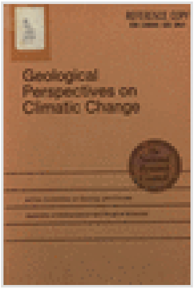

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Geological Perspectives on Climatic Change

Report of an
ad hoc Committee on Geology and Climate
Preston Cloud, *Chairman*

Assembly of Mathematical and Physical Sciences
National Research Council

National Academy of Sciences
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PREFACE

At the request of the Advisory Board to the Office of Earth Sciences of the Assembly of Mathematical and Physical Sciences of the National Research Council, a two-day meeting of an *ad hoc* Committee on Geology and Climate, chaired by Preston Cloud, convened on 28-29 September 1977. The primary purpose of the meeting was to determine whether an extended study by the NRC of the bearing of the geological sciences on understanding climate is needed and timely. Because of the relation of this question to studies under consideration by the Geophysics Study Committee of the Geophysics Research Board, the meeting was sponsored by the Board. The *ad hoc* Committee reviewed current research in the field with a view toward appraising its current status and identifying opportunities for the geological sciences to contribute to a better understanding of climate and the forces that make for climatic change. The report of the Committee was transmitted to the relevant units of the National Research Council in mid-November 1977.

The report was received with great enthusiasm. It provides in a small package a summary of the current state of understanding of the history of the earth's climate over the last hundred million years, of the detail in which each episode is known, and of the experimental and observational techniques which have made possible the synthesis provided. Further, the report offers a relatively detailed agenda of future studies required to add substance to the relatively sketchy framework presently available while also making a compelling case for the relevance of such understanding to future ability to monitor and predict climatic change. The *ad hoc* Committee offered one caveat, viz., its membership did not include representatives of all the specialties that might have contributed to a discussion of paleoclimatology.

This fact and the tight schedule of the Committee may somewhat limit the breadth and the depth of the discussion.

Nevertheless, both the Advisory Board to the Office of Earth Sciences and the Assembly of Mathematical and Physical Sciences urged that this report, originally intended as an internal document, be made more generally available, especially to the earth sciences community. I am happy to concur with that judgment, while noting that the present report complements, in part briefly summarizes, and extends, Appendix A, "A Survey of Past Climates," of the report Understanding Climatic Change, issued in 1975 by the U.S. Committee for the Global Atmospheric Research Program (GARP) of the National Research Council. Another related report of the U.S. GARP Committee, "Elements of the Research Strategy for the United States Climate Program," was published in 1978.

Philip Handler, *Chairman*
National Research Council

INTRODUCTION

Earth's climate is a product of forcing factors and complex feedbacks within an interacting system that involves atmospheric, hydrospheric, cryospheric, lithospheric, biospheric, and solar-terrestrial components. A study of climate must take into account air-sea interactions, oceanic and atmospheric circulation, heat fluxes, the effects of atmospheric gases (in particular CO_2), volcanism, variations in the reflectance or albedo of land and sea surfaces, and variations in solar activity and terrestrial orbit. Major climatic changes in the distant geological past can be related to shifts in the positions and orientations of continents and seaways relative to the poles and to one another as a function of plate tectonics and continental drift, with feedback to oceanic and atmospheric circulation. Changes in earth's orbit, its inclination to the sun, or other changes in its budget of solar radiation are superimposed on other forcing factors. And seemingly random elements may enter at any stage. To all this must be added other activities of man, who has himself, through force of numbers and intensity of activity, become a factor of geological magnitude.

Indeed, the atmosphere and hydrosphere themselves are the products of geological processes that can be reconstructed in part from the study of a sedimentary record that reaches billions of years into the past. Earth evolves and climate changes. The record of these changes is preserved in the sedimentary rocks of the earth. By studying the paleoclimatological components of the record, the pattern, timing, and sometimes the probable causes of climatic change can be reconstructed, the degree of detail improving as we near the present.

The best data come from paleontological records that identify local ecological and climatic conditions in a latitudinal context. They can be calibrated chronologically and related to paleotemperature estimates by way of isotope geochemistry or other means. Research by paleoclimatologists, paleontologists, glaciologists, dendrochronologists, isotope geochemists, and volcanologists has already produced enough well documented and precisely dated records to suggest periodicities in climatic variation similar to some recognized for changes in solar radiation, orbital changes, geomagnetic variations, or other geophysical phenomena. Some interesting data suggest a relationship between cooling episodes and the stratospheric injection of volcanic particulates.

Such records provide the possibility both of formulating predictive models and of forecasting future climatic trends. They also present the opportunity to test predictive models by looking backward in the geological record for systematic coincidences between paleoclimatological events and associated evidence of the work of postulated forcing factors.

