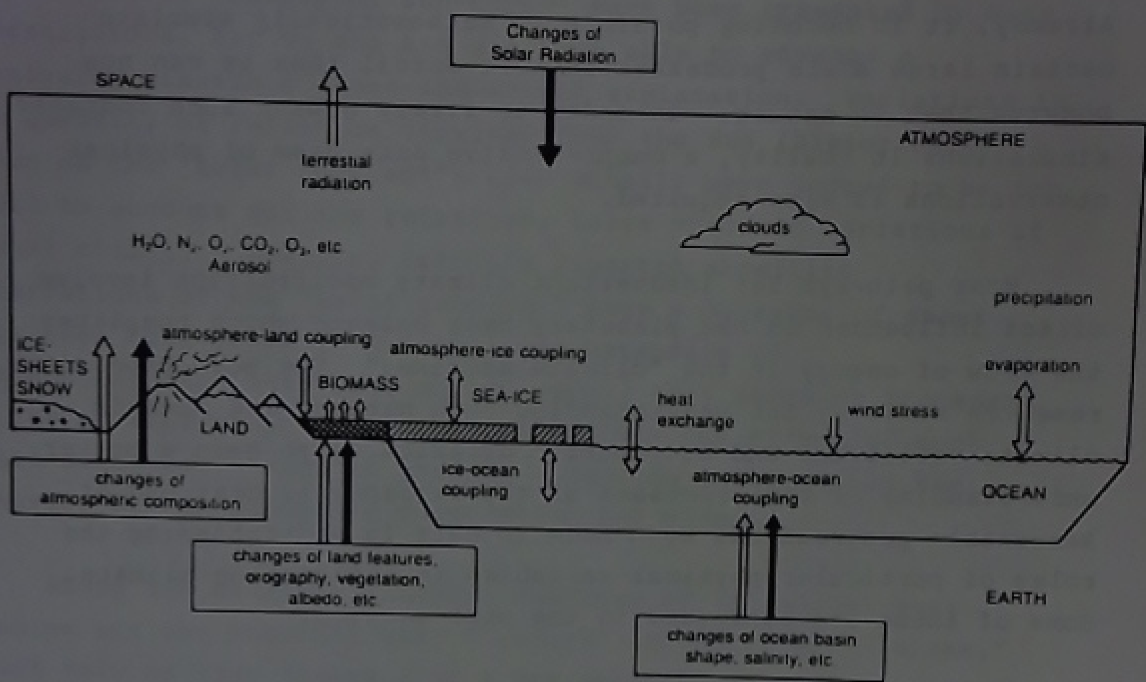


Fig. 4. Schematic illustration of the components of the coupled atmosphere-ocean-ice-land surface-biomass climatic system. The full arrows (⟶) are examples of external processes, and the open arrows (⟹) are examples of internal processes in climatic change. (Source: Global Atmopsheric Research Program (GARP) Joint Organizing Committee, 1975, The Physical Basis of Climate and Climate Modelling, GARP Publ. 16, ICSU/WMO)

atmosphere, the global sea level, the extent of polar ice, and the changing nature of the Earth's surface.

The most fundamental external factor influencing global climate is the input of energy from the sun. Statistical correlations between various climatic indices and indices of solar activity (including sun-spots) have been presented by many investigators, but no one has yet been able to advance a physically plausible cause-and-effect explanation. Variations in the quantity of radiation received from the sun (historically known as the "solar constant") have usually been judged to be too small to account for the relatively large observed variations of global climate. However, recently reported satellite observations of the "solar constant" show a decrease of about 0.1% over five years[7]. A better understanding of atmosphere/ocean interactions may reveal that feedback processes in the ocean/atmosphere system can amplify the effect of such small solar variations to produce significant changes in the behavior of the planetary circulation and climate.

Among the dominant internal features of the global heat machine are the tropical heat "sources" and polar heat "sinks," which vary on time scales from a few weeks to several years. The thermal mechanism that dominates weather and climate in the tropics is the changing distribution of rainfall (Fig. 5). The condensation of water vapor to form clouds and rain releases the "latent" energy the water acquired during its evaporation. More than two thirds of the heat received by the tropical atmosphere is from condensation, which often occurs far from where the evaporation took place. The distribution of tropical rainfall (heating) exhibits large variability on all time scales. A major project of the World Climate Research Program aims to understand the processes influencing this interannual variability[8]. The project, called TOGA for Tropical Oceans and Global Atmosphere, began officially in 1985. More than twenty countries are conducting or have pledged to carry out various parts of the

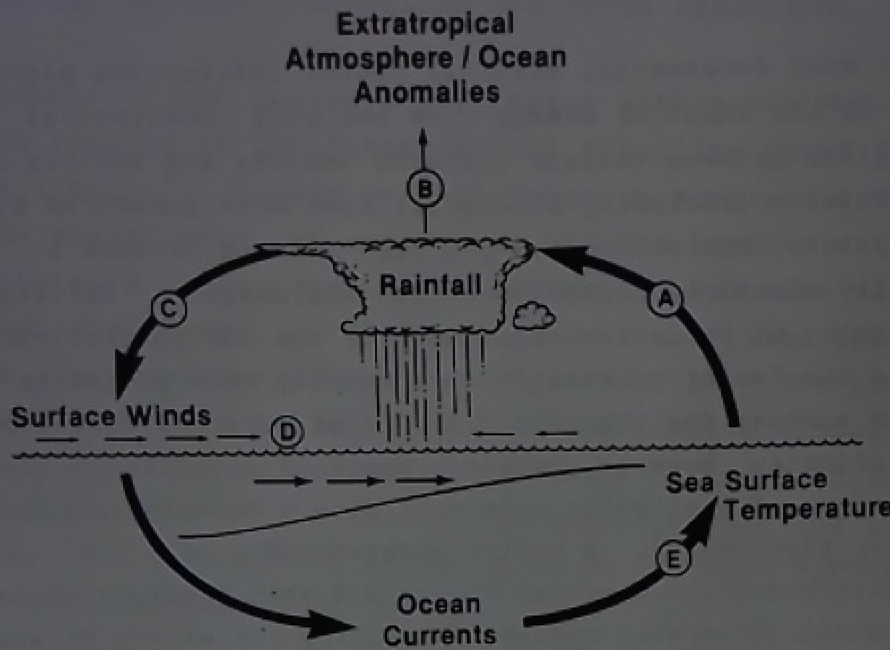


Fig. 5. The role of tropical rainfall and release of latent heat in the coupled climate system. (Source: National Reserach Council, 1986, U.S. Participation in the TOGA Program: A Research Strategy. National Academy Press)

A) atmospheric circulation and rainfall in the tropics respond to the sea surface temperature distribution,

B) tropical rainfall patterns influence the jetstream and major storm tracks in extratropical latitudes,

C) and the surface wind field over tropical oceans;

D) tropical winds drive currents in the surface layers of the equatorial oceans, which influence oceanic upwelling,

E) and sea surface temperature distribution.

effort. In the United States, NOAA, NSF, and NASA are the major participating agencies. Much progress has already been made and experimental climate predictions are being attempted.

