Life on a Warmer Earth
Possible Climatic Consequences of Man-Made Global Warming

Executive Report 3, based on research by H. Flohn
at the International Institute for
Applied Systems Analysis (IIASA)

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Foreword

IIASA Executive Reports communicate the findings of research conducted at and in collaboration with IIASA to a wide readership, especially those who can put the findings into effect, such as executives in government and industry.

This Executive Report derives from IIASA Research Report RR-80-30, *Possible Climatic Consequences of a Man-Made Global Warming*, by H. Flohn. It is based on research undertaken at IIASA in 1977 in conjunction with the Institute's Energy Systems Program, and makes use of information available up to March 1980. The work explored the interaction between energy and climate, including the impact on the global climate of three main energy sources: solar, nuclear, and fossil fuels. Its findings describe the global warming effects caused by carbon dioxide released by burning fossil fuels and by other trace gases released into the atmosphere.

The approach is paleoclimatic – it gains insights into what global warming will produce by considering what is known about past periods of the earth's history when the global average surface temperature was higher than it is now. The only other way to study the processes of the climatic system is with models. Both approaches have considerable shortcomings: no complete model of the climate system has yet been devised, paleoclimatic knowledge is limited, and the conditions of past periods differ from conditions today. However, by using both approaches, and combining the two to some extent, we can advance our knowledge of the global climate.

The IIASA research summarized in this Executive Report represents an admittedly speculative, yet carefully calculated global-warming scenario suggesting some dramatic changes in the global climate that could occur over the coming decades largely as a result of burning fossil fuels. It makes interesting reading for decision makers with responsibilities for energy development.

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Preface

Twenty years ago, if you had invited scientists to an international conference on global warming, you very likely could have held your sessions around a coffee table. Since then the subject has caught on dramatically, so that recent global warming get-togethers have been frequent and bustling – a workshop on Carbon Dioxide, Climate & Society and a follow-up meeting at IIASA in 1978; the 1979 World Climate Conference sponsored primarily by United Nations agencies; and in 1980, another IIASA workshop and two sponsored by the Aspen Institute.

The interest in global warming, like the problem itself, simmered awhile before boiling. In 1899, the American geologist Thomas Chamberlin sounded an early alarm. A frequent contributor to the *Journal of Geology* – best known for his hypothesis that the planets had spun off from the sun – Chamberlin attempted in one article to identify an atmospheric basis for glacial epochs and noted almost in passing that carbon dioxide released in the process of burning fossil fuels could warm the lower atmosphere and the surface of the earth.

The idea was elaborated by the Swedish physicist and chemist Svante Arrhenius, a founder of modern physical chemistry. Arrhenius published the second volume of his textbook on cosmic physics, complete with a description of the global warming process, in 1903, the same year that he received a Nobel Prize for earlier work on galvanic conduction in electrolytes.

Much was learned about global warming during the next six decades, but the knowledge caused little stir. In 1963, for instance, the Ford Foundation's encyclopedic *Resources in America's Future: Patterns of Requirements & Availabilities: 1960–2000* said not a word about global warming. Compare that with a similarly ambitious inquiry recently published in two volumes by the US Council on Environmental Quality: *The Global 2000 Report to the President*, which offers yes, no, and maybe scenarios for man-made global warming, and concludes: "The increased carbon dioxide concentrations implied by a continuation of present trends have momentous importance."

Official commissions began talking about the momentousness of the problem after *Inadvertent Climate Modification: Report of the Study of Man's Impact on Climate* was published by M.I.T. Press in 1971. Here were eminent international scientists firmly opposed to the conventional assumption that the global climate system was too big, stable, and resilient to be altered by the emissions of exhaust pipes and chimneys. Some of these scientists thought global warming had already begun; all agreed that global warming was possible.

The greenhouse and the sinks

The possibility of man-made global warming results from the "greenhouse effect," (although what occurs in greenhouses is not the same). As carbon dioxide increases in the atmosphere, the visible shortwave portion of the radiation spectrum still gets through from the sun to the earth about as well as ever. However, as heat is then radiated back from the earth in the infrared longwave range, it increasingly tends to be trapped in the atmosphere and radiated right back to earth. And since carbon dioxide spreads evenly through the atmosphere, all the world becomes a greenhouse.

Before the expansion of modern industry in the late 19th century, the atmospheric carbon dioxide content is believed to have been between 270 and 295 parts per million by volume (ppm). Today it is something like 338 ppm, up about 15 to 20 percent from pre-industrial levels.

Roughly five billion tons of carbon go up in smoke every year, but only about half this amount is known to stay up. The rest remains a mystery. About 2 billion tons may simply dissolve in water. But while the oceans are surely a net sink for carbon, the earth's greenery remains suspect. Plants absorb carbon dioxide in the photosynthesis process, true. But dead plants and humus release the gas into the atmosphere. So does burning wood. Deforestation at today's pace, particularly in the tropics, may add more carbon dioxide to the atmosphere than the vegetation of the earth can absorb.

There is doubt, then, about where atmospheric carbon dioxide comes from, where it goes, and whether the rate of increase will change. Nor is there any certainty about future petroleum and coal consumption rates. Furthermore, too little is known about external influences on climate – solar activity, volcanic activity, changes in the earth's orbit, rotation, and tides – to say for sure whether the global climate will get warmer because of man's interference in the carbon cycle, or cooler despite it.

But the real problems come in trying to convert atmospheric carbon dioxide increases into estimates of global warming and then to determine for specific regions what effect the global warming would have on the local climate.

There are two ways to predict global warming: by building models and by making analogies with warmer times. So far, both methods have had serious drawbacks. The current generation of models suffers because feedbacks among climatic subsystems are complex, and some processes have not yet been well described.

For example, there is uncertainty about the amount of heat deep oceans absorb. Another uncertainty for today's modelers is the way clouds may form after global warming. There are also problems with predicting climate on a regional scale.

Simply making analogies with periods when the earth was warmer has two main drawbacks. One is the limited amount of information. The other is that if you go backward in global history to a time when global temperatures were anything more than slightly higher than they are today, you are dealing with entirely different boundary conditions – vegetation lines, sea levels, glaciation, even mountain formations and placement of continents. A climate with higher global temperatures in the near future might not imitate similarly warm periods of the distant past.

A paleoclimatic panorama

Because of its urgency, complexity, and scope, global warming has emerged within a decade as a major scientific challenge. IIASA's interest in the subject began in the early stages of its Energy Systems Program, which has just completed and published results of a seven-year project on the development of future energy scenarios over the next 50 years. In 1977, Professor Hermann Flohn of the Meteorological Institute, University of Bonn, joined the Energy Systems Program to study the interaction of energy and climate. While at IIASA, Flohn did extensive research on global warming and prepared a report on this topic.

Flohn's work, updated to March 1980, is now available in two forms. IIASA RR-80-30 *Possible Climatic Consequences of a Man-Made Global Warming* is the technical research report. The report you are reading aims to put Flohn's findings in layman's language and add related information to provide a general introduction to the global warming problem.

Flohn makes comprehensive analogies with warmer times. From the best models now available, he takes readings of the future global average surface temperature (GAST). He modifies the figures to allow for other "greenhouse-effect" gases released to the atmosphere by man, such as nitrous oxide, methane, ammonia, and the chlorofluoromethanes. With temperatures and times roughly established (from a 1 °C increase in GAST by 2000–2010 to a 4 °C increase by 2040–2080), he then looks to past times when temperatures were similar.

To develop his global warming scenario, Flohn taps a store of information about the earth's history that has accumulated in several fields of science. He studies four periods with GASTs like those that may lie ahead: the early Middle Ages (1000 years ago), the warmest peak of the present Holocene interglacial period (6000 years ago), the previous interglacial (120,000 years ago), and a long stretch of the late Tertiary (2.5–12 million years ago) when the Arctic Ocean was ice-free and the Antarctic Continent was buried under about as much ice and snow as exist there today.

An ice-free north pole and a markedly asymmetric climate system aren't the only surprises for laymen in Flohn's paleoclimatic panorama. It is as if a fast-motion film of earth had been made from a point in space. GAST rises 1 °C and the forests of Canada and Siberia advance northward. Land where cereal crops can be grown increases. But fresh water starts to dwindle in California, Spain, and the Near and Middle East. Severe winters occur at the latitudes of many of the industrial cities of the northern hemisphere.

With GAST at 1.5 °C, Canadian and Siberian forests reach 200–300 kilometers further north than present lines. The Sahel region of Africa becomes verdurous again, and subtropical deserts shrink both north and south of the equator. At 2.5 °C, sea level has risen 5 to 7 meters. Scandinavia becomes an island. Deciduous trees grow on the northern coasts of North America, Europe, and Asia. But as the earth approaches a GAST 4 °C higher than it is today, summer droughts become frequent and increasingly severe in much of the temperate zones, and the Arctic ice disappears.

And so on. One could wish, however, for more development of the script. Paleoclimatic data are spotty and lack parallels. Here we count salt layers under the Mediterranean, there we inspect Alaskan insect fossils, yonder we note ice-rafted pebbles in sub-antarctic seas. But while the paleoclimatic facts at hand cannot give us the overall description of global warming that global climate models aspire to, paleoclimatic scenarios can suggest what is ahead on a regional basis – which the models have yet to do convincingly.

Other scientists have investigated past warming, particularly where good synoptic meteorological information is available. But Flohn is a pioneer in the development of a complete paleoclimatic scenario for the effects of global warming over the next 100 years, and his work serves as a cornerstone for the paleoclimatic approach.

The burning of fossil fuels may trigger the greatest single anthropogenic change in environmental history. It may eventually be possible to prepare better for this future – and if necessary prevent it – by studying aspects of life on a warmer earth.

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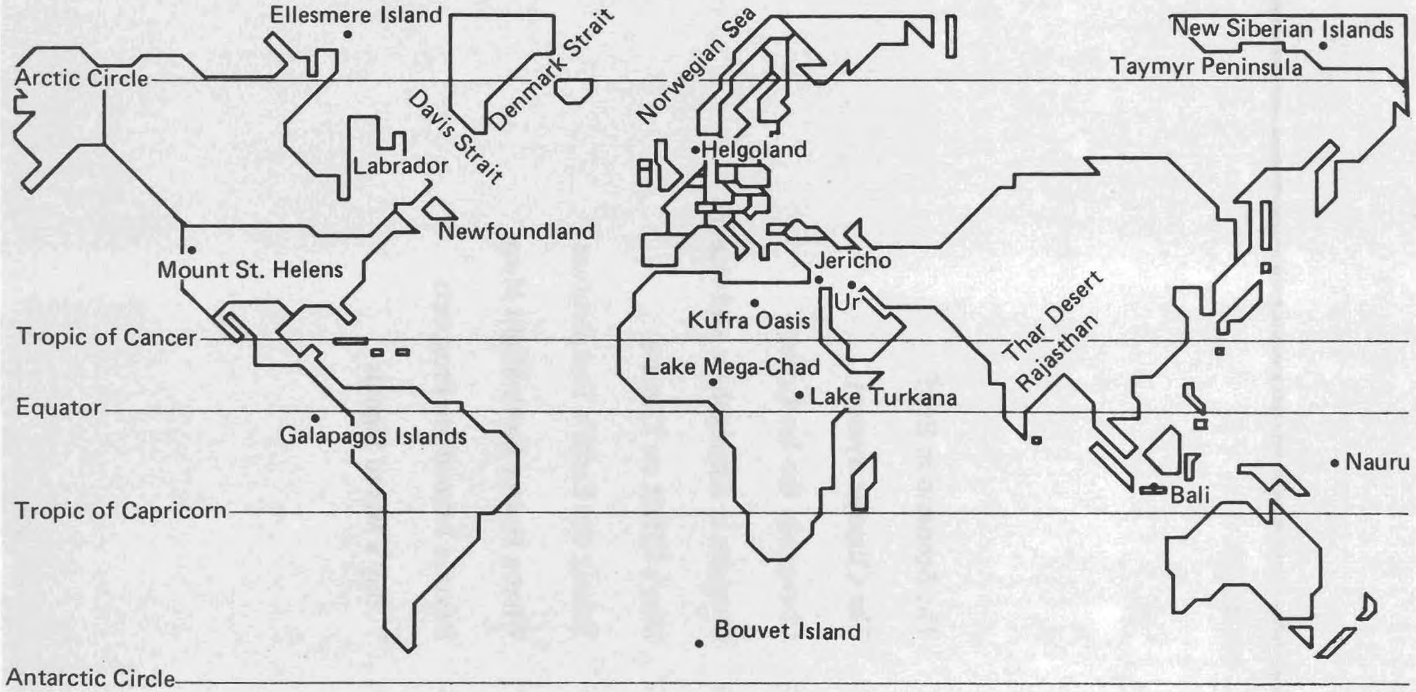
Approximate Locations of Some Areas Mentioned in the Text



1

The Scenario in Brief

Man may be changing the climate of the earth. Scientists are concerned in particular that burning fossil fuels (coal, petroleum, and natural gas) adds carbon dioxide to the global atmosphere, which could cause the surface temperatures of the earth to rise.

What man-made global warming would mean is not yet clear. Despite much progress in climate-related research, scientists still lack a complete understanding of climatogenic processes and how they interact. Without such knowledge, reliable long-term predictions of climate are impossible.

The need for such predictions, though, is great. Evidence accumulates to show that the earth has always been subject to dramatic changes in climate, and man's rising population may increase his vulnerability to them. A mere 1 °C increase in what scientists call the global average surface temperature could cause problems in many areas.

Short-term, local changes in climate also have eluded prediction, and they too cause suffering. A good example is the 1958 drought that displaced millions of people in northeastern Brazil. More recently, atypical conditions have increased concern about the prospect of climatic change. The year 1980 exhibited unusually heavy rains in Europe and a severe heat wave in North America, while the spring of 1981 saw rare snows in England and unexpectedly heavy rains in Somalia and Ethiopia after a three-year drought.

The uncertainties of climate have stimulated much debate among scientists. Because the subject is both controversial and highly topical, a research report published in 1980 by the International Institute for Applied Systems Analysis (IIASA) is of wide interest. The executive report you are reading has been taken largely from that paper: *Possible Climatic Consequences of a Man-Made Global Warming,* by Professor (emeritus) Hermann Flohn of the Meteorological Institute, University of Bonn. Additional material on the subject presented here comes from other IIASA research and conference proceedings.

The Flohn paper contemplates the climatic changes that global warming might produce. It bases a scenario for warming on the paleoclimatic information now available. The scenario is speculative, and it must be noted that the experts are not in full agreement on the evidence supporting it. Nevertheless, Flohn has provided a glimpse of some climatic possibilities by drawing extensively on

"A mere 1 °C increase in what scientists call the global average surface temperature could cause problems in many areas."

the climatic information now at hand. In addition, he offers much of interest to the nonscientist who wants to gain an understanding of today's anomalous climatic conditions and what they may mean for tomorrow.