If we know nothing else about climate we know that, like the rest of earth's system, it changes. The changes may be gradual or abrupt, but they are inevitable. Climates like those of today have actually dominated during only a relatively small part of the last few million years. Indeed climatic change has itself been a major forcing factor in the evolution and distribution of organisms. During the alternating glacial and interglacial episodes of the Quaternary, massive shifts occurred in the geographical distribution of plants and animals. Mankind also was affected. Some conclude, for example, that the climatically induced extinction of the large late-Pleistocene mammals in North America resulted in a shift in human cultures from hunting societies that depended primarily on big game to peoples who exploited a wider variety of food resources, leading ultimately to domestication of plants and animals in the New World. A case can also be made that the primary domestication of cereal grains in the Near East was a direct consequence of terminal Pleistocene climatic change and the accompanying vegetational shifts.

Climatic change is, therefore, to be expected, understood if possible, prepared for, and coped with. It is not a cause for panic. We must try to understand how, when, and at what rates it will change, and with what potential effects on different parts of the earth's surface. One person's flood is another's water supply. Drought in one region may be compensated by rain elsewhere. The same forces that lead to desertification here may improve growing conditions there. Where the rains fail at one place they may fall at another. Man (in the generic sense, of course) would have little cause for concern about the effects of climatic change if he were more flexible in the location of his settlements, and if he were less numerous and were not operating so close to the limits of agricultural and other natural resources dependent on climate.

Indeed as we become more populous and push closer to the limits of our resources we become more dependent on climatic factors and more vulnerable to climatic change. Any fluctuation in climate can cause societal and economic disruptions. Even bumper-crops can depress farm prices. *A better understanding of climatic variability can allow us to be better prepared for climatic variation.*

This report presents some thoughts of an *ad hoc* committee convened to discuss the unique role that earth scientists can play in seeking to establish a more nearly complete and better-dated record of past climates, to formulate a judgment as to the advisability of activating a detailed study in the near future, and to suggest goals for and the organization of such a study, should it be decided on.

In our understanding of the dynamics of modern climate, paleoclimatic data can provide information in at least four important areas:

1. *They constitute a basis for projecting expected directions and magnitudes of climatic change.* For example, knowledge of the magnitude of the glacial-interglacial temperature change provides a standard against which climatic changes in our times can be evaluated. A fundamental question is how large a temperature change is important. Paleoclimatic studies show that at the peak of the last glaciation the average global ground temperature was about 5°C less than now. A decrease of temperature by 1°C, therefore, would be 20% of the full glacial-interglacial change, while an increase of a few degrees Celsius would lead to accelerated melting of glacier ice, rise of sea level, and

shifts of earth's climatic, vegetational, and agricultural zones.

2. *Paleoclimatic data provide an answer to the question of where we are on the continuum of climatic change.* We find, for instance, that intervals of relatively warm stable climate such as today are short-term events relative to the more unstable conditions that have prevailed during most of the last several million years. The paleoclimatic record also gives some measure of the range of climatic variability. Sharp temperature declines occur during interglacial times.

3. *Paleoclimatic data provide important clues to how the climate system works.* They show how the climate of the oceans and of the land changes and whether these changes are in phase. Synoptic studies of selected time intervals provide information on interregional climatic changes and identify lags and leads in the climate system.

4. *Paleoclimatic data provide a basis for testing models of climate.* One of the practical difficulties in climate modeling using only modern data is the length of time required to validate the forecast of the model, and to make necessary adjustments. An alternative research strategy is to reconstruct and model past climates against which the predictive power of the model can be tested. Paleoclimatic data also provide grounds for evaluating the possible causes of climatic change, including the effects of volcanism, an episodic geological process.

In this brief report we stress what needs to be done rather than what has already been achieved, although the latter is important. *Thus we conclude with notes on some priorities in paleoclimatological research and a recommendation.* With few exceptions, the aspects discussed are general rather than specific. We are not a sufficiently representative group, nor was it our intention to be either comprehensive or detailed. Indeed, there are major omissions in this report, such as any consideration of solar-terrestrial effects or of soil-forming processes, the humic acid cycle, weathering, and the likely effects of these on the carbon dioxide budget of the atmosphere. Nevertheless, we did make an effort to deal broadly with the important issues pertaining to geology and climate during a two-day meeting in later September 1977 and subsequent exchanges of correspondecne and drafts of this report. And we do feel that the following interim report can serve as a useful guide to actions and studies needed as climatic change comes to be recognized as a pressing problem--pending the recommended organization of a more probing study and the preparation of its report. In keeping with the provisional and interim nature of this report, we do not include detailed documentation or a list of primary references.