Another of the projects undertaken within the World Climate Research Program is the International Satellite Cloud Climatology Project (ISCCP)[9]. Clouds reflect incoming sunlight back to space but also absorb heat and emit it toward the Earth's surface. Very little is known about the distribution and time variability of global cloudiness, even though present satellite observation systems are providing global coverage (Fig. 6). The ISCCP is a five year effort to collect, process and archive global cloud observations. Specific research projects included in ISCCP should shed light on the role of clouds in modulating global climate. The U.S. effort in the program is multi-agency in nature with NASA the lead agency.

Another important thermal mechanism in the climate system is the variable extent of ice on the ocean (Fig. 7). Ice reflects solar radiation back to space and insulates the oceanic heat reservoir. Both processes tend to maintain and reinforce a cold environment. In this manner, changing atmospheric and oceanic temperatures are linked to variations in the extent of sea ice.

More generally, small changes in solar heating may have amplified effects due to a number of self-reinforcing feedback mechanisms in the ocean-atmosphere-ice "climate machine". There are many such feedbacks, both positive and negative, in the machine and many thresholds beyond which the direction of the feedback can change. Whether initially small changes can eventually trigger sudden instabilities in the system cannot be judged now. It is vital that we address this question of instability, since, while we may be able to adapt to gradual changes in global climate, an abrupt shift in the system to a radically different regime or greatly increased variability may be too great a challenge to a modern society unprepared to respond.

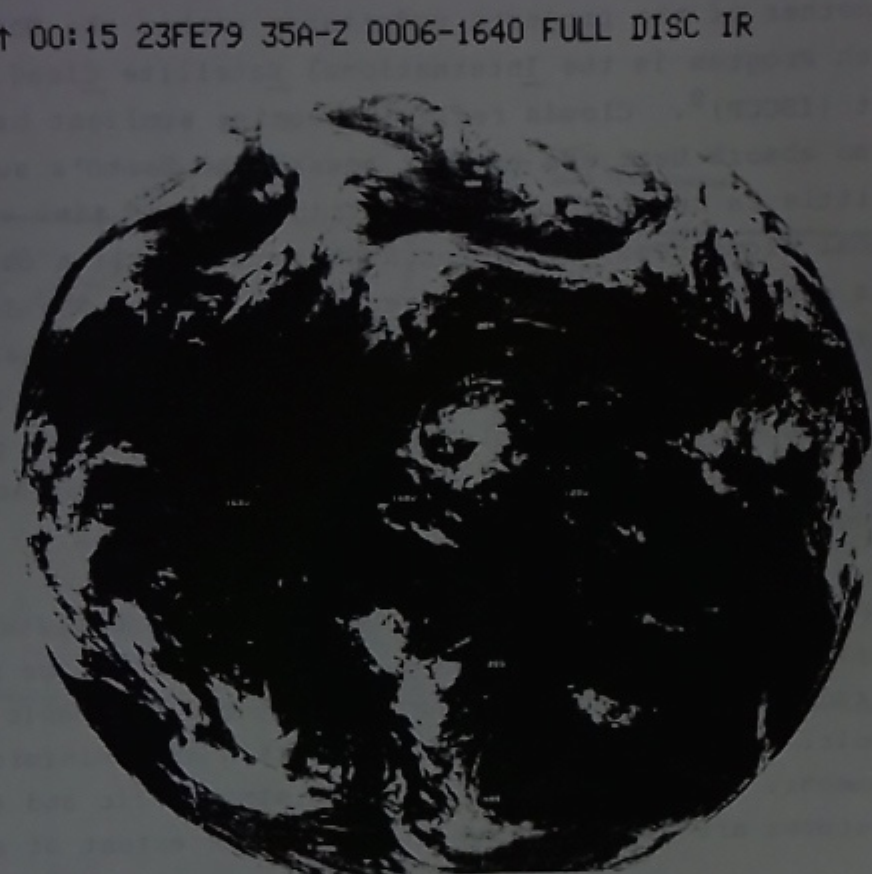


Fig. 6. A satellite photo of the clouds over the Western Hemisphere 23 February, 1979. (NOAA - GOES West)