The earth as a greenhouse

Man changes his local climate by polluting the air, producing heat, and altering the surface of the earth. So far there is no sure evidence that these activities influence climate in a global way. But the amount of carbon dioxide in the global atmosphere has been rising since man began to burn fossil fuels on a large scale in the latter half of the 19th century. At present, the carbon dioxide content of the atmosphere is about 15 to 20 percent greater than it was before 1860.

Further gains of carbon dioxide and certain other gases in the atmosphere could cause what scientists call the "greenhouse effect." As these gases are added to the atmosphere, heat from the visible shortwave portion of the radiation spectrum gets through from the sun to the earth nearly as well as before. But the heat reflected from the earth is part of the longwave, infrared portion of the spectrum and tends to be absorbed or radiated back to the earth by the gases man has added to the atmosphere. Solar heat that otherwise would be reflected off the earth to outer space gets trapped and raises temperatures at the surface of the earth. (The term "greenhouse effect" is imprecise. It occurs in real greenhouses, but most of a greenhouse's heat gets trapped because the glass roof keeps warm air in.)

At present, no one can say for sure what a hotter earth would mean, because truly comprehensive models of the earth's climatic system as a whole are not yet available. Such models must represent a complex, interacting system of atmosphere, oceans, soil and vegetation, and snow and ice. Within these systems are various subsystems that take vastly different periods to act: some atmospheric changes occur over a few days; by contrast, the gradual buildup of the Antarctic ice dome has taken many millions of years. This range of time scales greatly hampers model building.

Climatogenic processes are of two categories. Most of them are internal, resulting from natural feedback within the global climatic system. A few are external, such as changes in climate caused by variations in solar radiation and by explosive volcanic eruptions. While it remains impossible to foresee many aspects of future climate, conditional predictions, where one asks what the climatic consequences of a given process would be, may be feasible.

The formation and melting of polar sea ice is a major internal climatogenic process. Historical variations in Arctic sea ice and in the Antarctic continental ice sheet have been considerable. The Antarctic ice is now probably partially unstable, which eventually could cause catastrophic ice surges or deglaciation of western Antarctica. Global atmospheric circulation is asymmetrical because of the contrast between the Arctic ocean's thin cover of drift ice and the Antarctic continent's heavy glaciation.

Sensitive interactions between the atmosphere and the oceans in regions of frequent oceanic upwelling are another important internal climatogenic process. Upwelling, which occurs along the equator and some coasts, causes cooling and reduces evaporation from the ocean to the atmosphere. Downwelling has the opposite effect.

Among climatic changes produced or triggered by man, atmospheric increases in carbon dioxide and other gases are potentially the most important, and the only man-made changes suspected of having global effects already. Attempts to model the relation between increases in the gases and global warming must deal with the long residence times of the gases (between five and fifty years), their mixing throughout the atmosphere, and their combined greenhouse effect in absorbing radiation, which Flohn estimates to be about 50% greater than the effect of carbon dioxide alone.

Today's global average surface temperature is roughly estimated at 15 °C. The best models available indicate that doubling the carbon dioxide content of the atmosphere would raise annual mean temperatures at the earth's surface by an average of 2 ° or 3 °C in the low and middle latitudes. In polar latitudes with snow and ice, the warming could be 5–10 °C, and there may be various seasonal changes as well. Nitrous oxide (a product of nitrogen fertilizers and aircraft fuel combustion) and other trace gases add 50% to the effect of carbon dioxide, and this accelerates global warming.

Some possible climatic futures

Flohn estimates future temperature evolution by applying selected carbon dioxide growth rates to the most reliable radiation models for the relation between carbon dioxide content of the atmosphere and temperature. Then he selects thresholds of temperature increase to represent warm phases during the earth's history. He assumes no major changes in such external factors as solar radiation.

Flohn speculates that global temperatures may become 0.5 °C higher than present levels sometime between 1990 and 2000. His scenario considers four somewhat hotter periods of the past – when average annual temperatures at the surface of the earth were higher than now by 1 °C, 1.5 °C, 2.5 °C, and 4 °C. Global warming of 4 °C could occur after 2050, with an ice-free Arctic ocean and a glaciated Antarctic continent. Such conditions existed from 12 million to 2.5 million years ago.

Flohn's phase three is the interglacial period 120 000 years levels, vegetation, mountain formations, and others – interact with temperatures, affecting them and being affected by them. The farther back the phase in the earth's climatic history, the more these conditions vary from today's. Accordingly, each of the four paleoclimatic phases he cites are the most recent times when global warming has reached the temperatures described.

His first warmer phase is the early Middle Ages about 1,000 years ago, a time when global temperatures were about 1 °C higher than now. Cereal was then cultivated in Iceland, and Vikings settled in southern Greenland. Tree lines in European mountains were at higher altitudes, and Canadian forests were as much as 100 kilometers farther north.

By the early Middle Ages, sea ice around Greenland had retreated, and this caused cyclones to track farther northward, producing frequent droughts all over Europe. These drought conditions, if repeated, could be among the more devastating effects of global warming, and they could come in little more than two decades, according to an estimate Flohn derives from climatic models and his own calculations.

The second warmer phase is the peak of the Holocene warming period about 6,000 years ago, a time when the global average surface temperature was 1.5 °C higher than it is now. This produced more humidity almost everywhere, but particularly in the currently arid belt of the Sahara Desert and the Middle East, which then was largely semiarid grassland, densely populated by cattle-raising nomads – conditions not likely to return.

Learning more and knowing less

The oceans in particular exert a powerful influence on the earth's climates, yet we have inadequate oceanographic observations on the space and time scales needed for climatic studies. The important heat, moisture, and momentum exchanges that occur at the sea surface, and the corresponding transports that occur within the ocean, are not at all well known. Recent observations from the Mid-ocean Dynamics Experiment (MODE) reveal energetic oceanic mesoscale motions at subsurface levels, and our ignorance becomes even greater than we thought it was.

– *Understanding Climatic Change*, National Academy of Sciences, Washington, D.C., 1975.

Despite the warmth of Eurasia and Africa 6,000 years ago, eastern North America stayed relatively cool, especially in summer. This produced predominantly southwesterly winds over the Atlantic, which in turn probably intensified the Gulf Stream's northward-flowing branches. Canadian and eastern Siberian forests were 200–300 kilometers farther north than now.

Flohn's phase three is the interglacial period 120,000 years ago, when the average temperature was about 2.5 °C higher than now. Seas were from five to seven meters higher than today, which suggests a partial disintegration of the western Antarctic ice sheet. This higher sea level affected vegetation and coastlines everywhere. The sea penetrated deeply into northern and eastern Europe and western Siberia. Scandinavia was isolated from the continent.

The climate was moister than today. Forests extended all the way to northern coastlines where Arctic drift ice had retreated well away from land. Greater warmth and more moisture in the northern temperate zone could produce more arable land, despite inundated coastlines. However, a global average surface temperature 2.5 °C warmer than today's could cause migrations from some areas affected by heat and drought, particularly in the subtropics.

It is also worth noting that this hottest of interglacial periods (of the last 2.5 million years) ended abruptly. Most interglacials cool rapidly, but this one had ice accumulating at the poles so fast that sea levels appear to have dropped 60–70 meters within hardly more than 1,000 years. There is speculation that clustered volcanic eruptions may have contributed to cooling.

The fourth and last warm phase Flohn considers occurred just before the glacial–interglacial period that continues today. For 10 million years before this time, the Arctic ocean was ice-free. If global temperatures rose 4 °C, a possibility by 2050 if man releases greenhouse-effect gases into the atmosphere at Flohn's projected rates, the Arctic could be ice-free again. Its ice is now only two or three meters thick, which makes it sensitive to changes in ocean heat flow. The Arctic ice could melt within a few decades or less.

The eastern Antarctic continent has been fully glaciated for 12–14 million years, and it would probably stay that way with a global warming of 4 °C. This would increase the asymmetry of atmospheric–ocean circulation. Subtropical arid areas of the southern hemisphere would expand toward the equator, and the northern arid belt would extend to the Mediterranean, affecting even southern central Europe.

Temperature differences between the equator and the poles would decrease. Tropical and subtropical belts of the northern hemisphere would expand; temperate and subpolar belts would contract. After a possible series of catastrophic weather extremes, the earth's climatic zones would be displaced northward by 400–800 kilometers.

In some areas man would benefit, but in others such a drastic climatic change coming abruptly in a few decades or less would be highly destructive, drastically reducing freshwater supplies and causing unpredictable and potentially large agricultural losses. Flohn says the full effects are inconceivable, and the risks are unacceptable, and therefore man-made global warming must be prevented.

2

The Climatic System

Despite our highly advanced civilization, we still cannot predict the climate in any dependable way. Progress is being made, however, and one day man may be able to foresee potentially catastrophic changes in his biosystem. With this knowledge he may be able to avert such changes by adapting to them gradually or in some cases by preventing them.

The main obstacle to gaining control over man's long-term climatic destiny is the sheer complexity of the total climatic system of the earth. Global climate consists of five subsystems that interact through a great variety of processes.

The earth's most variable climatic subsystem is the atmosphere, its gaseous envelope. Temperature changes are absorbed by the atmosphere in about a week. The hydrosphere – water on and under the earth – varies in its adjustment to temperature changes. Upper layers of the ocean interact with the atmosphere in months to years; deep ocean waters take many centuries to make thermal adjustments.

The cryosphere is snow and ice – continental ice sheets, mountain glaciers, snow cover, and ice on bodies of water. Much snow cover is seasonal, related to atmospheric circulation. Glaciers and ice sheets have their own time scales, taking from hundreds to millions of years to change significantly.

The earth's surface land masses compose its lithosphere. This includes mountains, ocean basins, surface rock, soil, and sediments. Land takes the longest of any climatic subsystem to change. For example, continental drift takes hundreds of millions of years. Such events are not strictly climatic, but they do relate to glaciation. Also, the lithosphere affects climate as deep sea sediments accumulate, and more dramatically when volcanic debris is spread through the atmosphere.

Plants and animals of land, sea, and air compose the biosphere. They influence climatic changes and are themselves sensitive to climatic changes. Changes in surface vegetation taking from decades to thousands of years affect surface albedo, evaporation, and ground hydrology.

The climatic system can also be divided into an internal system of gas, liquid, and ice surrounding the earth and an external system of what lies under the surface of the earth and in the space surrounding it. Internal climatogenic processes include precipitation, evaporation, wind, and heat exchange between atmosphere, ocean, land, and ice. External processes include changes of solar radiation, earthquakes, volcanic explosions, changes of atmospheric composition, and changes in land and ocean shape.

Some problems of prediction

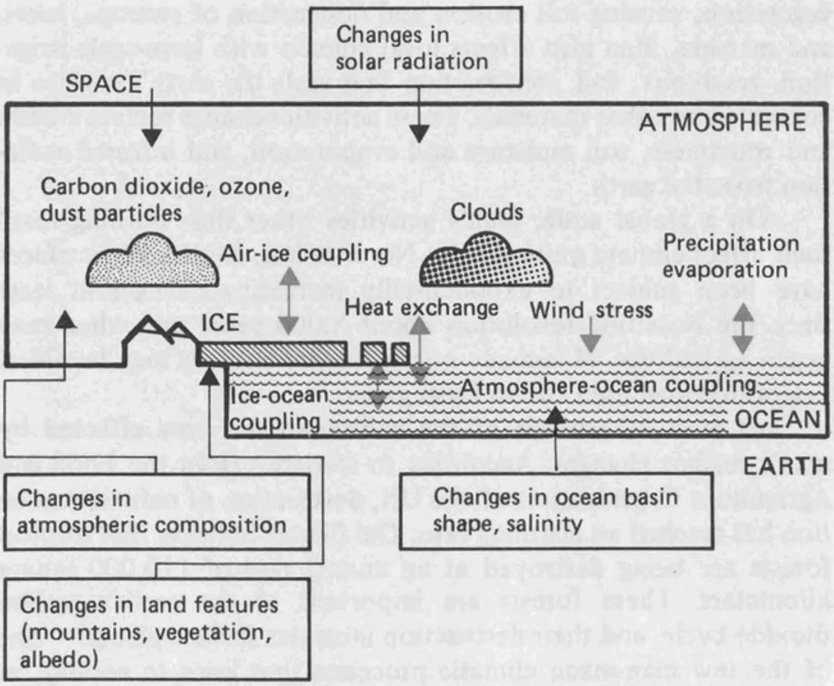
Internal climatogenic processes are caused by natural feedback within the system. For instance, expansion of the Arctic sea ice is both cause and effect of climatic fluctuations. External processes, by contrast, start spontaneously, with no feedback triggering them. Volcanic eruptions can produce large numbers of particles in the submicron range that float in the stratosphere, where they will absorb and scatter some components of solar radiation. Great volcanic activity could result in cooling.

The frequency of explosive volcanic eruptions varies greatly. They, like earthquakes, apparently result from the discontinuous motion of the tectonic plates of the earth's crust. There is at present no way to predict volcanic activity, and no assurance that a cluster of heavy eruptions will not produce global cooling despite the warming effects of most of man's activities.

A decrease in solar radiation could also cause global cooling, but there is limited and controversial evidence for such a process. The possibility of short-lived fluctuations of solar radiation in the visible and near-infrared part of the spectrum has been debated by specialists. A clearer picture awaits continuous high-precision measurement above the level of pollutants that exist in the dense layers of the atmosphere. Variations also occur in the sun's emission of particles and its radiation in the far-ultraviolet (X-ray) range.

Man's effects on climate are also elusive. It is generally agreed that so far they have been perceptible only locally. The role of

Components of the climatic system



Interaction of five physical components of the climatic system – atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. Black arrows indicate external processes, red arrows internal processes. Source: National Academy of Sciences, US.

atmospheric dust has sometimes been overrated, though it may be important in some deserts or semideserts (notably in Central Asia and the Middle East) and in large metropolitan areas. The effect of atmospheric dust depends on the size and quality of the particles and on surface albedo.

Great amounts of dust can have a warming rather than cooling effect, at least over continental areas. But there is an important difference. In contrast to the rather short residence time of tropospheric particles – days or weeks – the residence time of infrared-absorbing gases such as carbon dioxide is years and decades.

At present, waste heat affects climate only locally, and it does not pose problems comparable with those of carbon dioxide. Even substantial increases in waste heat would pass through the atmosphere in mere hours or days and probably have no great influence on climate.

By creating arable land and pastures, man destroys natural vegetation, causing soil erosion and desiccation of swamps, lakes, and marshes. Man also affects local climate with large-scale irrigation, reservoirs, and construction that seals the earth's surface in concrete and other materials. These activities change surface albedo and roughness, soil moisture and evaporation, and infrared radiation from the earth.