GOALS, QUESTIONS, OPPORTUNITIES, NEEDS

The central goal of modern climatology is well stated by K. Hasselmann as being "An understanding of the origin of climatic variability in the entire spectral range from extreme ice-age changes to seasonal anomalies." Paleoclimatology in the broad sense includes the goals of reconstructing and interpreting climates and climatic change throughout geological time, working toward a composite, coherent, quantitative, multidisciplinary picture of how climate does change. Toward this end it asks:

1. When, where, and how has climate changed in the geological past--what can we say about global climate states at selected times in the past and what major gaps exist in the available data?

2. What can we learn from the geological record about the causes of climatic change and the existence of periodicities of possible predictive value?

3. On what time scales do various forcing factors operate and what is the response lag for different parts of the climate system?

4. How can we sort out effects of different processes and forcing factors?

5. What are the geological consequences of climatic change--warming, cooling, variations in wind patterns and moisture content, etc.?

6. What are the kinds of questions and problems that studies at different time scales might formulate or contribute to?

7. How can we extend and refine the geological time scale?

8. How can we extend and improve an objective paleotemperature scale?

9. How can empirical studies be linked with theoretical modeling to cast predictions in a useful quantitative framework?

10. What are the sampling strategies and techniques by means of which paleoclimatological data might be used to test climatic theory evolved from other considerations?

11. Where are the best opportunities in terms of completeness and length of sequence and strategic location for the employment of those techniques and strategies?

In order to respond more rapidly and effectively to such questions and to design better research strategies there is need for:

1. More active exploration for an optimally dispersed network of sampling sites having a favorable combination of marine and nonmarine fossils, covering a long and continuous time range from the present backwards, and conducive to detailed and precise geochronological and paleotemperature controls.

2. Better sampling equipment and analytical methods.

3. More responsive and more quantitative modeling techniques.

4. More and better-trained personnel and a program for training them.

5. More general recognition by funding agencies and programs of the relevance of geological processes and paleoclimatological data for the understanding and prediction of climatic change.

We emphasize here also that the origin, effects, and eventual fate of atmospheric CO_2, currently the subject of much discussion, still need further evaluation in terms of geochemical and biochemical buffering processes and possibly compensatory climatic trends.

Yet all cannot be done at once. Thought, therefore, must be given to priorities in terms of fundamentality, timeliness in terms of presently available knowledge and instrumentation, availability of qualified personnel, prospective interaction with other disciplines, and relevance to perceived societal needs. In the light of such considerations, some opportunities present themselves more insistently than others.

WHAT DO WE MOST WANT TO KNOW AND WHY?

One goal that ranks high under all of the foregoing criteria--and which might be taken as a central (although by no means the exclusive) objective of climate-related geological research--is to achieve an understanding of the climate-determining processes and periodicities (if any) such as to permit forecasting of future climatic trends. Given such a goal, emphasis should be placed on identifying past temporal and geographical patterns of climatic change and on searching for causal factors, especially any that may recur at regular intervals. If the goal is narrowed to forecasting trends of practical significance for the next few decades, then the most relevant portion of the past paleoclimatic record amounts to a few centuries or a few millennia. That is because our ability to construct an accurate chronology fades with distance in the past, especially for the time for which standard methods of routine radiocarbon dating are not useful (*i.e.* before ~40,000 years ago).

Climatic periodicities of about 2400 to 2600, 1300, 400, and 180 years have been suggested by a number of workers involved with assessment of paleoclimatic data. If such apparent periodicities are real and global in their influence, they should be reflected in a variety of paleoclimatic data such as the records of glacial variation, ice cores, lake sediments, tree rings, and cores from areas of continuous sedimentation. In order to assess the longer periodicities, it will be necessary to convert radiocarbon dates to verifiable calendar ages based on independent evidence. Although at present this is possible only for about the last 7000 years, a determined effort should permit extension of the calibration curve at least back to the latest Pleistocene (about 10,000 to 12,000 years ago).

For very-near-term forecasting it would seem that research on geological events older than the Quaternary (*i.e.*, events of Tertiary or older age) would take a lower priority. That is because major variations in continental and oceanic geometry and orientation are such important elements in climate and climatic change in earlier geological times, while the determination of the patterns and chronology of such variations are likely never to achieve a precision useful for short-period forecasting.

Conversely, human activities such as the burning of fossil fuels and the overgrazing of semiarid regions may trigger climatic changes entirely different from fluctuations experienced over the past 100 to 1000 years. To anticipate such changes a deeper understanding of climate mechanisms is required. Theoretical studies alone will not provide all the answers. Climatologists will need all the information that can be wrung from the geological record as a base line against which to compare the recent past and the prospective future. Only by studying the more remote records of geological history can we see the full range of climatic variation that has existed.