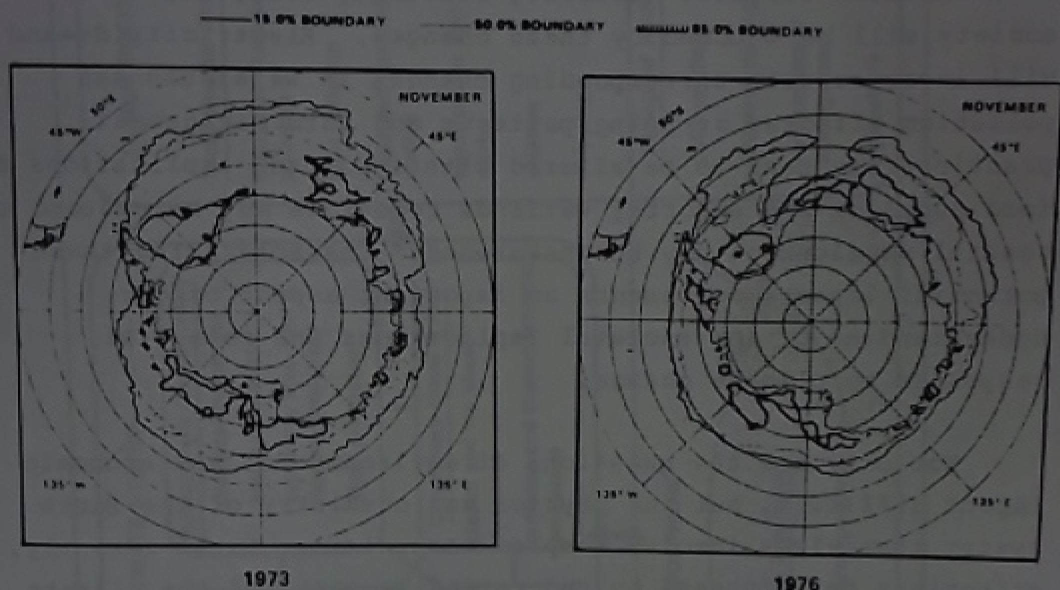


Fig. 7. The changing extent of Antarctic sea ice for the month of November, 1973 and 1976. Boundaries indicate zones that were ice covered 15%, 50%, and 85% of the month. (Source: Zwally et al., 1983, Antarctic Sea Ice: Satellite Passive-Microwave Observations, 1973-76, NASA SP-459)

3.2 The Scientific Challenge

Global climate change has the potential of affecting the environment in both unexpected and dramatic ways. Impacts on water resources, wetlands, agriculture, forests and human health are widely recognized as being among the most important environmental effects. However, virtually every aspect of society will be touched by these changes. Electricity demand will increase with corresponding changes in water use and pollution effects; cropping patterns and farm management practices may need to be altered with important implications for food supplies and exports; wetlands resources may be reduced and coastal development may be threatened. Characterizing these potential impacts represents an important aspect of our understanding of the societal implications and potential responses to climate change.

Not only are the questions of environmental and economic impact difficult, but the physics and chemistry of the Earth system themselves involve complex mechanisms. Until recently, scientists have focused on understanding parts of the climate machine as outlined above. Current thinking is that our climate system is what mathematicians call a "highly-coupled, interactive, non-linear" system. In coupled systems different mechanisms affect one another like cogs in a machine; turning one causes motion everywhere else. In non-linear systems the basic variables "feed back" into each other to such an extent that causes and effects can no longer be clearly distinguished and responses become predictable at best only in statistical terms (Fig. 8). This is especially true of the global climate. Thus it is simplistic to deal with individual physical and chemical mechanisms as isolated from the rest of the system.

Predicting the onset of a climatic instability may be realizable. It is also reasonable to think that we may predict the features of a probable new "equilibrium" climate

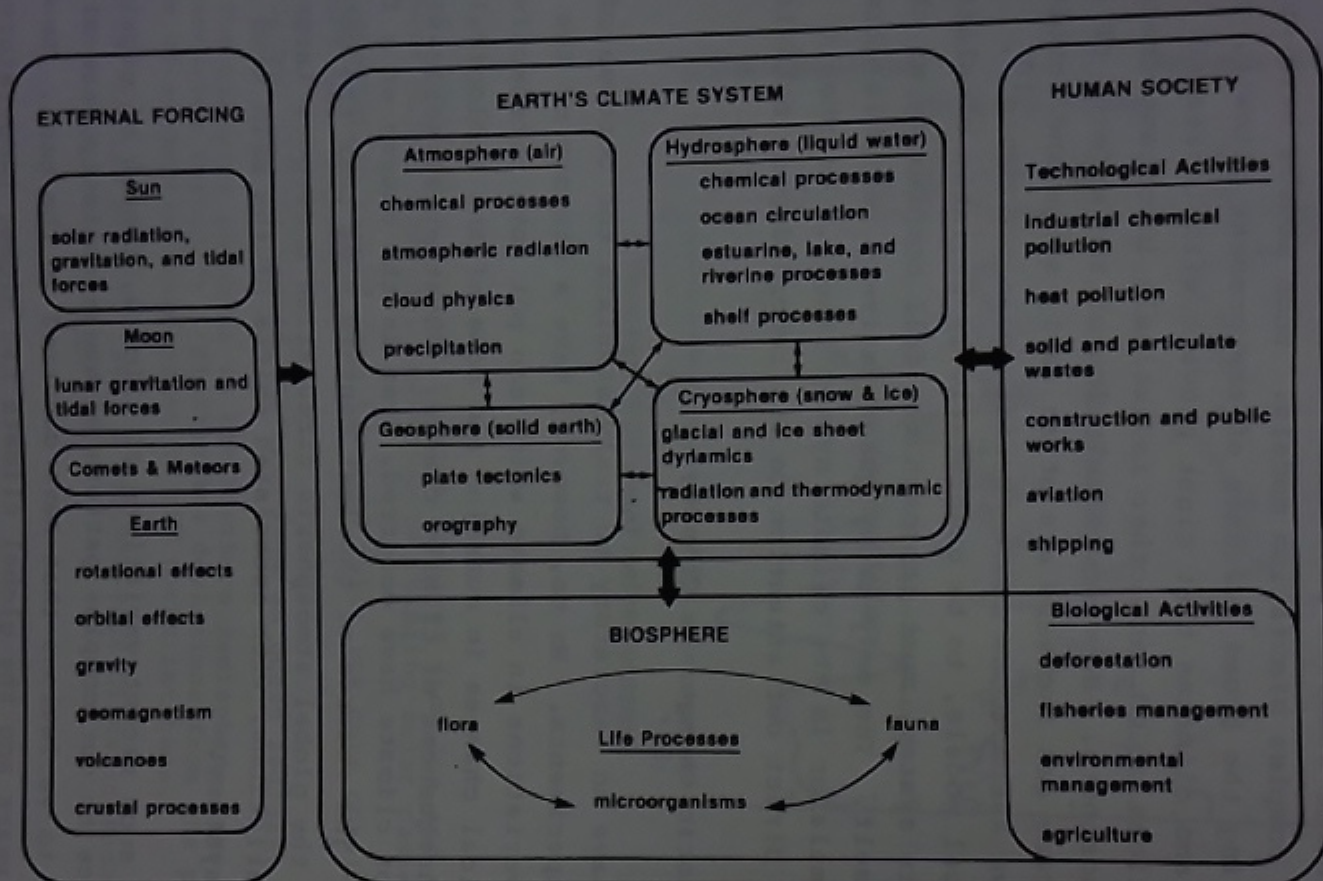


Fig. 8. Interactions of the climate system with the biosphere and external forcing mechanisms.

state. But the timing and exact nature of the transition to that state are probably inherently unpredictable, if we are indeed dealing with instability and transition problems in a non-linear climate system.