On a global scale, man's activities other than burning fossil fuels affect climate quite slowly. Nevertheless, continental surfaces have been subject to exponentially increasing changes at least since the Neolithic revolution about 8,000 years ago, when man began agriculture. Man-made microclimatic changes may be older; Paleolithic man used fire to flush game.

At least 30 percent of the continents are now affected by man's surface changes. According to statistics from the Food and Agriculture Organization of the UN, destruction of natural vegetation has reached an alarming rate. The figures indicate that tropical forests are being destroyed at an annual rate of 110,000 square kilometers. These forests are important to the earth's carbon dioxide cycle, and their destruction increases surface albedo – one of the few man-made climatic processes that leads to cooling, at least where surface heating does not result from a reduction of evapotranspiration (loss of water from the soil both by evaporation and by transpiration from plants).

"Despite our highly advanced civilization, we still cannot predict the climate in any dependable way."

Modeling versus paleoclimatic scenarios

There are two basic ways of making predictions about climatic effects. One uses numerical models of the climate system, and the other uses observations of analogous occurrences in nature. In modeling, the processes of the climate system are expressed in a set of hydrodynamical and thermodynamical equations for the atmosphere, oceans, and ice, together with equations for selected constituents – carbon dioxide, water, ozone, and others. These equations describe the processes that determine distributions of temperature, pressure, density, and velocity. Other climatic processes – evaporation, condensation, precipitation, radiation – can also be described mathematically.

Devastating climatic variation. A better understanding of climate may help avert such events as the desertification of a large area of Senegal shown here. Rainfall in the Sahelian region of Africa began declining progressively in the early 1960s. Severe drought occurred from 1968 to 1974, at times affecting a belt stretching across Africa from the Atlantic to the Red Sea. Flocks and herds were wiped out over a wide area, and soil and woody vegetation have been severely damaged. In 1974 alone, an estimated 100,000–250,000 people died of famine in the Sahel, and the Ethiopian government estimated in 1978 that 1.5 million people in the region faced the same fate. (Photo courtesy of International Communication Agency.)

The equations describing the climatic system become the basis of climate modeling. Because our knowledge of the physical system is incomplete, physical and numerical approximations must be used to compensate for computational limitations. These approximations differ from model to model in the hierarchy of climate models that has been created.

Models capable of simulating some of the important climatic interactions are still lacking, so we cannot now predict climatic changes. And, external influences on the climatic system are likely to remain unpredictable for some time, although conditional predictions may now be feasible.

Conditional predictions assume that external climatogenic effects, and perhaps some internal effects, will not change. For instance, we can model the implications of man-made changes in the composition of the atmosphere when all other factors remain constant. The model enables us to improve our understanding of climatogenic processes despite its limitations in predicting the future.

Given the limitations of modeling at present, a scenario based on historical and geological information is useful. It is essentially – but not exclusively – an empirical approach, and it too has serious limitations. One of the main problems is the difference between past and present boundary conditions – placement of continents, glaciation, tree lines, desert areas, water levels, vegetation, and other topography. To speculate about increasing average annual temperatures, it is necessary to study climatic behavior over many epochs, which means dealing with a variety of boundary conditions.

Time scale is a similar problem. The periods studied in the Flohn scenario cover more than 2 million years, while future climatic change is restricted to the next 50–100 years. As a result, the implications of global warming relating to the rate at which the warming takes place cannot be inferred from the scenario.

External climatogenic processes and some internal processes as well must be assumed constant. The scenario assumes no major change in solar radiation, no unusual clustering of major volcanic eruptions, and no unusually large advance of the Antarctic ice shelves. Among internal processes, it assumes no significant variation in average cloudiness. (The interaction of radiation and clouds is not well understood.)

Compared with a model, the scenario discussed in this report has one advantage: it describes a situation that has occurred and therefore could occur again. To put it in modeling terms, a scenario based on history lets us see how nature has solved the complete set of equations simultaneously and on line, in all subsystems, in all scales, with a fully four-dimensional (time-dependent) approach. Since the earth's boundary conditions vary slowly but constantly, climatic history can never repeat itself in all details. But it can repeat itself in substance, and we can alert ourselves to some of the possibilities.

3

Changes in the Ice Cover

Man has made his appearance on earth at a time of unusual climatic conditions. Ice caps at the poles and extensive continental glaciation are known to have existed during only one other epoch of the earth's history some 600 million years ago. Another period 300 million years ago probably featured glaciation only around the South Pole.

The earth was warmer until the end of the Mesozoic era 65 million years earlier in its history. After some temperature ups and downs, a cooling trend set in roughly 55 million years back. About 38 million years ago, glacial ice began appearing in the ocean around the Antarctic continent, and by 10 million years ago mountain glaciers had formed in the northern hemisphere.

About 5 million years ago glaciation intensified. The Antarctic ice sheet, which had been expanding gradually, began rapid growth that for a time made it larger than it is today. Some three million years back ice sheets began to form on the earth's northernmost lands.

A central core of Arctic Ocean ice has existed for at least the last 700,000 years and probably for more than 2 million years. Since ice caps became well established at both poles, they have expanded and contracted in a strikingly regular pattern. Over the last million years, northern hemisphere ice has peaked roughly every 100,000 years, and the western Antarctic ice sheet has generally kept pace. By contrast, ice sheet changes in the eastern Antarctic have been relatively minor, and they may not have coincided with northern hemisphere glaciations.

The two most recent glacial periods came 160,000–135,000 years ago and 24,000–14,000 years ago. They were of similar intensity, and both ended abruptly in warm interglacial periods.

The first of the two interglacials was warmest about 124,000 years ago. We are now in the second (the Holocene), which probably reached its thermal maximum about 6,000 years ago.

It was generally warmer than today from 7,000 to 5,000 years ago, although colder intervals have been coming in many areas roughly every 2,500 years. The most recent of these chills peaked in the late 1700s, in a period of roughly 300–400 years known as the little ice age.

In considering the effects global warming or global cooling might have on man in the present era, it is important to note seasonal variations in ice cover. Also of great importance is the fact that marginal areas vary more than the central core of ice. In these areas cooling, in effect, breeds cooling. Snow and ice increase albedo, allowing less solar heat to penetrate the earth. This accounts for the fact that, when global warming or cooling takes place, temperature variations are greatest at the poles.

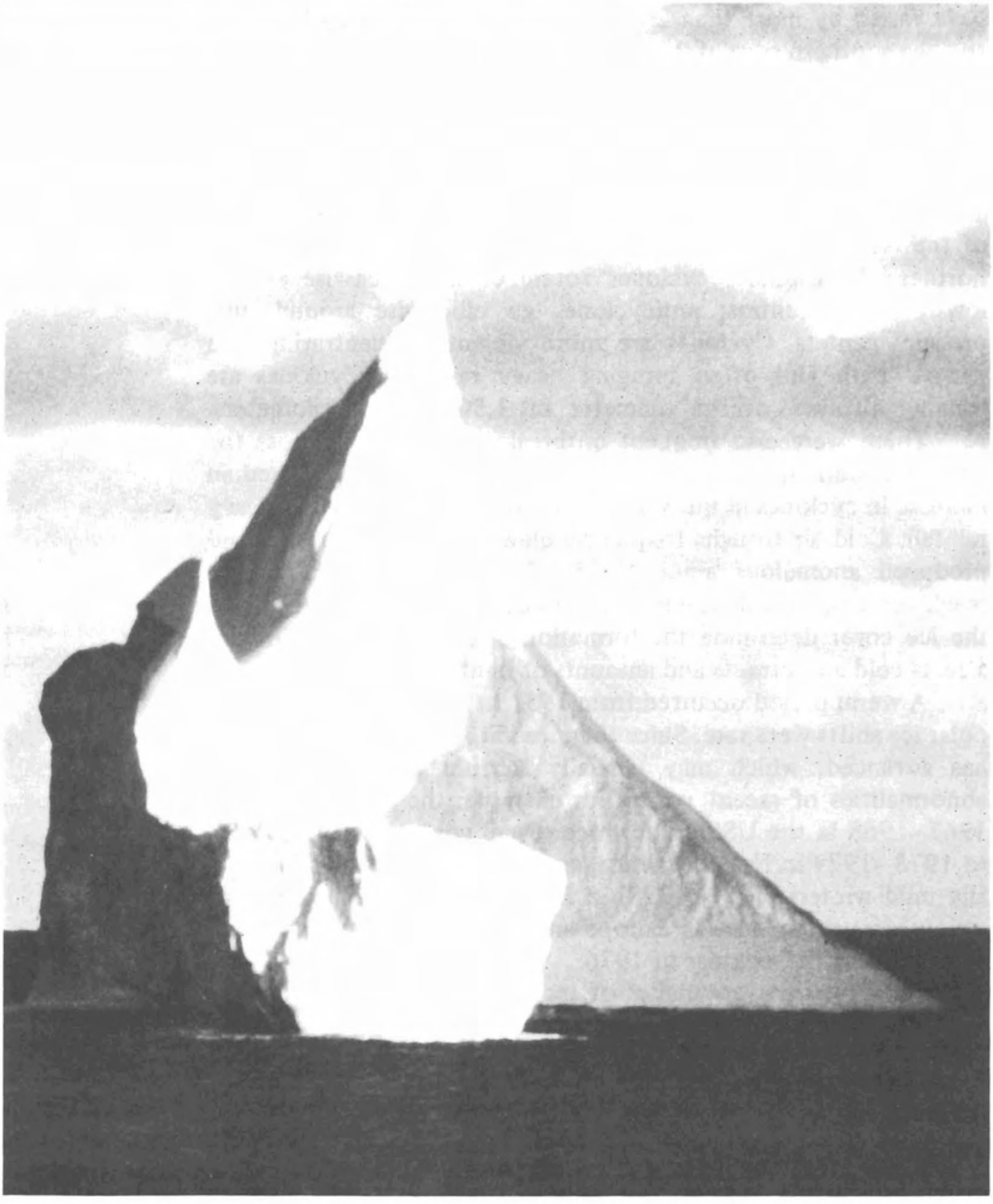
At present, large oceanic areas of both poles are seasonally or permanently (in terms of seasons) covered by a thin blanket of ice floes separated by narrow strips of polynya (open water areas in sea ice). For most of the year these floes are covered by ice and snow with an albedo of almost 80 percent. But in summer, when the polar sun is still low in the sky, the albedo of open water in polar regions is 8–12 percent. During the melting season – about ten weeks from mid-June to the end of August in the central Arctic – ponds of light blue meltwater decrease the albedo of the ice floes to about 60 percent.

The importance of drift ice

Ice about half a meter thick forms on the surface of the Arctic ocean. It drifts from the Arctic basin, pushed along by the strong east Greenland current and by a large anticyclonic gyre (circle) circling clockwise around the central core of ice between Greenland, Alaska, and Siberia. About one-third of this ice is seasonal, and the average life of one of its crystals is from five to ten years.

While the central core of Arctic ice has been highly stable in historical times, its marginal parts have fluctuated greatly. After gradually receding to Greenland's north coast, ice floes began again to advance along its eastern coast around 1320, sometimes blocking Iceland and the Denmark strait until late summer.

During the late 17th and early 18th centuries, the ice advanced as far as Norway several times. It has been speculated that eskimos and polar bears stranded on a floe were occasionally carried as far



Endangered species? Greenland icebergs such as this one drift to the Newfoundland area of the Atlantic Ocean, where an unusually large number of them appeared from 1971 to 1973. According to the Flohn scenario, however, global warming could cause them to disappear altogether. (Photo courtesy of International Communication Agency.)

south as the coast of Scotland. The total area of Arctic ice may have varied by more than 20 percent during the last 1,000 years, and the southern edge of this ice shifted more than 2,000 kilometers in that length of time.

Ice advanced on a large scale between 1550 and 1850, the little ice age period. At the same time, cyclones in the far south of the northern hemisphere tracked less to the north, as blocking anticyclones were more frequent above the colder surface waters of the Atlantic ocean north and west of the British Isles. In the northern hemisphere, cyclones rotate counterclockwise around low pressure centers; anticyclones go clockwise around high pressure centers. Cyclones are more violent, concentrating in a narrow path and often bringing heavy rain. Anticyclones are usually diffused over a diameter of 1,500–3,000 kilometers.

There were also frequent outbreaks of polar air across the Alps in eastern and central Europe during the little ice age, and an increase in cyclones in the Mediterranean area, which caused heavy rainfall. Cold air troughs frequently blew well into the tropics and produced anomalous amounts of rainfall. Today such troughs reach the tropics only rarely. Changes in albedo along the edges of the ice cover determine the formation of cold air, which in turn affects cold air currents and amounts of rainfall.

A warm period occurred from 1931 to 1960, and at that time polar ice shifts were rare. Since then ice in the northern hemisphere has advanced, which may partially account for some climatic abnormalities of recent years. For example: the severe winter of 1967–1968 in the USSR, the three severe winters of 1976–1977 to 1978–1979 in North America, an unbroken series of six unusually mild winters (1972–1978) in Europe, and the coincidence of serious drought in eastern Europe and abundant rainfall in central Russia during the summer of 1976.

Other weather anomalies of recent times include unusually large numbers of Greenland icebergs drifting to the Newfoundland area during the summers of 1971–1973 and frequent heavy gales in the North Sea between 1972 and 1976.

The physical reasons for climatic variation in the polar zones are not well understood. One possibility is that volcanic explosions trigger a series of events that lead to cooling. A large eruption, or a cluster of them, injects masses of minute particles into the stratosphere, where they converge over the interior of the Arctic and the Antarctic, forming a dust layer that lingers at an altitude of 10–15 kilometers or more. At this level, exchange processes such as winds and convection currents are too weak to disperse the dust.

By reflecting and absorbing solar radiation, the dust layer reduces surface temperatures of the earth and shortens the summer melting season. As a result, the average thickness of the ice may increase, which reduces heat flow between ocean and atmosphere. This may lead to more cooling and an extension of the ice. Albedo is increased during winter months, because thin seasonal ice grows faster than thick perennial floes.

In contrast to the Arctic ice, the sub-Antarctic drift ice is about 85 percent seasonal. An extremely cold, thin surface layer develops about the Antarctic ice dome in winter, with average minimum temperatures below minus 70 °C. The cold layer spreads outward, cools the sea surface, and produces an extended seasonal cover of drift ice about 1–1.5 meters thick. Extremely cold winds blow the ice out from the Antarctic.

Two sharp tongues of sub-Antarctic drift ice and cold surface water reach the warmer water of the middle latitudes, one in the Atlantic extending farther than its counterpart in the vast South Pacific. In the Arctic, by contrast, the climatic influence of drift ice is weakest in the Atlantic sector owing to the warm water of the Gulf Stream. Thus Bouvet Island (latitude 54 °S) is almost completely glaciated, yet Helgoland (latitude 54 °N) is a summer bathing resort.