To understand the timing and rates of climatic change requires precise and detailed geochronology. In particular we need reliable geochronometers behind the record of modern tree rings, especially for the interval between 40,000 and 250,000 years before the present (preceding the time during which routine radiocarbon dating is applicable but younger than the time for which potassium-argon dating is widely useful).

HOW AND WHERE MIGHT WE BEST SEEK THE ANSWERS?

Given the objective of forecasting for the immediate future, the best materials for detailed investigation are those whose sequences combine continuous and undisturbed formation with refined chronological control. Tree-ring studies are particularly promising for the shorter term because of (1) the excellent chronological control, (2) the possibility of relating stable-isotope variations as well as ring-width variations to climatic variables, and (3) the wide geographical range over which the technique is applicable, at least for the last few hundred years. For the sedimentary record, the most promising materials are the later Pleistocene bog and varved lake sediments or certain nearshore marine sediments that display uninterrupted sedimentation, high contents of organic matter, and a mixture of marine and nonmarine microorganisms, particularly if they are also varved. Onshore research might well focus on sites of potentially high sensitivity as well as resolving power, such as the above-mentioned peat bogs or varved lake sediemnts in areas of shifting ecology (*e.g.* the transition from forest to prairie or tundra).

There is also an urgent need to correlate deep-sea and continental stratigraphy, paleoecology, and paleoclimatology. Pollen and other biological sequences and dates on land need to be related to microfossil sequences and dates at sea; the best prospect for doing this is in continental borderland basins. Correlation by means of distinctive dated volcanic ash falls (tephrochronology) offers a potentially important means of establishing time equivalence in favorable areas.

Finally the geographical sampling net needs to be spread more widely if paleoclimatology is to be seen on a global scale. The polar regions and much of the southern hemisphere cry for attention both on land and at sea. If we listen they might tell us what are the most critical oceanic and land areas in terms of climate forecasting.

The inception of Quaternary and late Tertiary glaciations seems to have been in some sense a product of continental drifting during earlier Tertiary time. To assess the mechanisms leading to these glaciations calls for the modeling of probable global atmospheric and ocean circulations during earlier geological epochs in order to try to identify the contribution of such changes to general Tertiary climatic trends.

Major advances in paleoclimatology over the past decade have resulted from the development and application of quantitative methods for estimating past climatic variables, in particular in connection with the CLIMAP program (Climate/Long Range Investigation Mapping and Predictions). This multidisciplinary, multiinstitutional program of IDOE (International Decade of Ocean Exploration), funded by the National Science Foundation, seeks to reconstruct the paleogeography and paleoclimatology of the northern hemisphere at the peak of the last glaciation about 18,000 years ago. The CLIMAP project creates a bridge between geology and atmospheric science. But some geologists still tend to think of temperature as the central component of climate. We must ask ourselves what it is we really need to know to understand climate and how we can best find out. At sea we must consider and attempt to estimate not only temperature but also salinity, locations and intensity of upwelling or downwelling, nutrient concentrations, productivity, thermocline structure, the extent of sea and shelf ice, current direction and intensity, heat storage and transport capacity, and so on. On land we wish to know similar things--wind force and direction, humidity, amount and patterns of precipitation, extent and intensity of glaciation and volcanism, extent and boundaries of major vegetation types, and the like at a variety of times.

Reconstructions similar to CLIMAP, both at sea and on land, and with good correlations between, should be undertaken for other times of interest. Examples include; (a) the maximum of the "little ice age," about 1600 to 1650 (or 1820 to 1850) A.D.; (b) the interval of maximum warmth (hypsithermal) during the present interglacial, about 6000 to 7000 years ago; (c) the culmination of the Eemian (Sangamonian) Interglacial, about 120,000 years ago, when climates were warmer than today, (d) the late Miocene, about 6 to 7 million years ago, when the East Antarctic Ice Sheet is believed to have reached a size larger than now and (e) the later Cretaceous when both geography and climate were substantially different from later times.

WHAT IS NEEDED TO IMPROVE APPROACHES TO PREVIOUSLY INTRACTABLE PROBLEMS?

The objective of gaining a better basic understanding of how the climate system works will require a global network of samples and the integration of land and marine studies. It requires the reconstruction of an earth that is physically different from that of today. To do this we must not only determine past continental positions and boundaries, we must also find in the geological record indicators of the various components of the climate system. The criterion of having indicators of several parts of the system in a single section is met in the marine sedimentary record, but additional indicators of cryospheric and atmospheric conditions, as well as conditions on land, need to be incorporated. Such indicators should be developed to the point of providing quantitative estimates of past conditions. In this way an historical record can be extended meaningfully into the geological past, and its interpreted parts used to reconstruct climatic change.