In climate studies, physical laws and computers can be used to develop complex simulation models. Such models have succeeded in simulating the broad features of the present climate, past climates, and climates that might prevail with increased concentrations of CO_2 and other radiatively important trace gases in the atmosphere. However, simulation of the effects of a gradual trace gas increase are at an early stage and involve speculative assumptions about crucial ocean processes[10]. Mathematical models, to be quantitatively reliable simulators of the climate system, must approach the full complexity of the system itself. The only truly quantitatively reliable climate system simulator is the climate system itself. We should therefore direct our attention to its recorded past behavior.

3.3 Historic Changes in Climate

We have no laboratory to truly simulate the outcome of our global experiments. We do, however, have a history of the natural variations in climate which can put into perspective both the physical changes in question and some of the ecological and human consequences of climate change. Substantial world-wide changes of climate have occurred, even in the course of a few decades. The records of the last century show that the general vigor of the global atmospheric circulation undergoes large and sudden variations, with associated shifts of the main wind and weather systems.

Yet such recent variations of climate, though of growing importance to our complex pattern of human activity, are minor compared to variations that have occurred in the past. About 125,000 years ago the global climate had higher temperatures and larger atmospheric concentrations of CO_2 than present (Fig. 9).

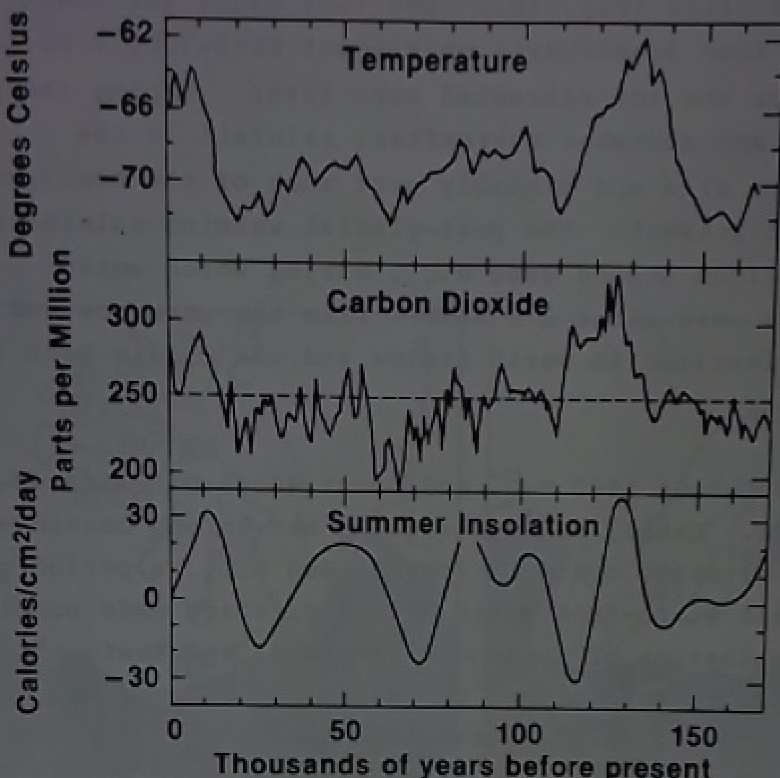


Fig. 9. Long term climate changes, derived from ice and ocean sediment cores, and their relation to changing solar radiation.

a. Temperature record from the 2100 meter ice core obtained at Vostok, East Antarctica.

b. Carbon dioxide record inferred from an ocean sediment core.

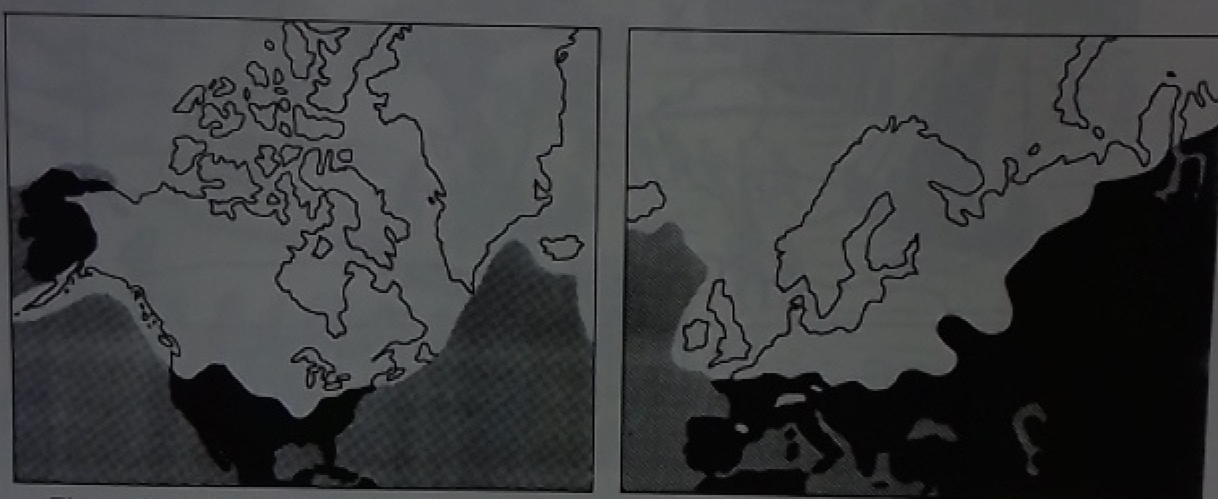
c. The changing sunshine in the Northern Hemisphere (the "Milankovich forcing"). Plotted are deviations from the present value of summertime insolation at 65° North latitude.

(Source: Lorius et al., 1985, A 150,000-Year Climatic Record from Antarctic Ice. Nature, 316, 591)

Less than 20,000 years ago, an ice sheet covered North America and stretched from the Atlantic to the Pacific with a thickness of up to two miles (Fig. 10). The last major ice sheet disappeared from Scandinavia only about 8000-7000 B.C., while in North America the ice retreated even later. During the period of ice retreat and somewhat thereafter, rainfall in the Mediterranean area and probably over much of the hemisphere was less than at present. The post-glacial warming culminated in a climatic optimum around 4000 B.C., during which world temperatures were about $1^{\circ}C$ warmer than they are now and rain was much more plentiful in North Africa and the Middle East (Fig. 11)[11].