"A central core of Arctic Ocean ice has existed for at least the last 700,000 years and probably for more than 2 million years."

"The European revolutions of 1789 and 1848 occurred after a succession of years with bad weather, bad harvests, and high cereal prices."

In addition to an enormous area of sea ice (about 22 million square kilometers at the end of the southern winter), the Antarctic also produces large-scale tabular (flat) icebergs with an average depth of 200–400 meters. Occasionally they reach the size of the Netherlands – 30,000 square kilometers. They break off from the large Antarctic ice shelves and drift northward, with their last debris sometimes reaching as far as latitude 35 °S in the Atlantic.

The Antarctic continental ice sheet

An unorthodox ice-age hypothesis was proposed in 1964 by A.T. Wilson, a geochemist from New Zealand. He assumed that a combination of pressure from above and geothermal heat flow from below would cause a sufficiently thick body of ice to melt at the bottom. This would make it possible for the Antarctic ice to move forward catastrophically on all sides, forming a quasi-permanent ice shelf of 20–30 million square kilometers. The result of such a gigantic ice slide would be a general cooling of the earth and the sudden spread of glaciation on the continents of the northern hemisphere.

While the bulk of the eastern Antarctic ice is stable and well above sea level (except for a few small meltwater lakes), the smaller ice dome of western Antarctica rests on bedrock below sea level. Indeed this ice may not be stable. It has been suggested that it has disappeared in the geological past, and there is some risk that this could happen again in the foreseeable future.

What small changes can mean

Changes in the global average temperature that seem small to the general reader can utterly mislead him as to their impacts. A temperature drop of 1 °C near the northern boundary of agricultural land (affecting, for instance, wheat in northern Canada or hay in Iceland), rather than having a trivial effect as one might naively expect, may reduce the growing season by several weeks, with detrimental effects on harvests. Even more essential are the accompanying changes in the frequencies of extremes in weather in lower and middle latitudes, causing long and cold springs, cool and wet summers, and so on. In recent history the most catastrophic years of sudden cooling were 1316, 1430, 1570, and several years in the 1690s and 1780s (the latter group apparently affecting Europe, North America, and Japan). The European revolutions of 1789 and 1848 occurred after a succession of years with bad weather, bad harvests, and high cereal prices; some of the most severe climatic conditions were reported in the years following some very heavy volcanic eruptions, for example, after 1766, 1783, 1815, and 1883.

There is little doubt that the peaks of volcanic activity by and large coincide with series of particularly cool years (and especially cool summers). The major volcanic eruption for which the best long-term documentation has been gathered occurred at Tambora in Indonesia in 1815. It was followed by two catastrophic years in many areas of the world. In the eastern US, 1816 was the "year without summer." During the same year central European cereal prices were the highest in centuries. The link between climate variations and changes in food availability, with concomitant pressures for migration, is readily apparent.

4

Changes in Atmosphere and Oceans

Global atmospheric circulation is asymmetrical with respect to the equator, as is the wind-driven upper layer of the oceans. In equivalent seasons, the Antarctic troposphere averages about 11 °C cooler than the Arctic. Stronger atmospheric circulation in the southern hemisphere crosses the equator and pushes the "meteorological equator" northward, so that it varies between latitudes of 0 ° and 15 °N, annually averaging 6 °N.

Different heat and radiation budgets for the two hemispheres explain the asymmetry. The nearly landlocked Arctic ocean and its thin, perforated cover of drift ice contrasts with the isolated Antarctic continent covered by a sheet of ice more than two kilometers thick. The Antarctic has greater albedo and less cloudiness.

Oddities of the equatorial belt

Another important climatic variation at the equator is the irregular fluctuation of sea surface temperatures and of rainfall in a long, narrow belt across both the Pacific and the Atlantic, but not across the equatorial Indian Ocean. In a latitudinal belt between about 0 ° and 4 °S, sea surface temperature drops in the Atlantic and Pacific from the average value for tropical oceans of 26–27 °C, to 18–22 °C during the southern winter, and in some areas, such as the leeward side of islands, to below 15 °C. The occurrence of penguins at the equatorial Galapagos Islands suggests both the extent of sea-surface temperature fluctuations and the possibilities of bioclimatic adaptation.

The southeast trade winds cross the equator and reach latitude 5–8 °N. Passing the equator does not change their clockwise turning motion, so their flow is cyclonic in the southern hemisphere, but anticyclonic in the northern. While the southeast trades blow strong over ocean currents, upwelling of cold, deep water takes place just south of the equator and downwelling just north. At the same time, water temperature rises as ocean surface layers cross the equator from south to north.

The asymmetry of atmospheric and oceanic circulation is greatest during the season of northern summer and southern winter. Upwelling in the belt from 0 ° to 4 °S is greatest from June to September – when asymmetry is greatest and the southerly components of the trade winds predominate.

Currently, equatorial upwelling is a normal feature of the air–sea system, but marked changes and even reversals of the process occur at irregular intervals, most commonly during the season of northern winter and southern summer. At such times the meteorological equator tends to be close to the actual equator at latitude 0 °, because the southern wind and sea currents have weakened to the strength of the northern currents. (The meteorological equator is generally referred to as the intertropical convergence zone (ITCZ) to distinguish it from a "front," which occurs between two wind systems of the same hemisphere and has quite different characteristics.)

During one of these atypical periods, upwelling stops and downwelling occurs at the equator. This produces a sterile layer of warm water that drastically reduces the fish catch along the coasts of Ecuador and Peru. The period of anomalous seas usually appears around Christmas time, which accounts for the name by which it is generally known, El Niño (The Christ child).

Ocean surface currents

A schematic representation of ocean surface currents from February through March. Source: Bryan, K. *et al*. (1974) Global ocean–atmosphere climate model, Princeton University, Princeton, NJ.

Winds and ocean currents are extremely variable. The monthly average intensity of the large zonal ocean currents varies over a year by plus or minus 50 percent. Major ocean wind currents vary over a year between plus 44 percent and minus 25 percent when similarly measured, with rates for individual months varying from the average by as much as plus 100 percent and minus 52 percent.

Upwelling coincides with high zonal winds (the trades), and downwelling takes place when these winds weaken on both sides of the equator. The vertical circulation of the ocean at the equator

"The occurrence of penguins at the equatorial Galapagos Islands suggests both the extent of sea-surface temperature fluctuations and the possibilities of bioclimatic adaptation."

"The monthly average intensity of the large zonal ocean currents varies over a year by plus or minus 50 percent."

then reverses. Upwelling becomes downwelling, producing the El Niño phenomenon over a wide area between 80 °W and 160 °E, a distance of about 13,000 kilometers.

El Niño is accompanied by torrential rainfall, by thermodynamic instability (as the temperature of the water becomes greater than the temperature of the air), and by falling relative humidity that increases evaporation. Rainfall variations in the area are greater than anywhere else on earth. For instance, at Nauru (latitude 0.5 °S, longitude 169 °E) the rainfall during two nearly consecutive 12-month periods between 1916 and 1918 varied between 95 and 5,000 millimeters.

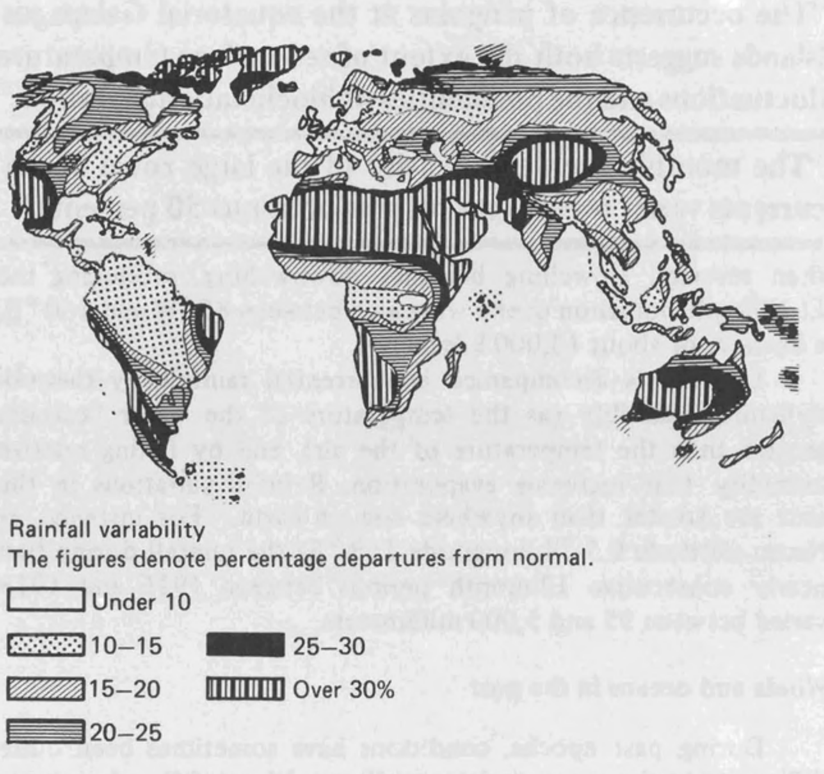
Winds and oceans in the past

During past epochs, conditions have sometimes been quite different. At times equatorial upwelling, with rainfall and evaporation at a minimum, has taken place because of strong atmospheric circulation from the southern hemisphere. At other times weak circulation from the southern hemisphere has made downwelling at the equator the rule rather than the exception, so that the equatorial belt was typically an area of high rainfall and rapid evaporation.

During past glacial epochs, strong zonal circulation and equatorial upwelling may have taken place from 90 to 100 percent of the time. Some interglacial epochs probably had equatorial downwelling nearly all of the time. There is evidence that water temperature fluctuations were greater in the past. In glacial times, a permanent southerly air flow probably increased upwelling and spread cool water to greater distances on both sides of the equator.

When water temperatures are less than air temperatures, thermal stability increases and evaporation decreases. In glacial times evaporation may have reversed to condensation, producing dew on the cool surface of the equatorial waters. During inter-

The variability of rainfall



In some areas, rainfall can vary 30 percent or more from one year to the next, causing serious problems of crop failures. Source: Petterssen, S. (1969) *Introduction to Meteorology*, McGraw-Hill, New York.

glacial periods, when circulation was distinctly weaker, tropical warm water at temperatures of 26–27 °C may have produced high instability, evaporation, and torrential rains more than 90 percent of the time.

In considering the effects of global warming and cooling, it is important to note that relatively weak variations in atmospheric circulation can lead to enormous variations in evaporation and rainfall. A comparison of two past epochs illustrates the point. During the last glacial period, about 24,000–14,000 years ago, it was considerably more arid almost everywhere than it is today. However, the last interglacial period, about 124,000 years ago, was a lot more humid than today. It is possible that the temperature fluctuations involved in these major climatic differences took place for the most part within an equatorial ocean belt of the Pacific and the Atlantic between latitudes 10 °S and 10 °N.

Recent investigations based on a great number of ocean core samples indicate that at the peak of the last glaciation, 18,000 years ago, water temperature at one location on the equator was 16 °C in August – about 7–8 °C colder than it is currently at the same time of year. At the peak of the last interglacial period, 124,000 years ago, the equatorial water temperature was approximately 26 °C. In subtropical latitudes, water temperature has remained essentially unchanged from the last interglacial period until the present.

February equatorial temperatures, by contrast, were only 1–3 °C colder 18,000 years ago than they are today. This indicates a strong upwelling during southern winter and the extension of southerly circulation beyond the equator into the northern hemisphere. The vigorous circulation resulted from expansion of sub-Antarctic seasonal ice.

5

Man's Effect on Climate

As the foregoing chapters suggest, natural climatic variations are far greater than any man may have caused until now. Also, future natural changes could effectively counteract man's influence over climate. Nevertheless, man's effects on climate are growing, and it is possible that man-made global warming will have significant effect on the climate of the earth within the coming century.

The IIASA Energy Program has published information on the amount of heat released into the atmosphere by present-day human activities. It estimates that about 8 terawatts of energy are now being generated by man (one terawatt is one trillion, 10^{12}, watts). This amount of heat is small compared with the solar energy received by the earth, an estimated 80,000 terawatts. Man's heat may affect climate in some local areas, but since it is unlikely to have global effect, Flohn has not included it in his study.

The combined greenhouse effect

Man-made global warming, if indeed it soon begins to occur, will not be caused by carbon dioxide alone, but this one chemical is clearly the villain of the story. It is one of the products of the combustion of fossil (carbon) fuels – coal, petroleum, and natural gas – and its content in the atmosphere has probably been increasing exponentially since industrial production reached large-scale proportions in Europe and North America in the 19th century.

Currently more than 5 billion (10^9) tons of carbon are released into the earth's atmosphere every year. The global atmosphere now contains more than 700 billion tons of carbon, which is an increase of about 6 percent in the last 25 years.

If the rate of carbon dioxide release continues, and many experts feel that it will not only continue but accelerate, it is likely that the earth will start getting warmer. Carbon dioxide in the atmosphere is transparent to most of the solar energy reaching it, but it is not transparent to the energy re-radiated by the earth. Energy in the infrared range – heat – that once bounced back out to space becomes trapped between the carbon-dioxide-laden atmosphere and the earth. This produces what is called a greenhouse effect by warming the earth's surface and the lower layers of its atmosphere.

Determining the extent of the global warming that results from adding more carbon dioxide to the atmosphere is no easy matter. For one thing, water vapor, which is the strongest absorber of infrared radiation in the atmosphere, is also involved in man-made global warming.

Whenever air temperature rises, water vapor plays an important and complex role. A warmer atmosphere would cause the evaporation of the oceans to increase appreciably because of higher temperatures of both air and water. This increase of water vapor in the atmosphere could contribute to heating. Rising temperatures would also weaken southern hemisphere wind and sea currents, increasing periods of downwelling in the equatorial belt. As noted in the previous chapter, this condition increases evaporation significantly.

But water vapor also illustrates the compensating changes in climate that sometimes occur. More water vapor in the atmosphere produces clouds that can reduce the amount of solar radiation reaching the earth. But cloud cover changes rapidly, and the extent to which it can offset global warming is difficult to determine.

There are other factors that must be considered in estimating the effects of releasing more carbon dioxide into the atmosphere: the natural formation of carbon dioxide in the atmosphere; the absorption rate of the gas and particles released along with it; the degree of concentration of these materials at the poles where temperature variations are more pronounced; "feedback" effects such as changes these materials cause in cloud structure and distribution; and the role of other trace gases released into the atmosphere by man.

Other trace gases may add to man-made global warming. These gases – primarily nitrous oxide, methane, ammonia, and the freons – absorb terrestrial radiation just as carbon dioxide does. Release of these trace gases is not expected to rival carbon dioxide in quantity, but their effect when combined with the effect of carbon dioxide is considerable.