Better support for development of new and improved sampling and analytical techniques could result in a new surge of advances in paleoclimatology. For example, the development and refinement of the piston corer and the radiocarbon method of dating virtually revolutionized the field, and the development of the oxygen-isotope paleothermometer has had a major impact. Other isotopic methods (*e.g.* carbon 12/13 ratios) need to be tested as stratigraphic tools, but their application must have a sound biological or geochemical basis. The availability of a device that would take a continuous undisturbed core 100 meters long could provide complete sequences through marine Pleistocene successions, while a simple and inexpensive method to extend reliable radiocarbon dating routinely to records older than 40,000 years would permit the calibration of paleoclimatic events over the most critical part of climatic history.

Another serious operational shortcoming is the communication gap between climatologists and geologists. On the paleoclimatological side, studies are commonly carried out by geologists, paleobotanists, or micropaleontologists who lack climatological backgrounds and generally work in isolation from climatologists.

Such a lack of communication is found in conventional sediment-sampling methods, in which short-term (<1000 years) climatic changes are likely to be obscured and the conventional expectation of gradual climatic change tends to be reinforced by imprecise data. The use of the smaller sampling intervals needed to define rates of change (1 cm or less, instead of the usual 5 to 10 cm interval) is limited only by cost and time. More detailed sampling could be encouraged by an informed interest in *rates* of climatic change and the prospect that they may be more rapid than supposed. The convention of spending little money on radiocarbon dating of late Quaternary pollen diagrams (frequently with gaps of 2000 to 3000 years between dated samples) leads to guesswork and interpolation of the chronology of climatic events, and subsequent errors in correlating events between regions. Support is needed for more adequate radiocarbon control. Still further refinement can be obtained from studies of tree rings or annually layered (varved) sediments where applicable, and from studying relatively undisturbed sediments such as prevail in areas of uninterrupted burial and in peat bogs.

Above all, we need to organize cooperative studies where, without submerging individual initiatives, specialists in the various relevant fields are brought together with generalists to define, articulate, and solve multicomponent problems in paleoclimatology and climate forecasting.

As for identifying rates of secular change and cycles that may prevail over long intervals of time, and perhaps discovering universal processes, attention might profitably be paid to the study of well-preserved tree rings in fossil woods of Tertiary and older age.

Possible new techniques for estimation of paleotemperature include the use of amino acid racemization and of variations in deuterium and carbon-13 content in tree rings and fluid inclusions in cave evaporites. If internal inconsistencies and conflicts can be resolved, such methods could generate a host of interesting new measurements. It has also been proposed that variations in solar activity may be reflected by the concentrations of NO_2, NO_3, and NH_4 in ice cores, and preliminary comparison of such variation in ice cores with sunspot activity is reported to be promising.

NATURE OF THE GEOLOGICAL RECORD OF CLIMATE

The instrumental record of climatic change is useful only for the past hundred years or so, depending on the locality. For earlier historical time, legal documents, ships' logs, manor records, and other written sources have been used in ingenious ways to work out synoptic climatic conditions for northwestern Europe and other areas. But studies of paleoclimatic history before the keeping of written records must be based on geological evidence, with which, as a special case, we include the results of tree-ring studies. The paleoclimatological analysis of tree rings has provided an ever-increasing amount of detail about climates of the last 7000 years in some areas, and it holds out the prospect of extending the record back an additional few thousand years. Other special cases include the oxygen-isotope records of cave evaporites. These may provide, by their regular increments of calcium carbonate, a history of past ground-water temperature, which presumably reflects average annual air temperature in some indirect way.

But the longest and most substantial geological records of past climates are contained in ocean-basin and lacustrine sediments, particularly those sections that are free of unconformities and other indications of discontinuities in sedimentation. Excluding the uncommon examples of annually laminated sediments, however, it is not ordinarily possible to calibrate such records on a scale of divisions of a year or a few years each. Not only are the sediments commonly mixed by burrowing bottom organisms to a depth of several centimeters, but the sample size necessary for most analyses may involve several decades of sedimentation. As a result, stratigraphic profiles delineated may not reflect high-frequency fluctuations.

Two requirements are necessary in reading paleoclimatology from the stratigraphic study of such materials: (a) the presence of biogenic, chemical, or physical components that have climatic significance, and (b) an adequate means of chronological calibration and control.

Many possibilities, nevertheless, exist for paleoclimatic interpretations of the fossil record. Methods and results are most convincing for the Quaternary (the last two million years), especially the late Quaternary. That is because during this range of time, fossil organisms may commonly be referred to modern species or at least to genera whose environmental requirements are known from modern ecological or taxonomic studies. For earlier epochs, much can be inferred about environmental conditions from the associations, morphology, and taxonomic affinities of fossil species and even genera that are now extinct.