Between about 1000 B.C. and about 400 B.C. climatic conditions deteriorated. Later, renewed warming set in and continued until a 'secondary climatic optimum' in 800-1000 A.D., a period characterized by a warm and storm-free North Altantic, which made possible the great Viking colonization of Iceland, Greenland, and Newfoundland. A subsequent climatic cooling, during which arctic pack ice advanced southward in the North Atlantic, occurred abruptly around 1300 A.D., and was followed by a recovery around 1500 A.D. The continuing decline culminated in the 'Little Ice Age' of 1650-1840 A.D (Fig. 12).

Since about 1861, a global warming trend has predominated with short term warming and cooling trends embedded in the longer term change[12]. The periods of general warming were accompanied by decreasing vigor of the atmospheric circulation in both hemispheres, poleward displacement of storm paths, and a pronounced warming of the Arctic. The cooling trends exhibited a reverse pattern: stronger circulation, more variable storm paths displaced towards the equator, and a colder Arctic. At the start of each period the atmospheric circulation exhibited abrupt changes in behavior that had been relatively stable for decades.



The areas of North America covered by glaciers during the last Ice Age.

The areas of Europe covered by glaciers during the last Ice Age.

Fig. 10. Ice extent during the last glaciation. (Source: J.D. Hays, Our Changing Climate, New York, Atheneum, 1977)

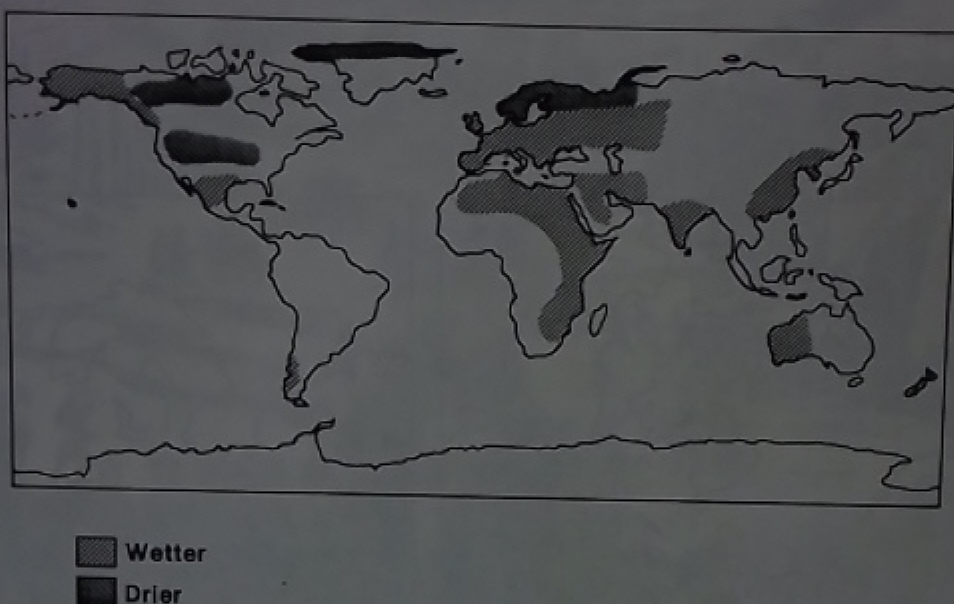


Fig. 11. A reconstruction of the summer rainfall regime during the climatic optimum (about 4000 B.C.) as compared with the present. (Source: Kellogg, W.W, and R. Schware, 1981, Climate Change and Society: Consequences of Increasing Atmospheric Carbon Dioxide, Boulder, CO, Westview Press)

Fig. 12. Frost fair on the frozen Thames River in the winter of 1683-84, at the height of the Little Ice Age. (Source: J. Gribbin, 1975, Our Changing Climate, Faber)

Historical variability in local water resources is closely linked with climate change. For instance, in about 1900 the discharge of the Nile River, after five decades of relatively high values, suddenly decreased by about one third and remained at the lower levels. In 1962 the discharge of the White Nile doubled and remained at the higher levels. In 1930 the average discharge of the Colorado River decreased by about one fourth and has remained at low levels until the 1980's. The "Compact" dividing the water between the several states of the U.S. and Mexico had been concluded in 1922 based on the higher flows, not taking in consideration the possibility of a large decrease in flow. From 1962 to 1986 the surface area of the Great Salt Lake has more than doubled. Today the water level of four of the Great Lakes is higher than it has been for a century. This hydrological response is only one manifestation of the effects of global climate variations that occur on the time scale of decades.

3.4 Inadvertent Modification of Global Climate

In view of the extreme consequences that natural variations in global climate have had throughout history, the prospect that human activities may be inadvertently changing the climate system in a variety of ways deserves serious consideration. Table 1 and Fig. 13 provide the necessary perspective. The table lists the various factors, both human and natural, known or believed to play roles in climate change, while Fig. 13 shows their relative contribution to the total "variance", or statistical deviation from the mean state, of climate on different time scales. Some of these factors are discussed below.

The factor in the foreground of current interest is the increasing concentration of carbon dioxide and other trace gases in the atmosphere. There is no doubt that carbon dioxide concentrations in the atmosphere have been increasing in this century, apparently by about 25%, mainly due to the increased combustion of fossil fuels (Fig. 14)[13].