"Currently more than 5 billion (10^9) tons of carbon are released into the earth's atmosphere every year."

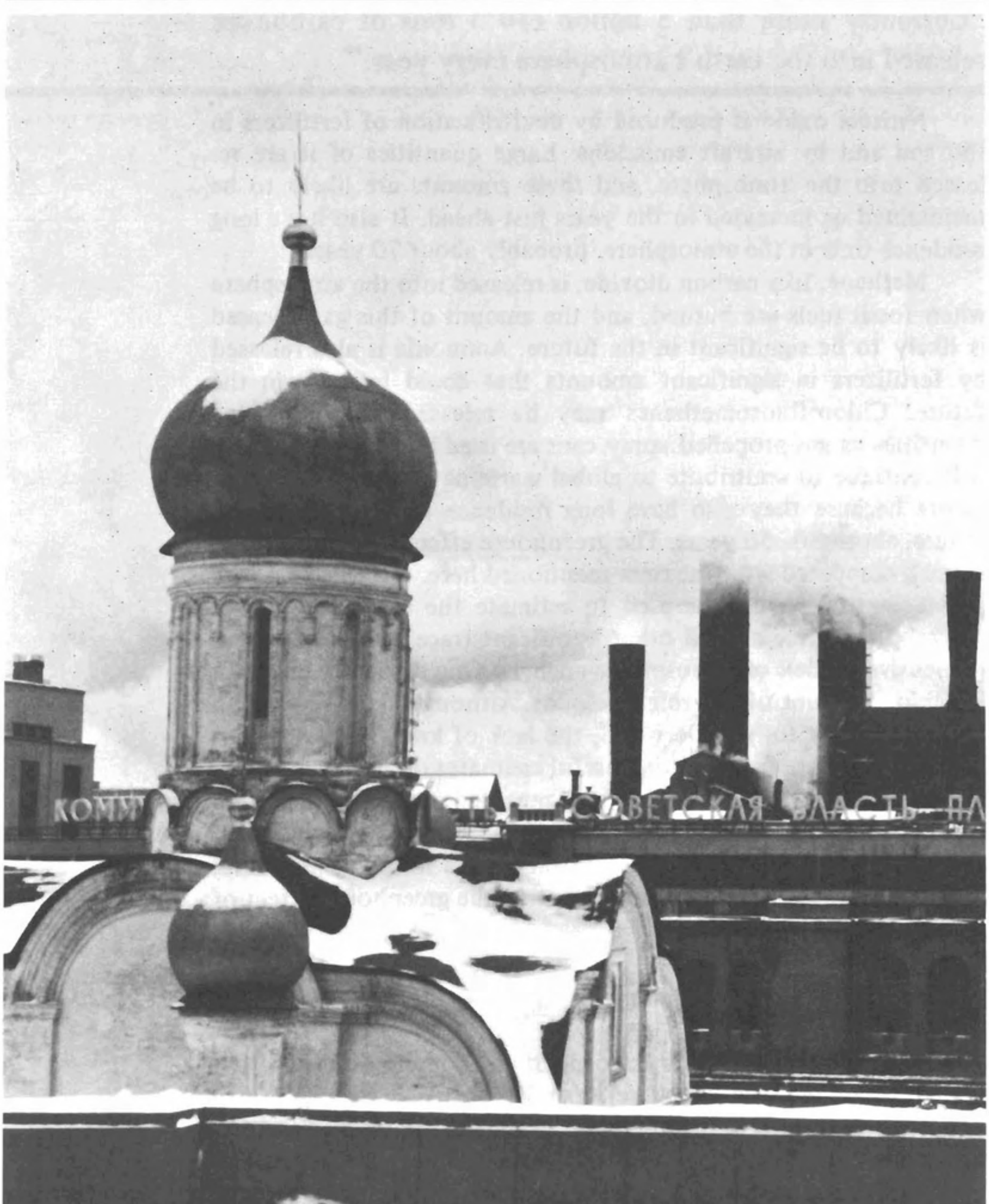
Nitrous oxide is produced by denitrification of fertilizers in the soil and by aircraft emissions. Large quantities of it are released into the atmosphere, and these amounts are likely to be maintained or increased in the years just ahead. It also has a long residence time in the atmosphere, probably about 70 years.

Methane, like carbon dioxide, is released into the atmosphere when fossil fuels are burned, and the amount of this gas released is likely to be significant in the future. Ammonia is also released by fertilizers in significant amounts that could increase in the future. Chlorofluoromethanes may be released in diminishing quantities as gas-propelled spray cans are used less, but these gases will continue to contribute to global warming at least in the near future because they also have long residence times in the atmosphere, about 30–50 years. The greenhouse effect of all other gases is small compared with the ones mentioned here.

Scientists have attempted to estimate the combined effects of carbon dioxide and all other significant trace gases using comprehensive models of atmospheric changes. One difficulty has been in taking account of the role of clouds. Although cloud–radiation feedback is not fully understood, the lack of knowledge does not prevent scientists from making useful estimates of global warming. Flohn bases his estimate on two well-regarded models of the atmosphere that have reached similar conclusions by dissimilar means and on other scientific studies of trace gases in the atmosphere. He assumes that other trace gases increase the greenhouse effect of carbon dioxide by roughly 50%.

A timetable for global warming

The amounts by which atmospheric carbon dioxide and other gases increase in the atmosphere depend importantly on man's fossil fuel consumption rate in the years ahead, the use of chemical fertilizers, and the use of chlorofluoromethanes. This relates to matters of public policy, economic growth, and consumption patterns that are not dealt with in the Flohn research report. Flohn notes that at the IIASA workshop in 1978 (Jill Williams, editor, *Carbon Dioxide, Climate and Society*, Pergamon Press, Oxford, 1978) participating specialists tentatively concluded that there would be



Carbon dioxide on the increase. The burning of fossil fuels in all regions of the world adds carbon dioxide to the atmosphere. Here a Moscow power station contributes to global warming. (Photo courtesy of United Nations/ P. Teuscher.)

a "manifold increase" in atmospheric carbon dioxide if all economically exploitable fossil fuels were burned, and if the growth rate of fossil fuel (carbon) combustion could not be reduced to less than 3 percent a year.

One survey has estimated that atmospheric carbon dioxide will double around 2040 and increase by a factor of from three to five (or even more) by the 22nd century. But such predictions are controversial. For one reason, the role of forest cover is not well understood. Forests, like oceans, are a "sink" for carbon – they absorb and store it. Harvesting forests and transforming them into other types of vegetation that store much less carbon releases carbon dioxide into the atmosphere. According to the Food and Agriculture Organization of the UN, virgin forests are now being destroyed at the rate of 110,000 square kilometers a year. Deforestation at such rates may make the earth's vegetation a net source of increased atmospheric carbon dioxide.

Using some of the most reliable recent projections of atmospheric carbon dioxide growth, Flohn has devised a global warming timetable that assumes that other trace gases will add 50% to the greenhouse effect. The timetable also assumes that fossil fuel combustion will continue to increase at the current rate for the next 100 years. He calculates an increase in fossil fuel combustion of 3.5–4 percent per year. This is a conservative rate; some recent studies report that fossil fuel combustion is now increasing at 4.3 percent per year.

According to the Flohn timetable, global warming of 0.4–0.5 °C could occur between 1990 and 2000. Global warming of 1 °C would then take place early in the 21st century, producing global temperatures similar to those existing about 1,000 years ago, during the early Middle Ages.

Global warming could reach 1.5 °C between 2005 and 2030, which would produce temperatures corresponding to those at the peak of the Holocene warming period about 6,000 years ago. Global warming would reach 2.5 °C between 2020 and 2050, when temperatures would be about the same as during the last interglacial period, which occurred 120,000 years ago. Global warming of 4 °C could also be reached by 2050 or soon after, and this would produce conditions similar to those of a long period from about 12 million to 2.5 million years ago, just before the current series of glacial and interglacial periods began.

6

Taking the Earth's Temperature

To gain insights into climatic changes possible with warming, whether by modeling the future or by paleoclimatic reference to the past, temperatures must first be determined in some useful way. This has proved to be one of the most difficult problems in dealing with global cooling and warming.

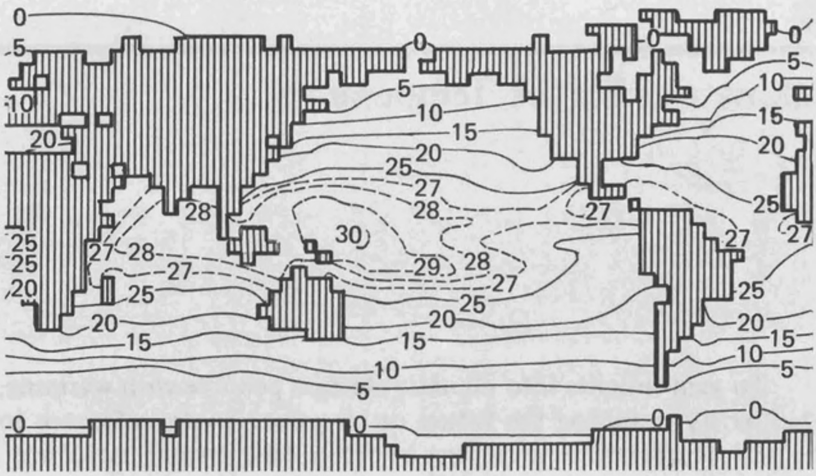
Flohn has taken global average surface temperature estimates as being representative. He has compared global average models that compute the change of temperature for a given increase in carbon dioxide. He has then adjusted the figures to account for other trace gases. This provides a useful calculation, despite the uncertainties briefly outlined in earlier chapters of this report, the most significant of them being the lack of knowledge of the climate's feedback systems.

Making do with global averages

But there are other serious limitations to working with changes in global average surface temperatures, and the reader should keep them in mind. For one thing, regional climatic changes do not always correspond to global climatic changes. A significant change in global average surface temperature could result in large changes in only a few regions. There might be minor changes in other areas. Or, climate could change drastically over large regions without making any substantial change in globally averaged temperature.

A current estimate of global average surface temperature widely cited is 15 °C, a very rough figure at best. It is simply not possible to determine such a figure and its recent changes precisely with the meteorological network available today. Many large areas of the earth are not represented in this network.

Ocean surface temperatures



The annual average ocean surface temperature in degrees centigrade, based on US Navy Hydrographic Office data. Source: Bryan, K., *et al.* (1974) Global ocean–atmosphere climate model, Princeton University, Princeton, NJ.

Short-lived fluctuations in weather present another, completely different problem. These changes are unpredictable over the long time scales needed to determine climatic change. Such short-term fluctuations are called "climatic noise."

At present, global or hemispheric variations in surface temperature are detected primarily with the help of climate stations on the continents and on a number of islands. There are many gaps in the coverage, especially in oceanic regions, where the small number of stationary weather ships has been reduced drastically since 1973. Generally, the northern hemisphere is represented far better in the network than the southern.

More stations reporting would serve to smooth out temporary irregularities in climate data that occur over months, seasons, and years. Because of the inadequacy of the worldwide station network, hemispheric temperature variations of 0.2–0.3 °C can hardly be distinguished from climatic noise.

Another reason why global average temperature figures are difficult to determine and to use is that climatic changes are always subject to major longitudinal variations over a given latitude. For example, trends in the Asiatic and the American sectors of the Arctic region are often just the opposite, with one area cooling while the other warms. A similar alteration occurs in what is called the Greenland–Northwestern Europe seesaw, with temperatures rising in one place while falling in the other until the process reverses. This phenomenon has been observed for more than two centuries.

Recent climatic changes

Various scientific papers prepared within the last few years provide an overview of the most recent temperature fluctuations. The most striking variations from 1950 to the present have occurred primarily in the latitude belt 60–85 °N, a band that takes in Alaska, Greenland, and other northern land bordering on the Arctic Ocean. As we would expect from the action of albedo and other factors relating to the formation of snow and ice, interannual temperature fluctuations have been greatest in subarctic and arctic latitudes. For example, from 1940 to 1975, temperature changes from year to year averaged 0.5 °C in a belt from 57.5 °N to 72.5 °N, and in the polar belt from 72.5 °N to 87.5 °N they averaged 0.63 °C.

"Climate could change drastically over a large region without making any substantial change in globally averaged temperature."

The average temperature in the northern hemisphere increased from 1890 to 1940 by about 0.6 °C, then decreased until 1975 by about 0.3 °C. Since then it has been rising slightly, at least at the polar cap. The absence of major volcanic eruptions during a period of several decades may be one of the reasons for the warming period that extended roughly to 1940.

In the high (poleward) latitudes of the southern hemisphere, weak warming has been going on since 1943. Most of the interannual fluctuations in climate since then have been short-lived throughout the southern hemisphere and especially at the equatorial belt. The long-term trend has been warming at about 0.01–0.02 °C a year for the southern hemisphere as a whole.

From 1940 until now, the northern hemisphere has cooled about 0.3–0.4 °C. There are signs that the cooling has passed its climax. Since 1974 the north polar region has not been as extremely cold as it was between 1964 and 1972, a time when the

The limits of observations

In order to discuss the effects of changing the atmospheric CO_2 [carbon dioxide] concentration using observations or modeling, the simplest approach is to define climate as the global average surface temperature. A global average (or one-dimensional) model can be used to compute the change of "climate" for a change in atmospheric CO_2 concentration and we are presently able to make calculations of this kind although our lack of knowledge of feedbacks means that there are uncertainties in the results. With regard to observations, recent studies have shown that not only the amplitude but also the direction of global trends in surface temperature during the last 100 years are uncertain.

– Jill Williams, *Introduction to the Climate/Environment Aspects of CO_2 (A Pessimistic View).* In Jill Williams, editor, *Carbon Dioxide, Climate and Society,* Pergamon Press, Oxford, 1978.

Arctic ice was progressing toward Iceland and Newfoundland. The small changes in temperatures of the low latitudes suggest that the cooling of the Arctic from 1940 until 1972 was not a global phenomenon.

If future man-made warming is superimposed on the natural fluctuations that have occurred in irregular intervals over several decades, it can be expected to intensify the natural warming episodes and weaken – or even reverse – the natural cooling episodes. A warming of about 0.5 °C above the noise level maintained for about ten years would very likely have such an effect.

Consequently, a global warming of 0.5 °C provides a reasonable threshold for a general perception of warming – even though it still may be impossible to determine how much of the resulting climatic change is natural and how much is caused by man.

7

What a Hotter Earth Might Mean

If man keeps releasing carbon dioxide, nitrous oxide, and other heat-absorbing gases into the atmosphere at current rates and no natural changes occur, the global average surface temperature will rise about 0.5 °C by 1990–2000, Flohn estimates. This would likely produce some of the climatic patterns of the period from 1916 to 1950, which was one of the warmest times of the last 500 years.