The techniques of paleoecological stratigraphic analysis have been perfected in the study of deep-sea cores, where species of fossil planktonic animals and plants provide a detailed record of past changes in ocean surface waters, which in turn reflect contemporaneous climates. Similar techniques apply to pollen analyses of lake sediments, because the pollen content reflects the nature of the vegetation of the surrounding upland, and the vegetation in turn is generally a manifestation primarily of regional climate. Other microfossils in lake sediments may record conditions of level and water chemistry of the lake and thus the paleohydrology and regional paleoclimate.

On the chemical side, the stratigraphy of oxygen isotopes in the carbonate shells of certain fossils reflects the isotopic composition of the water and thus the integrated volume of glacial ice tied up on the land or, in preglacial times, the temperature of the ocean water. This method has been used extensively in constructing paleoclimatic time series from ocean-sediment cores, providing a detailed record primarily of continental glaciation during the late Cenozoic, or of ocean-water temperatures for earlier times.

A special type of stratigraphic record is the oxygen-isotope profile in glaciers. The most notable study yet available is for a core from northern Greenland, in which large changes in oxygen isotope ratios are believed to reflect mostly changes in volume of ice throughout the world and thus, indirectly, changes in world temperature during late Pleistocene and Holocene (Recent) time. Perhaps a third of this variation in oxygen isotopes, however, is related to ocean surface and adjacent air temperatures near Greenland. The time scale is estimated not by isotopic dating, but rather by the assumption of a specific rate of accumulation of snow and a depth-dependent flow rate for ice. The unique paleoclimatic record in ice sheets may have counterparts in regions other than northern Greenland, and these might be found if geochemical techniques other than oxygen-isotope analysis could be employed.

Besides stratigraphic studies, certain other geological approaches can occasionally be used in paleoclimatic investigations. Landforms of various types, such as coastal and river terraces, slope features, glacial moraines, weathering features, and lake strandlines, can provide information about paleoclimate. The principal problem in their utilization is the lack of materials suitable for dating by isotopes or other direct means--unless the landforms contain sediments, in which case they more properly fall under the category of stratigraphic materials. In some instances minimal ages for relatively young landforms (3000 to 1000 years or less) may be given by growth ring counts of trees, shrubs, or crustose lichens growing on them.

A catalogue of other geological features that have been used as paleoclimatic indicators can be very extensive. For instance, if volcanism is a climatic factor, then ash layers in a stratigraphic sequence qualify. Buried soils, redbeds, dune sands, evaporites, and glacial sediments all have paleoclimatic implications, even when found in pre-Quaternary rocks without geomorphic expression. Here, however, the chronology ordinarily must be based on traditional methods of biostratigraphic zonation. Only occasionally is material suitable for isotopic or paleomagnetic dating associated with such sediments.

Paleoclimatic reconstruction has proved particularly fruitful in recent years in areas and stratigraphic sequences having good potential for chronological control. The previously mentioned CLIMAP program for the investigation of deep-sea cores is an example of a comprehensive and intensive study of such sequences and areas. It has provided varied paleoclimatic data from the major ocean basins--enough to furnish the basis for calculating a numerical model of global climate at the climax of the last glaciation 18,000 years ago. Reconstruction of older Cenozoic and Mesozoic oceans can also be based on interpretation of the fossils and chemical components of marine sediments, with appropriate attention to boundary conditions for these more remote times.

Similar studies of very old lakes should be undertaken in order to obtain long uninterrupted records of terrestrial climates, using pollen analysis, sedimentology, and paleolimnology, with dating by the paleomagnetic method for the earlier parts of the record. Sites might be selected where continental or mountain glaciation leaves a record in the sediments, or where ash layers furnish an additional means of dating.

Not to be ignored in paleoclimatic research is concurrent investigation of geological processes that control the formation of different types of sediments and landforms, as well as of ecological processes that affect the geographical and habitat distribution of plants and animals of types that have been found in fossil form. It is only in this way that interpretation of prehistoric records can be properly disciplined. On the other hand, it must be appreciated that some ancient environments or assemblages of organisms lack good modern analogs because of the unique ecological conditions imposed by continental ice sheets in middle latitudes and the paleoclimatic or paleo-oceanographic side effects thereof. For example, major vegetational assemblages of the last glacial interval in North America may not be matched by any vegetation type existing today, and the associated larger mammal assemblage may also have been unique. Recognition of such limitations is important to ecological theory concerned with the stability of ecosystems and of vegetational associations.