TABLE 1: POSSIBLE CAUSAL FACTORS IN FUTURE CLIMATIC CHANGE

ORIGIN	FACTOR	CONFIDENCE* THAT FACTOR WILL PRODUCE EFFECTS	CONFIDENCE* THAT FACTOR WILL APPRECIABLY AFFECT CLIMATE	ESTIMATED PRINCIPAL CLIMATIC EFFECT(S) TO THE YEAR 2000 A.D.	TIME SCALE(S) OF CLIMATIC VARIATION INVOLVED
Man	Carbon dioxide increase	High	Moderate-High	Warming (1°C**)	Trend
	Increase in chlorofluorocarbons (CFC) and other greenhouse gases	Moderate	Moderate	Warming (1°C**)	Trend
	Ozone depletion by CFC, NO_2, etc	Moderate	Moderate	Ultraviolet radiation increase (10%)	Trend
	Particle increase	Moderate	Low-moderate	Warming-cooling	Days & longer
	Thermal pollution	High	High (local effects)	Warming: local clouds/storms	Trend
	Land use changes	Moderate	Moderate (regional effects)	Temperature/ Precipitation Changes	Decades & longer
SUN	Total solar radiation	Low	High	Warming-cooling	Months & longer
	Ultraviolet & other variations	High	Low-moderate	(Not Clear)	Days & longer
MOON/SUN	Tidal variations	High	Moderate	Rainfall/ cloudiness changes (1-10%)	Two weeks & longer
VOLCANOES	Stratospheric particle injections	High	Moderate-high	Cooling (0.1-1°C)	Years & longer
OCEANS	Sea surface temperature variations	High	Moderate-high (regional effects)	Temperature/ precipitation changes	Months & longer
CRYOSPHERE	Sea ice/snow cover variations	High	Moderate (regional effects)	Temperature/precipitation changes	Months & longer
	Polar ice sheets surges	Moderate	High	Rise in sea level.	Decades & longer
BIOTA	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 numerical values are order-of-magnitude estimates for each as a whole; regional effects may differ substantially.
**Cumulative effect by year 2000 A.D.

Modified from Proceedings of Conference Workshop on 'Living with climatic change'. Toronto 17-22 November 1975. Science Council of Canada 1976

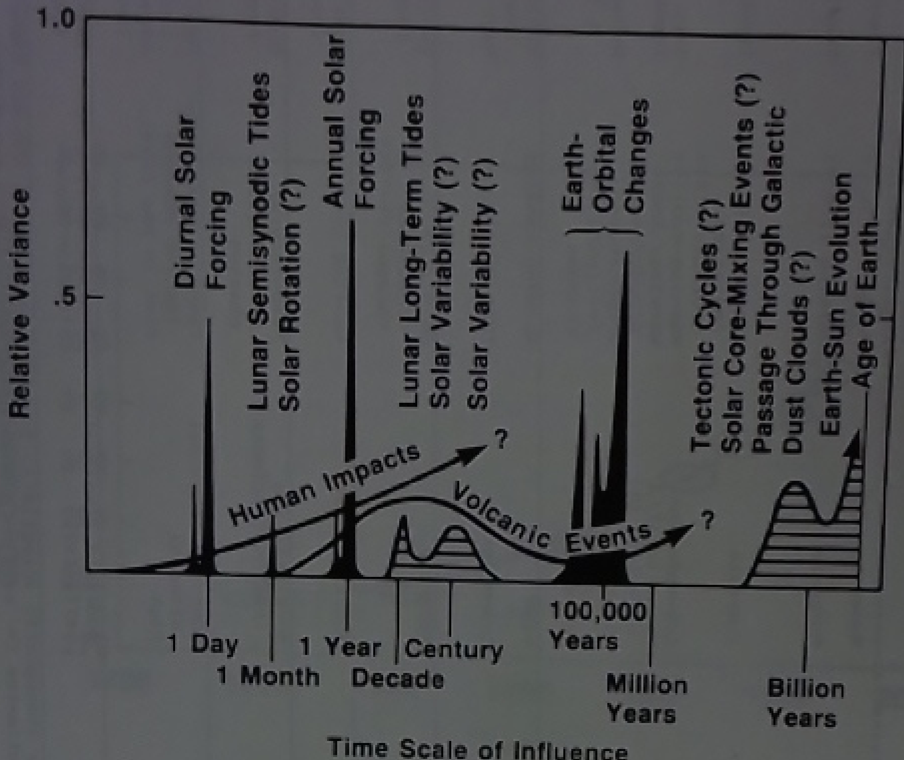


Fig. 13. Contributions to the total climate "variance" from known or proposed periodic forcing phenomena. The full vertical scale corresponds to the maximum known variability of the system at the time scale in question (horizontal scale). Solid black indicates well-known forcing phenomena, whereas hatching indicates less well established ones. (Source: J.M Mitchell Jr., 1980, "History and Mechanisms of Climate" in Oeschger, H., et al., eds, Das Klima, Springer)

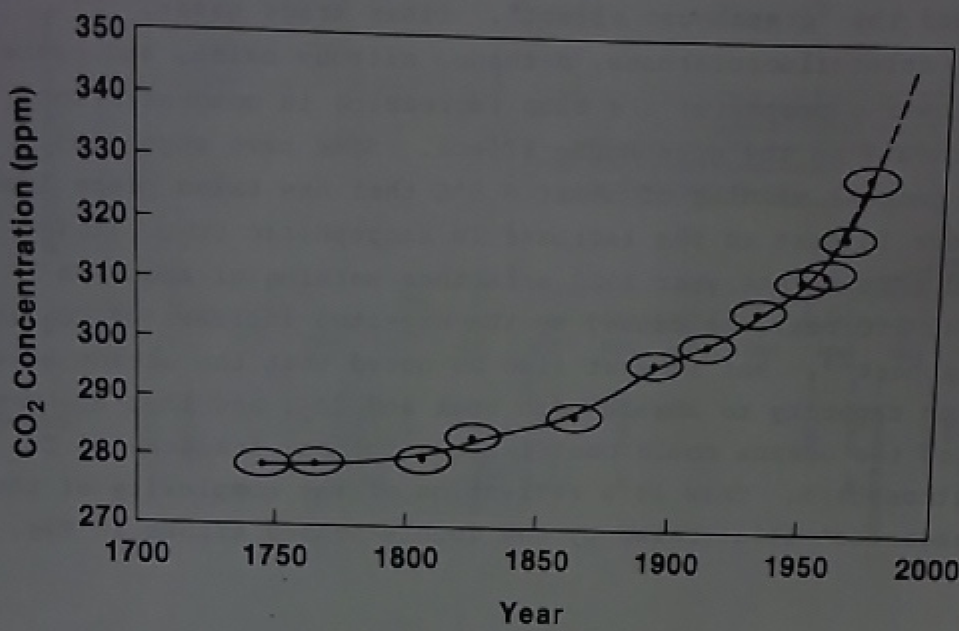


Fig. 14. The growth of atmospheric carbon dioxide concentrations. The solid curve (with ellipses showing the time and concentration uncertainties) has been derived from an ice core obtained at Siple, Antarctica. (Source: Neftel, A. Moor, E., Oeschger, H., and Stauffer, B., 1985, Evidence from polar ice cores for the increase in atmospheric CO_2 in the past two centuries. Nature 315, 45.)