However, major climatic changes affecting man in significant ways would probably await a period of further global warming. By 2000–2010, a rise of 1 °C from the present global average could be reached, and this could begin to have economic and social consequences directly attributable to man-made global warming.

Global warming of 1 °C would correspond to the global average surface temperature of the early Middle Ages, which was the warmest period of the last millennium. The time when highest temperatures were reached varies by area, but the greatest variation from present climatic conditions was probably during a period between 900 and 1050.

This period saw warm conditions in the Arctic latitudes, with no sea ice in the east Greenland current. In Iceland and Norway, cereal was cultivated up to 65 °N, and there were settlements as far north as Ellesmere Island and the New Siberian Islands.

In Canada, forests advanced 100 kilometers north of their present limits. Forests also ranged to higher latitudes in Europe, and vegetation zones shifted upward in European mountains. Frequent droughts occurred in all parts of Europe south of 60 °N. The Caspian Sea was 2–3 meters lower than today (even though much of its water is removed today for irrigation). The Dead Sea was nearly as low as it is now.

Some parts of the Sahara were apparently wetter in the early Middle Ages than they are today. Horse caravans crossed the northern Sahara, and the Kufra oasis, which is now near the center of the desert, was an area of cattle raising. China and Japan had warm summers, but severe winters were also recorded in China during the period.

Paleoclimatic evidence is somewhat scanty for North America during this period. However, tree-ring data from the mountains of California suggest higher temperatures and less rainfall in the area, conditions that also existed in southwestern Colorado.

While evidence from the tropics is also thin for the early Middle Ages, it appears that Cambodia and the Yucatan peninsula, areas of tropical latitude on opposite sides of the earth, both flourished under conditions somewhat drier than those of today. In Africa, there were heavy rains in southern Ethiopia, Nile floods were low, and Lake Turkana was high. On the Antarctic coast there are indications that a long period of warming existed, and in New Zealand there was a period of severe drought and forest fires.

These conditions have been interpreted to suggest that the cyclone track was shifted northward by 3–5 °, so that it reached 60–65 °N, or well into northern Europe. The prevailing high pressure conditions over Europe would thus have produced conditions similar to the warmest and driest summers of the period from 1931 to 1960.

Clearly, if 900–1050 can indeed be taken as a hint of 2000–2010, an increase of 1 °C in the global average surface temperature caused by man would be a serious matter. Higher tracking cyclones would mean extended droughts in summer and blizzards in winter, conditions that were especially prevalent in eastern Europe during the early Middle Ages. The pattern is consistent with the marked retreat of Arctic sea ice during the period. Sea ice withdrew from most of the sea around Greenland; Atlantic sea ice retreated north of latitude 80 °N, which made nearly all northern coasts ice free.

Since feedback processes and other factors that lead to a reversal of the global temperature trend are not fully understood, it is important to consider what came directly after the period in question. Cooling in northern Greenland after 1160 has been identified. This coincides with a marked advance of glaciers in the Alps and other mountain ranges, and with the reappearance of Arctic sea ice around northern land masses at roughly 1320. At this time extreme climatic anomalies and severe famines began to occur throughout Europe. In the Iowa and Illinois areas of North America, a drought period of 200 years resulted in mass migrations. After some fluctuations, these events led to the little ice age (1550–1850).

Global temperatures 1 °C higher than those of today could be a costly development for man. The problems of maintaining agricultural production during extended drought could be enormous at levels of world population projected for the beginning of the 21st century. Serious shortages of freshwater supply could affect many countries in the subtropical belt of winter rains, such as California, Spain, and the Near and Middle East. Severe winters could occur in the temperate zone, which includes most of the highly industrialized areas of the northern hemisphere.

The severe weather conditions imposed by a 1 °C increase in global warming could begin within the next two decades. A person now 20 years old might see food shortages and population migrations in areas of high living standards before reaching mid-career. Economic setbacks in developing countries could have catastrophic results as competition for the world's food resources intensified.

It is possible, in fact, that the most severe consequences of man-made global warming lie immediately ahead. Further warming – to a 1.5 °C increase – could produce entirely different climatic conditions that might to some extent be more favorable to man, as the next part of Flohn's paleoclimatic scenario suggests.

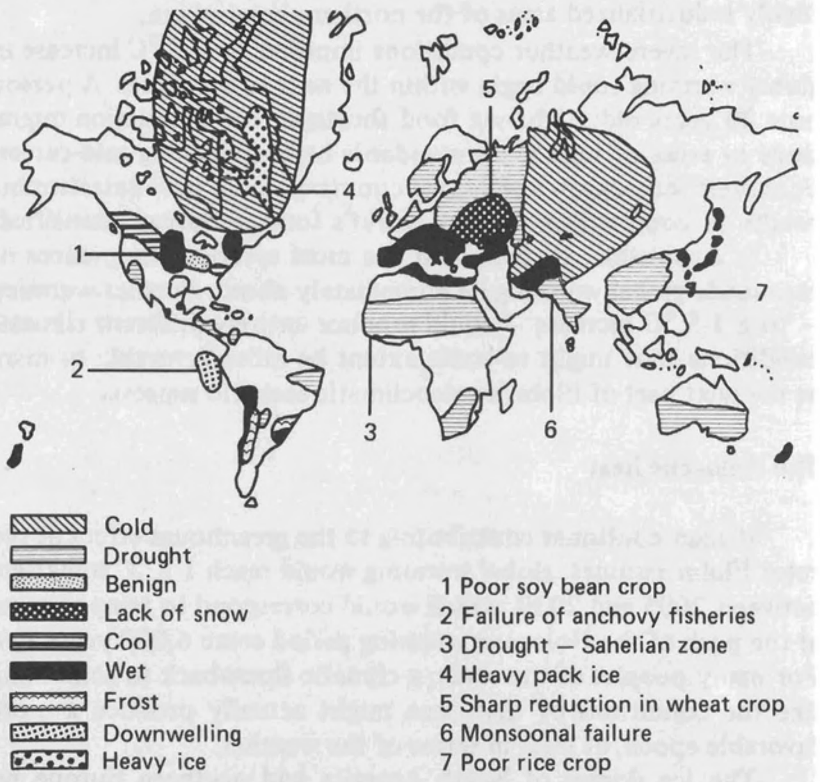
The Holocene heat

If man continues contributing to the greenhouse effect at the rates Flohn assumes, global warming would reach 1.5 °C sometime between 2005 and 2030, which would correspond to temperatures at the peak of the Holocene warming period some 6,000 years ago. For many peoples of the earth, a climatic throwback to something like the conditions of that time might actually produce a more favorable epoch, at least in terms of the weather.

The ice domes of North America and northern Europe retreated after the peak of the last ice age around 18,000 years ago. While the smaller Scandinavian ice sheet finally disappeared some 8,000 years ago, the North American ice sheet at that time had only retreated to about half of its former area. Then came an incursion of the sea into Hudson Bay roughly 7,800–7,600 years ago, and after that separate ice sheets remained – a Labrador sheet that disappeared by 4,500 years ago, and Baffin Island ice that remains today.

The retreat of the Arctic ice created a marked longitudinal asymmetry of the atmospheric circulation between 8,000 and 6,500 years ago. By 4,500 years ago it had faded out. At the Holocene peak around 6,000 years ago, Eurasia and Africa experienced the warmest epoch of the last 75,000 years, while eastern North America remained relatively cool, especially in summer when the heat was relieved by frequent outbreaks of cooling polar air.

Global climatic anomalies



The year 1972 featured downwelling at the equatorial belt and other climatic anomalies that had harsh repercussions for man. Anchovy fisheries failed along the coasts of Equador and Peru, a severe drought in the Sahel region of Africa (beginning in 1968) decimated herds of cattle, North American soy bean crops were poor, and wheat crops of the USSR also failed. It is important to learn whether or not man-induced climatic changes will bring such unfavorable conditions permanently. Source: Daniel, H. (1980) *Man and Climatic Variability,* World Meteorological Organization, Geneva.

Note that in describing events at the warmest time of the Holocene period, approximate dates are given in radiocarbon years, which are determined by establishing the half-life of radioactive carbon particles, such as carbon 14. Conversion of these dates into calendar years, with possible differences of up to 12 percent, is a matter of controversy among scientists. The data available cannot be determined to within 100 years, or even 500 years.

Winds over the Atlantic were predominately southwesterly, which probably intensified the Gulf Stream and its northward-flowing branches at the peak of the Holocene. In winter, anticyclonic ridges occurred frequently in the Atlantic, suggesting that outbreaks of polar air were also common over central and eastern Europe and extending – with copious rainfall – to the Mediterranean Sea and northern Africa.

At the same time, forests in western Canada and in western Siberia extended 200–300 kilometers farther north than they do today. Summer temperatures in these areas were probably 2–3 °C higher than they are now. Subarctic forests covered the northernmost islands of Norway and the entire Taimyr peninsula of the far northern USSR.

The warming ended rather abruptly, which is not uncommon. A polar outbreak lasting no longer than 200 years shifted the Canadian timberline more than 300 kilometers south. At roughly the same time, shifts toward a neoglacial climate were taking place in many areas, with general conditions similar to those in the little ice age. As this cooling developed, deserts gradually expanded.

While the peak of the Holocene warming appears to have come about 6,000 years ago, there was variation by area. The interior of the Arctic Ocean was not at its warmest until later, about 4,500 years ago. At that time, open waters flowed in the fjords and along the northern coasts of Spitzbergen, Greenland, and Ellesmere Island. Siberian driftwood reached these coasts as far north as latitude 83 °N. There is no indication, however, that the core of the present Arctic drift ice between Greenland, Alaska, and eastern Siberia disappeared at any time from the Holocene to the present.

In subantarctic seas, drift ice shrank faster than in the Arctic, which led to a warming peak as early as 9,000 years ago. The warming also peaked early in eastern Siberia where no major ice sheets had formed during the previous glaciation. Warming there was well started by 7,000 years ago and, at Lake Biwa in central Japan, by 8,000 years ago.

As temperatures rose from the previous glaciation period to the peak of the Holocene warming, a series of abrupt fluctuations between cooling and warming took place between about 13,500 and 10,800 years ago. Toward the end of this period global temperatures similar to those existing today occurred, and tropical oceans became slightly warmer than they are now, a condition that probably weakened tropical circulation substantially.

Increased evaporation would have raised the water vapor content of the tropical air, leading to a rapid expansion of tropical rainbelt and rain forests into higher latitudes. During the previous ice age these forests had been reduced drastically.

As is to be expected, the amount of warming during the Holocene period also varied by area. The waters of the Kuroshio Sea between Japan and Taiwan were as much as 6 °C warmer than they are now. On mid-latitude ocean coasts, temperatures were probably 1.5–2 °C above current amounts. In northeastern North America, and probably in other inland continental areas, temperatures were not as high. A prairie extending into the present states of Wisconsin and Illinois in the US, some areas in southwest Siberia, and an area in eastern Turkey were all drier during the Holocene than now. Yet there is evidence that some northern European and Asiatic forests had somewhat higher temperatures and rainfall than at present.

In eastern Siberia, the southern boundary of permafrost was several hundred kilometers north of its present position, and a similar retreat can be assumed for Canada and Alaska because of the northward extension of vegetation lines. In the mountains of these northern regions, tree lines shifted northward by 100–150 kilometers, which indicates warming of nearly 1 °C.

The Holocene humidity

Global warming of 1.5 °C would correspond roughly to the peak of the Holocene warming some 6,000 years ago. While warming of up to 1 °C or so would produce drier conditions in many temperate areas, further warming up to 1.5 °C might result in more humid conditions in some subtropical areas that are dry today, as well as generally drier conditions elsewhere.

In subtropical latitudes, the present arid areas were wetter during the Holocene. Since temperatures everywhere were either higher or similar to those of today, the humidity must have been related to greater rainfall, caused in turn by greater evaporation of the tropical oceans. This probably coincided with a weakening of the subtropical anticyclones and trade winds (see Chapter 4).

Perhaps the most dramatic example of the Holocene's greater humidity occurred in the Sahara desert and the deserts of the Middle East. Remnants of the North American ice and frequent outbreaks of cold air over Europe and Africa between 8,400 and 5,900 years ago may have caused Mediterranean winter rains to reach the north flank of the Sahara. At the same time, tropical rains could have penetrated into the south flank, as happened previously, so that both flanks of the desert shrank and expanded together. The central belt of the Sahara also experienced some amount of rain during the period.

Among now-dry Sahara lakes that then had water is Lake Mega-Chad, which at 320,000 square kilometers was about the size of the present-day Caspian Sea. At times it overflowed into the Benue–Niger catchment. Even in what is now the hyper-arid center of the Sahara between the Kufra Oasis and the Tibesti Mountains (now with less than five millimeters of rain per year), permanent or periodic rivers were flowing, indicating at least 250 millimeters of rain per year, and possibly as much as 400 millimeters. Grasslands in this area were used for raising cattle by many groups of nomads.

"Clearly, an increase of 1 °C in the global average surface temperature caused by man would be a serious matter."

"A person now 20 years old might see food shortages and population migrations in areas of high living standards before reaching mid-career."

Similar evidence has been found all across the arid belt that runs from Mauretania in western Africa to Rajasthan in India, which includes the Afar–Danakil depression and the Arabian interior. At the margin of the Tharr desert in India, which now has an average annual rainfall of about 250 millimeters, rain fell at a rate of 500–800 millimeters a year during a long moist period between roughly 10,500 years ago and 3,600 years ago. Evidence from more than 30 locations in the whole area suggests that both extratropical winter rains and monsoonal summer rains increased substantially and simultaneously.

Desiccation set in throughout the region around 5,500 years ago. The gradual drying was interrupted by wetter periods. Several of the early high civilizations – the old empire of Egypt from the first to the fourth dynasties, the urban cultures of the Near East between Jericho and Ur, and the Indus culture – began at the end of the humid period and had to struggle against increasing dryness.

Evidence of climatic conditions in the arid southwest of the US during the Holocene is limited. A freshwater lake is known to have existed in central New Mexico, indicating greater moistness. In California and Nevada, lake levels were high between about 13,000 years ago and 10,000 years ago, and this moist period was followed by a marked dry period lasting until about 5,000 years ago.

Deserts in the southern hemisphere generally appear to have followed the pattern in the north. In Australia, precipitation increased at northern and southern margins of the desert areas at the peak of the Holocene, and slight warming occurred in the mountains of New Guinea. Evidence from South Africa, however, does not conform to the pattern. There the interior plateau had warmer, but drier semidesert conditions during the period.