Accordingly, the most substantial and most credible paleoclimatic research involves related studies of geological processes and ecological factors in the matrix of a knowledge of modern meteorological and climatic relations. Once these provisions are satisfied, the geological dictum that the present is the key to the past may be followed, and, by the use of transfer functions, the fossil data can be converted quantitatively to paleo-oceanographic or paleoclimatic data which, in an appropriate time framework, may in turn provide a key to the future. If a sufficient number of well correlated points is available, then paleoclimatic maps can be prepared for a given time in the past. A synoptic map is the preferred end product of much climatic research. The success of the CLIMAP program rests in part on the strategy that led to the preparation of paleo-oceanographic maps, for these provide most of the basic data for the model experiments that lead to the production of global paleoclimatic maps. A similar program has been designed to gather terrestrial paleoclimatic data through pollen analysis and to prepare paleoclimatic maps, although the quantitative transfer functions are more difficult to develop because of the greater variability of the terrestrial scene.

CLIMATIC CHANGE, FORCING FACTORS, AND THE RELEVANCE OF PALEOCLIMATOLOGY TO CLIMATE FORECASTING

Climatic change is unending. It has occurred throughout geological time. The forcing factors that create present and future climates are, in an important sense, a product of preceding terrestrial and solar-terrestrial evolution, and paleoclimatology can tell us something about them at all time scales.

Figure 1 suggests in a general way what some of the important forcing functions might be and the time scales at which they may operate.

The subsections that follow deal with the results of these forcing factors as they may be read from the geological record at different time scales, beginning with the past 100 million years and moving through ever shorter intervals to the past thousand years. Actually, the geological record includes substantial evidence of climate extending for more than two billion years into the past and worthy of study in connection with a comprehensive analysis of paleoclimatology. Here we limit ourselves to the last 100 million years as the shortest interval over which the effects of *all* the major forcing factors in climatic change can be observed.

THE PAST 100 MILLION YEARS

The ultimate objective in studying paleoclimate over a long span of time is to improve our skill in climate forecasting by developing a more adequate theory of climate. The record of the past 100 million years shows an irregularly varying change from the warm, apparently equable climate of Cretaceous time to the cooler, more variable

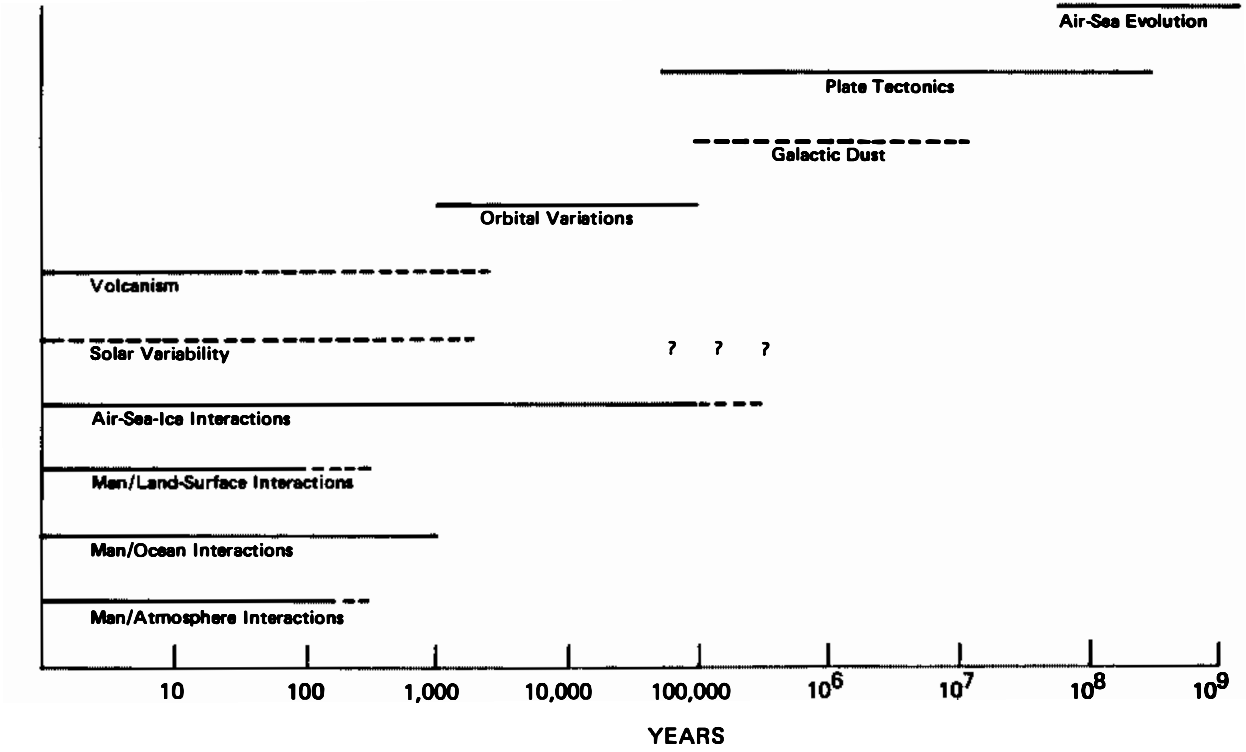

FIGURE 1. Time scales at which different classes of climatic forcing factors may be relevant.

one of today. It was a time of drifting continents and opening oceans during which oxygen isotope records from ocean sediments suggest long-term fluctuations with sharper cooling intervals at 28, 11, and beginning about 4 million years ago. The time involved is long enough for all important factors in climatic change to record themselves.