The broken curve is measurements of atmospheric CO_2 concentrations beginning in 1957 and smoothed to eliminate seasonal effects at Mauna Loa Observatory. (Source: Atmospheric Carbon Dioxide and the Global Carbon Cycle, 1985, U.S. Dept. of Energy, DOE/ER-0239, J.R. Trabalka, ed.)

The implications according to the current state-of-the-art in understanding are documented in a series of reports issued by the Department of Energy. The physical effect of a greater CO_2 concentration in the atmosphere is to decrease the loss to space of heat radiated by the Earth's surface. This phemonenom has been termed the "greenhouse effect". Other trace gases, including chlorofluorocarbons, methane, nitrous oxide, and ozone (in the lower atmosphere) are also increasing in concentration and contribute to the greenhouse effect. Some have suggested that the general warming of about 0.5°C that has taken place from 1860 is due in part to the increase in atmospheric CO_2. It is estimated that by the year 2000 a further warming of about an additional 1°C could be caused by the expected increase of CO_2 in the atmosphere[14]. But it must also be noted that the oceans have a changing capacity to absorb both heat and CO_2, and that a warming of the oceans could contribute a further increase of CO_2 to the atmosphere. This is a reflection of the complexity of the many "feedbacks" illustrated by the double-headed arrows in Fig. 8.

Thus, it appears that, other factors being constant, the CO_2 and other gases generated by human activity could bring about important changes of global climate during the next few decades. But other factors, such as the particulate load and cloudiness of the atmosphere and the characteristics of the Earth's surface, are not constant, and we do not yet have even a rough idea of how much they vary over several decades.

Some have in fact attributed climatic changes primarily to changing amounts of solid and liquid particles in the atmosphere, caused primarily by volcanic eruptions but supplemented in recent decades by man-made pollution (Fig. 15). The effect is to reduce the transparency of the atmosphere to both incoming solar radiation and outgoing heat from the surface. The net impact on climate is as yet unclear.

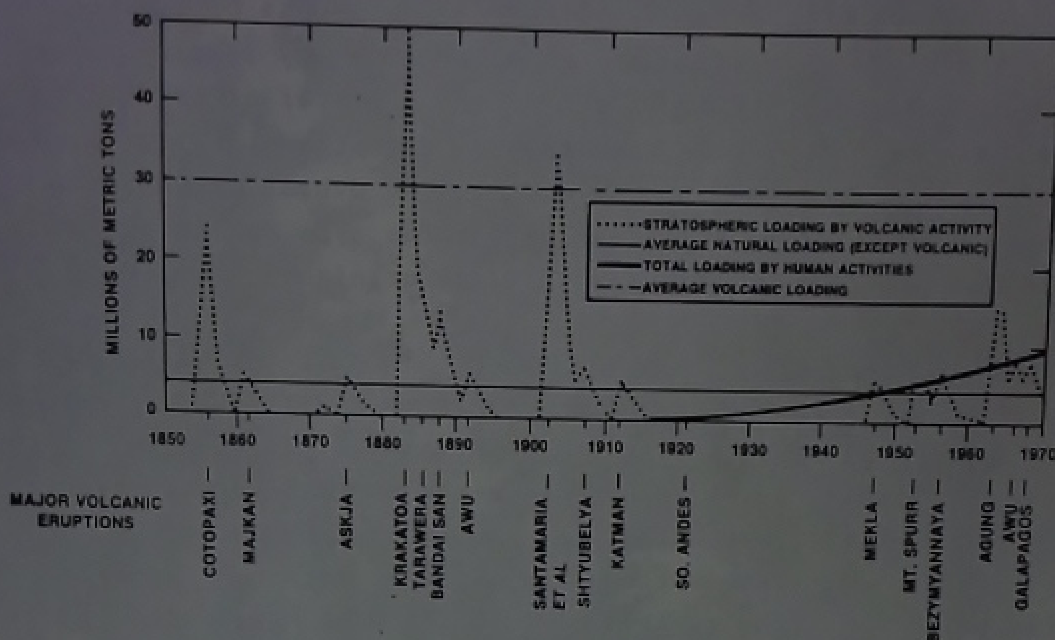


Fig. 15. Recent particle injections into the atmosphere by volcanoes and by humans. The growing input of anthropogenic particles that started around 1930 has been called a "human volcano" and may explain the global cooling between 1940 and 1970. (Source: J.M. Mitchell Jr., 1978, in J.R. Miller, ed., Prospect for Man: Climate Change, York University)

Still another form of pollution, and one whose possible effects have received little study, is the creation of cirrus cloudiness (vapor trails) by the exhaust products of high-flying aircraft (Fig. 16). Increased cloudiness of any form tends to increase the reflectivity of the Earth. However, increased cloudiness at high levels also reduces radiative loss to space, thereby warming the Earth. Here, too, the overall influence is difficult to evaluate as it depends on the type and height of the clouds and on whether they are in a day or night hemisphere of the Earth.

Changes in the characteristics of the Earth's surface are also linked to the climate system. Although difficult to quantify, a substantial reduction in the world's forests has occurred over the last 200 years, mostly in tropical areas. Because plants consume carbon dioxide, this decline in forest cover globally may be contributing to the greenhouse effect. Precipitation patterns are also affected as water runoff to rivers increase due to decreased cycling through trees. This is just one of a myriad of interactions between the climate and life on Earth.

We must conclude that man is inadvertently influencing global climate in a variety of ways. However, there are so many variables in the global system that it is difficult to determine when we may cross a critical threshold to an unprecedented change in climate regime. While it may not be possible to formulate specific cause and effect relationships, our minimum goal must be to determine the potential range and direction of climate change likely to be superimposed on the natural variability of the system.