The effect of boundary conditions

As noted, boundary conditions (such as ice sheet size, vegetation lines, and tide levels) were not the same 6,000 years ago as they are now. There were two main differences: ice sheets in the

A case of desertification

The desertification process associated with the Sahelian drought also poses a serious threat to many other arid and semi-arid countries. This threat prompted the United Nations Conference on Desertification in Nairobi in 1977. The conference considered that the drought of 1968 to 1973 was the culmination of a desiccation dating back to the late 1950s or early 1960s in most parts of the Sahel. It was not unprecedented, though it was prolonged, severe and widespread. Records exist of similar droughts 30, 50, and 60 years earlier. The desertification that accompanies the drought, that is, the spread of nonproductive land conditions, had two causes: heavy stocking of animals and continued dry land cultivation, until the land could no longer sustain the human and animal populations during the drought years.

– Howard Daniel, *Man and Climatic Variability*, World Meteorological Organization, Geneva, 1980.

northern hemisphere still remained in eastern Canada (though they had retreated from other major land masses), and there were no significant desertification processes resulting from the activities of man.

The ice in eastern Canada probably disappeared during the period of dryness that began soon after the peak of the Holocene. While it existed, however, it was a permanent cold source that no doubt influenced circulation patterns in Europe, producing frequent blocking anticyclones around the British Isles and Scandinavia (similar to current conditions there in the spring) and causing increased cyclone activity in the Mediterranean.

Such conditions could only be expected in the near future if a permanent snow cover developed on Baffin Island and Labrador, which is not likely. Nor can a substantial increase in rainfall be reasonably expected along the north margins of the Sahara and Middle East deserts. More rain along their southern flanks might be possible, however, if subtropical anticyclones weaken slightly and shift toward higher latitudes. This would weaken the trade winds of the northern hemisphere and decrease coastal and equatorial upwelling, which in turn would lead to greater oceanic evaporation and to increased rainfall in the Sudan–Sahel belt of Africa.

In recent times man has destroyed vegetation enough to create deserts by means of eroding soil, depleting groundwater, and increasing the salt content in the groundwater. To reverse such desertification processes seems possible only if large-scale rainfall triggers the growth of an adequate cover of vegetation that can be protected from overgrazing and the strains of population. Only in this situation could the weak positive feedback effect of "desertification–increasing albedo–increasing subsistence–less rainfall–extended desertification" be interrupted and possibly reversed.

Much additional research of a broadly interdisciplinary nature is needed on the subject of man-made desertification. If such an effort is not forthcoming, it is doubtful whether a mild global warming would produce sufficient rainfall to arrest the process in many of the areas where it now occurs.

8

Beyond Immediate Prospects

Speculation on global warming of 1 °C and 1.5 °C is relatively tangible. Such temperature increases could occur within 20–50 years and leave ice sheets and sea level much the same as they are today. Similarly, as noted in the last chapter, looking back 6,000 years for comparative temperatures does not evoke a time when boundary conditions were greatly different from today's.

Looking a little farther into the future – and a lot farther into the past – to imagine an earth with a global average surface temperature 2.5 °C warmer than it is today is decidedly more conjectural. Nevertheless, taking note of what is known or reasonably inferred about the interglacial period 120,000 years ago provides useful insights into what the earth might be like, thanks to man-made global warming, between the years 2020 and 2050 or beyond.

The last interglacial period

Over the past 2.5 million years, at least 17 large-scale glaciations of northern continents have occurred. They have been interrupted by an equal number of interglacial periods when at some point climatic conditions approximated those of the present day. Detailed information is available only for the more recent of these glacial fluctuations, and especially for the last glaciation between 73,000 and 14,000 years ago. It had major glacial peaks at its beginning and at its end, and there were at least five short periods of slightly warmer climate (interstadials).

The most recent interglacial period continued from about 130,000 years ago to 75,000 years ago, with two important interruptions of cooling. Scientists know much about the climate in Europe and Asia during the period, but information on North America falls short of providing a regional description, and evidence from other continents is almost completely lacking.

Climate during the earliest warming peak of the last interglacial period (the Eem interglacial) is now being investigated extensively. The warming, which peaked about 125,000 years ago, appears to make this period the warmest of all the interglacial periods of the last 2.5 million years. Climatic data from polar and mid-latitudes in Eurasia and North America indicate that temperatures were generally 2–3 °C higher than today, and it was slightly more humid.

In northern and eastern Europe the climate was much more oceanic than at present, mainly because of a sea level 5–7 meters higher than today's. Scandinavia was isolated from the continent by an oceanic channel connecting the Baltic Sea and the White Sea. The sea also penetrated deeply into the continent in western Siberia along the Ob and Yenisey flood plains up to a latitude of 62 °N.

Deciduous trees such as oak, linden, elm, and hazel prevailed in the poleward reaches of the temperate zones. Such forests also existed in eastern Siberia, indicating a marked retreat of permafrost to latitude 57 °N, compared to 50 °N today. Boreal forests extended up to coastlines, suggesting that Arctic drift ice had retreated well away from the coasts. The coasts, however, were inundated by high sea levels.

While marginal parts of the Arctic drift ice were probably displaced poleward, the central core of ice between Greenland, Alaska, and eastern Siberia has remained unchanged at least for the last 700,000 years. Yet the markedly warmer climate of the northern temperate zone can be illustrated by evidence that such animals as hippopotamuses, forest elephants, and lions roamed southern England during the last interglacial period 125,000 years ago.

This warmest of known interglacial periods only lasted about 10,000 years. It ended, as such periods commonly do, with an abrupt, short period of cooling, during which the global ice volume sharply increased, possibly causing sea level to fall 60–70 meters, and then decreased. Atlantic polar ice remained north of latitude 76 °N for about 8,000 years. Subtropical waters (which apparently did not get higher in the northern hemisphere than latitude 44 °N in the Holocene period) reached 52 °N.

Two other warm phases followed the peak period. In all interglacial periods for which sufficient information is available (except for the Holocene that continues today), abrupt cooling has lasted from a few centuries to no more than 1,000–2,000 years. These "abortive glaciations" seem to recur not more than once in 10,000 or 20,000 years. Their cause is unknown, but speculations have suggested clusters of volcanic explosions or Antarctic surges as the triggering mechanisms.

Life on a lopsided planet

Flohn cites widely quoted estimates (see Chapter 6) that envisage projected increases in the use of fossil fuels as doubling atmospheric carbon dioxide around 2040. The best models of climate available (see Chapter 1) indicate that a doubling of carbon dioxide and other trace gases would raise temperatures 2 ° to 3 °C in low and middle latitudes and 5–10 °C in polar latitudes.

Such a development could make it possible for a young child of today to witness a remarkable climatic transformation within a normal life span. Global warming of 4 °C could cause Arctic drift ice to disappear completely, leaving an expanse of open water at the North Pole, while ice more than two kilometers thick remains over the land mass of the South Pole. The possibility is currently one of the more controversial subjects for scientists in climate-related research, but Flohn presents a strong case for it.

Flohn points out that it has not yet been established conclusively that global warming of 4 °C would melt the Arctic ice, but he cites modeling efforts and paleoclimatic evidence that both support such an assumption. If 4 °C is somewhere near the temperature increase needed to trigger an ice-free Arctic, then such a possibility is well within the conceivable results of man-made global warming.

Arctic ice floes are highly changeable. They vary greatly by season and from year to year. The air–snow–ice–ocean system is particularly sensitive to oceanic heat flow, the albedo of the ice–

"Hippopotamuses, forest elephants, and lions roamed southern England during the last interglacial period 125,000 years ago."

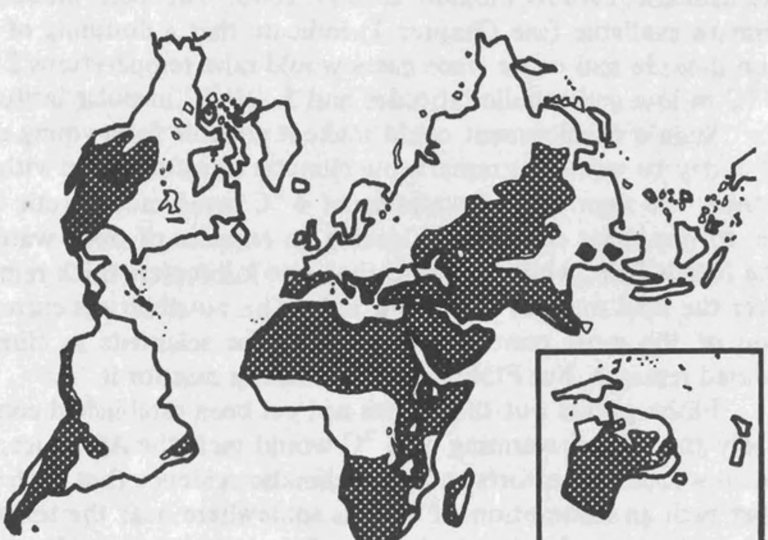
"During the remarkable cooling period 6.5–5 million years ago, the Arctic Ocean had a cool to temperate climate."

snow surface during the melting season, and the length of the melting season (which normally ends with the first snow cover).

The sea ice melts from above and freezes from below. During the melting season beginning in early spring, melting takes only 50–60 days; snowmelt takes an additional 20 days. Currently the process shrinks the average mass of an ice floe by 15–20 percent. During the rest of the year, a similar amount of water freezes from below, replacing an average of 50 centimeters of ice per year.

Over the last 1,000 years, marginal sections of Arctic drift ice have often demonstrated an ability to disappear rapidly. However, as just noted, the central core of Arctic ice has been intact for at

Today's areas of frequent droughts



The map above indicates areas where frequent droughts occur in present times. It includes the permanently arid zones. An increase in global average surface temperature of 4 °C could make large areas of the southern hemisphere more prone to drought and extend the drought areas of the northern hemisphere to include most of the highly industrialized areas of North America and Europe. Source: Daniel, H. (1980) *Man and Climatic Variability*, World Meteorological Organization, Geneva.

least 700,000 years and possibly for 2.3 million years. During that span of time, as major glaciations have alternated with warmer interglacial periods, global warming has probably not raised global average surface temperature more than 2.5 °C above today's levels.

Just before large-scale glaciation of the northern continents began some 2.5 million years ago, the earth was warmer. Evidence now available indicates conclusively that the Arctic Ocean was then substantially ice-free and the Antarctic continent covered with an ice dome for a period of at least ten million years between about 12 million and 2.5 million years ago.

This period, the late tertiary, had boundary conditions differing from today's, but locations of continents, oceans, and atmospheric currents were enough like those now existing to permit useful comparisons. An ice-free North Pole and an icebound South Pole probably also existed for 20–30 million years during the Permo-Carboniferous glacial period about 250 million years ago, but then boundaries were vastly different. For example, several continents including the Antarctic formed a supercontinent (Gondwana) in the high latitudes of the southern hemisphere.

For the last 12 million years or longer, the Antarctic continent has been under more or less constant glaciation. From 12 million to 2.5 million years ago, the Arctic Ocean was in a fairly stable ice-free condition. Then began the sequence of glacial and interglacial periods that continues today.

At the end of the period of an ice-free Arctic and a glaciated Antarctic – about 3–5 million years ago – our early ancestors, the hominids, had just learned to use stones as weapons and tools in the savannas of equatorial East Africa. The climatic changes then occurring may have influenced the evolution of the species.

The Antarctic ice dome reached its glacial maximum for the ten-million-year period of an ice-free Arctic around 6.5–5 million years ago. The dome must have been several hundred meters higher then, with a volume of ice significantly greater than today's. Global cooling occurred, cold Antarctic surface waters extended 300 kilometers farther north, and strong upwelling took place in the equatorial Pacific.

One of the most important consequences of this cooling phase was a drop in sea level of 40–50 meters below today's level, a result of water storage in the Antarctic ice dome. The Gibraltar area water receded, cutting off the Mediterranean Sea, which evaporated eight or ten times to a depth of 3,700 meters and refilled, leaving a laminated salt layer 300–500 meters thick.

During this remarkable cooling period 6.5–5 million years ago, the Arctic Ocean had a cool to temperate climate. Boreal forests extended to the northernmost tips of land. The entire north continental shelf of Asia and Alaska was then dry, and the northern continents extended 200–600 kilometers farther north. Siberia then reached latitude 81 °N, Canada 83 °N.

Just before the first appearance of ice on the European continent about 2.5 million years ago, Siberia was evidently free of tundra and widespread permafrost. Summer temperatures were probably 4–5 °C higher than now, winter temperatures at least 5–10 °C higher. Since mountains in the area were lower, oceanic rainfall penetrated farther inland, making annual rainfall 300–400 millimeters greater than at present.

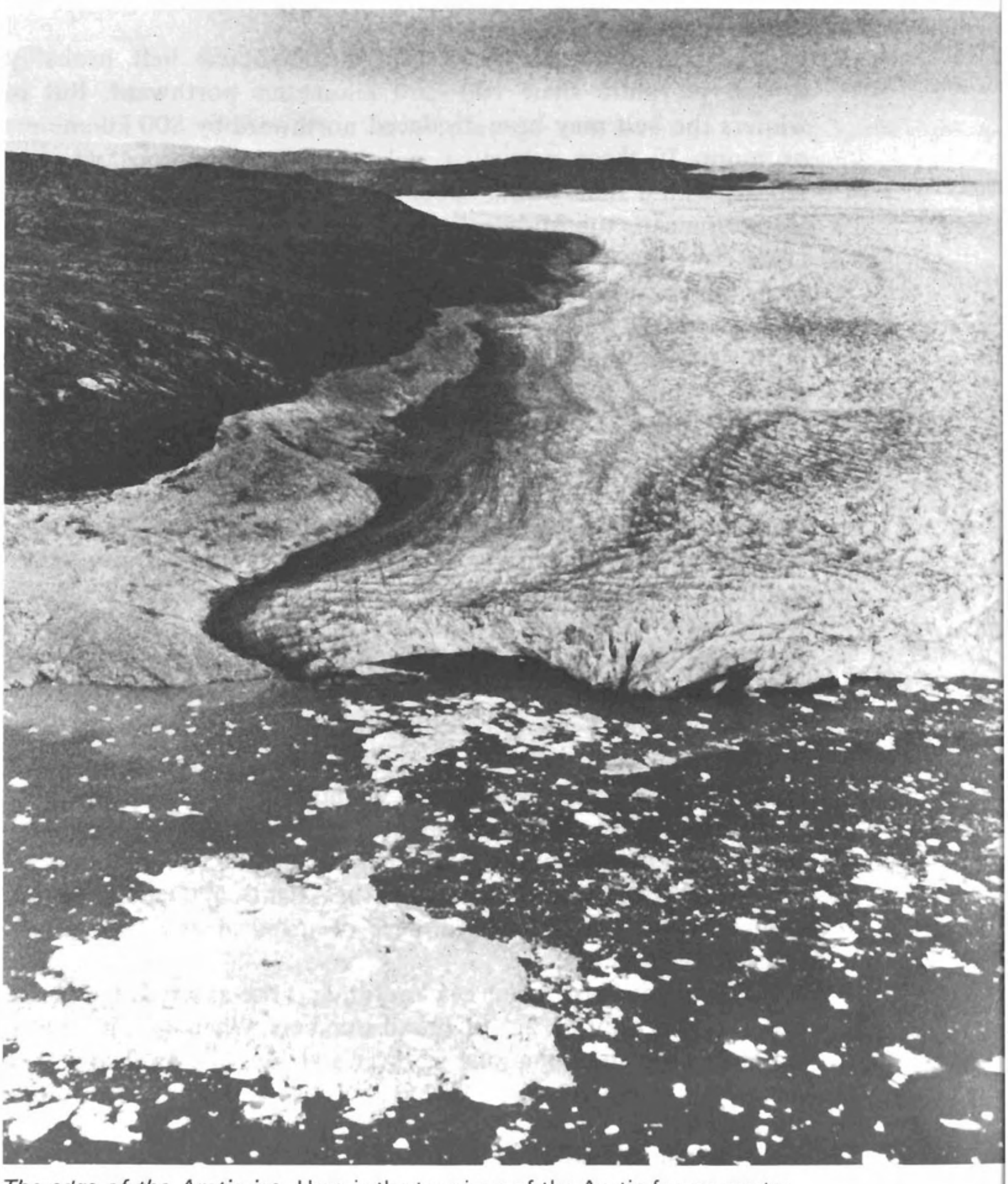
In a few areas – Iceland, Greenland, and even in the high mountains of California – glaciers probably formed along with boreal forests, but this produced no significant large-scale climatic effect. Along the coasts of Alaska, well-developed boreal mixed forests extended more than 800 kilometers north of present tree lines. Fossil insects of the time at latitude 66 °N resemble those now living at latitude 48–50 °N (the Vancouver–Seattle area).