Fig. 16. High clouds developing from airplane exhaust particles injected into the upper troposphere. (NCAR photo)

4. Prospects for Progress

From the foregoing examples it is evident that modern technology is already influencing the global system by altering distributions of heat and chemicals, but the consequences of such acts cannot yet be fully predicted. The global system is a single, interacting "heat engine" in which a substantial action anywhere may influence subsequent behavior everywhere. At present, we do not understand the system well enough to predict this behavior. Our inability to predict adequately the impact of our lifestyle should cause us to examine our activities with an eye toward minimizing deleterious outcomes.

In theory, it is possible to solve the equations which describe the behavior of the atmosphere and the ocean, given the conditions of thermal forcing and the initial state of the system. Such a quantitative analytical approach was formulated by V. Bjerknes in 1904 and expanded by L. F. Richardson in 1922. Since neither the means to observe the state of the system nor the necessary computational power existed at that time such an approach had little immediate impact.

As recently as the Second World War, not more than 20% of the global atmosphere was observed at one time. With the advent of satellite observing systems, some quantities are now observed over the entire planet every day. This observational breakthrough makes possible the surveillance of the entire global system, and the sophistication of the observations that can be made by satellite and other new observational systems is rapidly increasing.

Modern computer technology is rapidly overcoming some of the computational aspects of the problem. Mathematical simulations of the interacting atmosphere/ocean system have already been carried out with some success (Fig. 17). With more powerful

Numerical Climate Model Simulation and Prediction

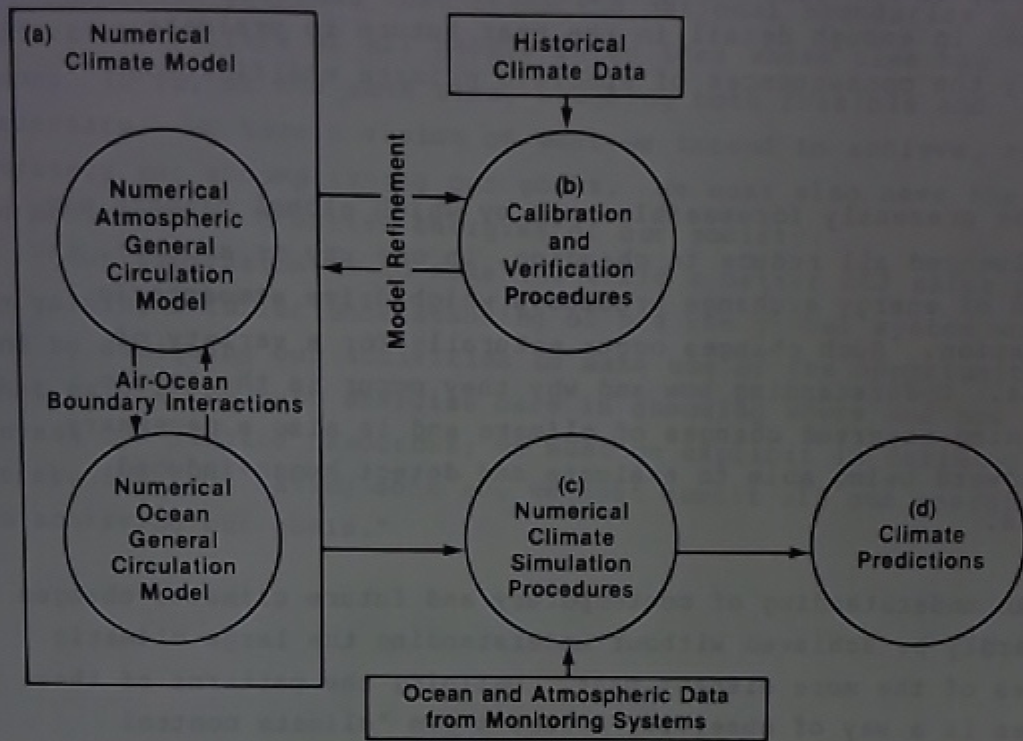


Fig. 17. Conceptual Flow Chart of the Climate Modeling Process. (a) Numerical General Circulation Models represent the dynamics and energy transport of the atmosphere and ocean. These are coupled together through mathematical formulations of the air-sea interaction and other boundary processes to provide a numerical picture of the global climate (simulation). (b) The climate simulations are compared with historical climate data (verification) and adjustments are made to certain model coefficients to improve agreement (calibration). (c) Starting with data on current ocean and atmospheric conditions, the model uses these data for initialization or boundary information (initial values and boundary conditions), or otherwise incorporates it into the simulation process (data assimilation). (d) Starting from the best simulation of the present climate, the model projects the simulation into the future through a step-by-step mathematical process (prediction).

computers and advanced climate simulation models now being developed, we can reasonably hope that such simulations can be performed in enough detail in the near future to evaluate reliably the consequences of specific climate modification acts.

The presently foreseeable ways by which global climate may be influenced all reduce to changing, in one way or another, the pattern of energy exchange processes which drive atmospheric circulation. Such changes occur naturally for a variety of reasons. Understanding how and why they occur is the key to explaining observed changes of climate and is also a necessary step toward being able to evaluate and detect human-induced changes.

An understanding of contemporary and future climatic changes can hardly be achieved without understanding the large climatic changes of the more distant past. Defining the patterns of these changes is a way of observing nature's own "climate control experiments." The collection and systematization of paleoclimatic evidence, as well as data on changes over shorter (historic and prehistoric) time scales, is a task of great practical importance.

From the foregoing considerations we arrive at the following conclusion: We are reaching a technological threshold from which progress in understanding can be proportional to the investment of effort. This conclusion, combined with the need to formulate policy regarding current climate modification activities, deserves the attention of scientific and governmental leaders who must determine and muster the needed resources. It is this realization that underlies the growing consensus articulated at the interagency press conference on "Earth System Science" (June 26, 1986)[15].

"Every great achievement was an idea before it became a reality. The growing sense of global community concerning environmental problems that transcend national boundaries and affect the welfare of all people is an idea whose time has come. It is, at the same time, becoming both feasible and necessary. We have a vision of what we intend to achieve, and a strategy for accomplishing our goals. We must also have the will to mobilize the creative energies of our society.

Our aspiration is to make the world a better and safer place by gaining a fuller understanding of how the global system works and by designing our activities to make use of the opportunities that exist. We must exercise care in choosing where and how to invest our limited resources; we must be explicit in defining our strategies and, having done so, we must commit all our energies to achieving our goals."

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