The southern hemisphere's climate from 5 to 2 million years ago may have been at times as cool as the peaks of the long glacial–interglacial age that followed. The Ross ice shelf in Antarctica extended beyond its present boundary. Glaciation started in southern South America about 3.6 million years ago. From observations of ice-rafted pebbles it has been inferred that as cold Antarctic surface water shifted northward, Antarctic tabular icebergs reached farther north than previously.

Arid parts of the north temperate zone extended farther northward before the glaciers came. From 6.5 to 5 million years ago, even south-central Europe was partly arid, with steppe or desert vegetation reaching nearly to Vienna. Southwest Germany was much drier than now, and in what is now the US, the dry belt included most areas west of the Mississippi River.

In the tropics, savanna climates with seasonal rains were much more extensive than they are today, but the equatorial rain forest with all-year rain was much smaller. While the southern Sahara was covered with a tropical humid or semihumid vegetation (which now remains in southern Nigeria), southern Africa and the Zaire basin were dry and sometimes fully covered with desert. Similar aridity occurred in northern Australia after the peak of Antarctic glaciation 6.5–5 million years ago.

The evidence suggests that the hemispheric asymmetry of both atmospheric and oceanic circulations was substantially greater than now during the long period of an ice-free Arctic. The average annual temperature difference between Arctic and Antarctic was then on the order of 20 °C; now it is about 11 °C. It appears that the northern subtropical high-pressure belt reached 43–45 °N, compared to its present northern limit of 37 °N. The southern



The edge of the Arctic ice. Here is the terminus of the Arctic frozen wastes in the fjords of Norway. Ice sheet size is a boundary condition that can change rapidly, and it augments the prevailing temperature trend, so that during a warming phase temperatures are further increased by the contraction of the ice sheet as it reflects less solar radiation. Land and water both absorb more solar heat than ice. (Photo courtesy of International Communication Agency.)

subtropical belt probably reached about as far south as it does today, to 31 °S.

During summers, the northern subtropical belt probably shifted no more than 100–200 kilometers northward. But in winters the belt may have displaced northward by 800 kilometers or more. If these particular paleoclimatic conditions were to repeat, winter rains would be reduced drastically in California, the Mediterranean, the Middle East all the way to Turkestan in the USSR, and the Punjab region of India. Summer droughts would probably be frequent in a belt from 45 °N to 50 °N.

Although the northern subtropical belt would shift to the north, the southern subtropical belt would remain constant with global warming of 4 °C. The hottest belt of the earth, its "meteorological equator," would then shift northward from its present position at 6 °N to a latitude of 9–10 °N. In northern winter, equatorial rain would probably remain in a belt between the mathematical equator and latitude 20 °N, reaching south of the equator only rarely. This rain is actually the tropical summer rain of the southern hemisphere, and such a marked decrease in its amount would lead to a natural desertification of areas in the belt between the equator and 20 °S, including Brazil, central Africa, and Indonesia.

The drought would probably be made more severe by more frequent and more intense equatorial upwelling that would drastically reduce oceanic evaporation in much of the area, especially during the southern winter, when the meteorological equator reaches its northernmost position. Strong equatorial upwelling (and no El Niño) would be likely in the Atlantic and Pacific oceans, although it is not known to have occurred at any time in the Indian Ocean.

The amount by which sea levels might rise as a result of global warming can only be put in round numbers. When drift ice melts, sea level stays the same, just as the water line in a drink stays the same as an ice cube melts. Within the next 100 years a significant worldwide rise in sea level could only be caused by large-scale surges of the Antarctic ice cap. As a rough gauge, each 100,000 cubic kilometers of ice slide could be expected to raise sea level 25 centimeters, and a slide of less than 100,000 cubic kilometers would probably not affect sea level significantly.

The most recent ice slide of sufficient size to raise sea level may have occurred during the last interglacial period, when an Antarctic ice surge of some 2 million cubic kilometers could account for a 5-meter rise in sea level at that time. Flohn says the risk of such an event recurring as a result of a 4 °C increase in global warming is not great during the next century or so.

Nor does he consider it likely that the continental ice caps of the Antarctic and of Greenland would melt soon after the North Pole. Even with an ice-free Arctic, Greenland would get more winter snowfall due to increased cyclone activity and probably retain the bulk of its glaciation. But the risks of rising sea level should not be completely disregarded, even though, as we have just seen, the risks of a large-scale shift of climatic belts due to global warming are far greater.

9

Today's Mixed Signals

Anyone unwilling to regard man-made global warming as a serious problem could argue as follows:

"The experts know so little about climate that they can offer nothing more than a far-ranging choice of future possibilities. They have no idea whether global warming will melt the Arctic ice, or whether a cluster of volcanic eruptions will trigger a period of cooling. Either way, widespread disruption results. Burning less fossil fuel is no answer. It would surely cause privation now, and it could hasten the arrival of a new ice age."

The fallacy of the argument above is that, while man-made global warming could bring on the future possibilities Flohn suggests, it is not likely that a cooling large enough to matter will occur during the next 100 years. Convincing evidence from ocean cores shows that over the last 450,000 years, the great glaciations have coincided with long-term variations in the earth's orbit that alter its distance from the sun. It suggests that glaciation similar to that of 18,000 years ago is not likely for 5,000–50,000 years.

The onset of a new ice age within a century has a very low probability, considering the paleoclimatic frequency of such events. The conditions that could trigger it – a rapid decrease in solar radiation, a surge of a million cubic kilometers or more of Antarctic ice, or a cluster of strong volcanic eruptions – are extremely rare, and they remain unpredictable.

Some practical conclusions

If atmospheric carbon dioxide content continues to rise, and if other man-made trace gases continue adding another 50 percent

Nonfossil options

. . . Nevertheless in view of the present uncertainties in quantifying the effects of carbon dioxide, it seems premature to recommend only those energy strategies that actively discourage the use of fossil fuels. At the same time, in view of the probable climatic implications of increased concentration of carbon dioxide in the atmosphere, it would be unwise to build future energy strategies that continue to rely greatly on the use of fossil fuels. *A prudent policy, in our opinion, would be to have sufficient nonfossil options incorporated in the energy supply system over the next few decades so as to allow expansion from that base, if necessary, as the effects of carbon dioxide become better quantifiable through further research.*

– Energy Systems Program of the International Institute for Applied Systems Analysis, W. Häfele, Program Leader, *Energy in a Finite World: A Global Systems Analysis*, Ballinger, Cambridge, Massachusetts, 1981.

or more to the greenhouse effect of infrared absorption, developments similar to those outlined in Chapters 7 and 8 could be expected. The last interglacial period 120,000 years ago serves as a guide to what might happen if carbon dioxide and other trace gases in the atmosphere rise from the current level, estimated by Flohn to be 335 parts per million (ppm), to about 610 ppm. The average global warming would then be about 2.5 °C.

The consequences of a 2.5 °C increase in global average surface temperature would be climatic changes more drastic than any man has experienced over the last 10,000 years. In some regions the effects on man would be benign, in others beneficial, and in many others catastrophic.

The real danger, however, comes when the carbon dioxide and other trace-gas content is greater than a doubling. Flohn refers to what he sees as the decisive threshold, which he sets at somewhere between 550 and 750 ppm of carbon dioxide and other trace gases, or between 800 and 1,100 ppm for carbon dioxide alone. Beyond this amount of man-made gas release, the probability of an evolution toward an ice-free Arctic Ocean increases greatly. Not only could Arctic melting occur rapidly – within a few decades or less – it would be irreversible once the central core of Arctic ice had gone. As noted, an ice-free Arctic and a large dome of Antarctic ice coexisted for no less than 10 million years just before the present Arctic ice core began to form.

The evolution of an ice-free Arctic could lead, possibly after a series of catastrophic weather extremes, to a displacement of today's climatic zones by 400–800 kilometers. The problems that this could cause for mankind are enormous.

"Not only could Arctic melting occur rapidly, it would be irreversible once the core of Arctic ice had gone."

A report by an IIASA working group of specialists has concluded that mankind can afford between five and ten years for "vigorous research and planning" to narrow the uncertainties enough to justify changes in energy policies that would avert the kind of future described here.

SELECTED ENERGY-RELATED PUBLICATIONS BY IIASA

ENERGY IN A FINITE WORLD: PATHS TO A SUSTAINABLE FUTURE
Report by the Energy Systems Program Group of IIASA, Wolf Häfele, *Program Leader.* 225 pp. $16.50.

Written by Jeanne Anderer with Alan McDonald and Nebojša Nakićenović

ENERGY IN A FINITE WORLD: A GLOBAL SYSTEMS ANALYSIS
Report by the Energy Systems Program Group of IIASA, Wolf Häfele, *Program Leader.* 837 pp. $45.00.

Both of the above volumes are available from Ballinger Publishing Company, 17 Dunster Street, Cambridge, Massachusetts 02138, USA.

The other publications listed here are divided into five subject areas:

1 Global, regional, and sectoral energy models – whether for energy demand, energy supply and conversion, or for economic, resource, or environmental impacts of energy technologies.

2 The analysis of different energy sources – i.e., fossil fuels, nuclear power, solar power and other renewables – and the conversion, storage, and transportation technologies associated with them.

3 The analysis of energy demand patterns.

4 Environmental and safety risks of energy technologies.

5 The analysis of total energy systems and energy strategies including all the dimensions of the first four categories taken together.

Books in the International Series on Applied Systems Analysis (Wiley) can be ordered from John Wiley & Sons Ltd., Baffins Lane, Chichester, Sussex PO19 2UD, United Kingdom.

Books published by Pergamon Press can be ordered from Pergamon Press Ltd., Headington Hill Hall, Oxford OX3 0BW, United Kingdom, or Pergamon Press, Inc., Fairview Park, Elmsford, N.Y. 10523, USA.

All other publications can be ordered from the Publications Department, IIASA, A-2361 Laxenburg, Austria.

1. Energy Models

RR-80-31. The IIASA Set of Energy Models: Its Design and Application. P.S. Basile. December 1980. 65 pp. $7.00

RR-78-17. MEDEE-2: A Model for Long-Term Energy Demand Evaluation. B. Lapillonne. November 1978. 45 pp. $6.00

RR-79-8. The Economic IMPACT Model. Yu.D. Kononov, A. Por. October 1979. 72 pp. $8.50

The Energy Supply Model MESSAGE. L. Schrattenholzer. 1981. (Forthcoming Research Report.)

A Long-Term Macroeconomic Equilibrium Model for the European Community. H.H. Rogner. 1981. (Forthcoming Research Report.)

Modeling of Large-Scale Energy Systems. Proceedings of the IIASA–IFAC Symposium on Modeling of Large-Scale Energy Systems. W. Häfele, Editor, L.K. Kirchmayer, Associate Editor. 1981. 462 pp. (Available from Pergamon Press.) $72.00

CP-74-3. Proceedings of IIASA Working Seminar on Energy Modeling, May 28–29, 1974. May 1974. 342 pp. $13.00

RR-74-10. A Review of Energy Models: No. 1 – May 1974. J.-P. Charpentier, Editor. July 1974. 102 pp. $8.50

RR-75-35. A Review of Energy Models: No. 2 – July 1975. J.-P. Charpentier, Editor. October 1975. 133 pp. $10.00

RR-76-18. A Review of Energy Models: No. 3 (Special Issue on Soviet Models). J.-M. Beaujean, J.-P. Charpentier, Editors. December 1976. 33 pp. $4.00

RR-78-12. A Review of Energy Models: No. 4 – July 1978. J.-M. Beaujean, J.-P. Charpentier, Editors. July 1978. 48 pp. $6.00

CP-77-2. Methods of Systems Analysis for Long-Term Energy Development. Yu.D. Kononov, Editor. March 1977. 38 pp. $5.00

RR-76-11. Modeling of the Influence of Energy Development on Different Branches of the National Economy. Yu.D. Kononov. October 1976. 15 pp. (Microfiche only.) $4.00

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Dynamic Linear Programming Models of Energy, Resources, and Economy Development Systems. A Propoi, I. Zimin. 1981. (Forthcoming Research Report.)

2. Energy Sources

North Sea Oil. Resource Requirements for Development of the U.K. Sector. J.K. Klitz. 1980. 260 pp. (Available from Pergamon Press.) $36.00

Future Supply of Nature-Made Petroleum and Gas. R. Meyer, Editor. IIASA, UNITAR. 1977. 1046 pp. (Available from Pergamon Press.) Hard cover $60.00, soft cover $40.00

Conventional and Unconventional World Gas Resources. M. Grenon, C. Delahaye, Editors. 1981. (Forthcoming from Pergamon Press.)

Future Coal Supply for the World Energy Balance. M. Grenon, Editor. 1979. 720 pp. (Available from Pergamon Press.) $90.00

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CP-77-5. Medium-Term Aspects of a Coal Revival: Two Case Studies. Report of the IIASA Coal Task Force. W. Sassin, F. Hoffmann, M. Sadnicki, Editors. August 1977. 90 pp. $8.50
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