As suggested in Figure 1, the response time of the ocean is on the order of 1000 years; for continental ice sheets it is about 10,000 years, with changes in the solid boundaries to the fluid spheres taking 100,000 to a million years. The most pronounced changes in earth's climate have taken place on these time scales. If we are to learn exactly how the climate system behaves during such major changes, we must study the only record of them that is available to us--the geological record.

The major scientific opportunity is to stimulate past global climates quantitatively, using boundary conditions for running coupled atmosphere-ocean models of the climate system.

In order to make models of climatic change over such long intervals, however, one should ideally know the variations in time and space of all of the geological and biological variables or features of the environment listed below. In practice we do the best we can with what we have.

Important Variables of Oceans and Continental Shelves

1. Changing positions and dimensions of continents and ocean basins through time.

2. Areal extent of oceans and coastal plains as determined by the distribution of coastal and marine sediments.

3. Variations in faunal diversity and changing geographical distributions of marine organisms--distribution of tropical, temperatate, and coldwater assemblages; changes in benthonic fauna such as have been observed in benthonic ostracods and foraminifers.

4. Eustatic changes of sea level and evidence for rates of change.

5. The irregular cooling of ocean bottom and surface waters based on oxygen isotope ratios in marine sediments.

6. The changes in calcium carbonate and silica dissolution in the oceans since the Cretaceous.

7. Variations in ocean boundary currents evidenced by alternate periods of scouring and deposition on the continental slopes, changes in the distribution of planktonic microfossil assemblages, and areas of upwelling based on geological and paleontological evidence.

8. Types of sediment and rates of deposition of sediments along continental margins (to identify river systems), carbonate shelves, areas of evaporitic sedimentation, and the like.

9. Types and amounts of subsidence or uplift.

10. Specific ages and rates of submarine canyon cutting and erosion.

11. Distribution of organic matter for estimates of CO_2 fixation and distribution of oxidizing and reducing conditions.

12. Distribution and composition of submarine igneous rocks.

13. Quantitative geomorphological features significant for interpreting paleoclimate--direction of cross bedding, orientation of submerged sand dunes, indicators of tidal range, and so on.

14. Indications of glaciation such as ice-rafted pebbles and glacial-marine conglomerates (diamictites or mixtites).

Important Terrestrial Variables

1. Variations in floral and faunal assemblages as to geographical distribution, north-south temperature gradients, and biotic provinces.

2. Distribution, type, and timing of volcanic activity, volcanic sediments, and crystalline rocks.

3. Key features of mountain building and topography and their variations with time based on fossil plants and thickness and type of sediments.

4. Geochemical variations, based on such evidence as rock weathering or trapped samples of ancient atmosphere.

5. Location, orientation, and dimensions of lands and seas.

6. Paleoclimatological indicators comparable to items 8 to 14 above.

In order to model past climates quantitatively we need to define specific intervals of geological time for which we can map on a *global basis* geological and paleontological indicators such as those listed above. Our recommended approach for interrelating such variables is to analyze key cross sections which span the major oceanographic boundaries and include a number of continental to ocean settings around the globe and to prepare regional and eventually global maps of selected intervals of time based on such cross sections. The cross sections would utilize seismic sequences that are tied to shelf boreholes, deep sea cores, and regional geological data as well as paleontological and geochemical data. The maps should include data on thickness of sediments deposited during the time interval under study and be superimpsoed on a plate-tectonic reconstruction for that time. The final maps should show paleogeogrpahy and paleoecology and give quantitative estimates of environmental variables such as temperature, runoff, and intensity of circulation. From this information the boundary conditions for interpreting climate can be estimated, and paleoclimate can be interpreted directly or used as a data base for mathematical modeling in order to provide a more complete and at least partially testable picture of past climatic states. An appropriately prepared succession of maps such as described above would show changes in geological and paleontological factors related to climate and thus provide a synopsis of climatic change through time. This could provide valuable insights for the development of an improved theory of climate.

Models of this nature, whether quantitative or not, ought to provide the basis for reconstructing such aspects of paleoclimate as:

1. *Atmospheric particulates and the evidence they provide about atmospheric attenuation and circulation.* Variations in dust veils and sulfate particulates may be inferred from distribution of volcanoes and volcanic ash shown on paleogeographical maps. Dust storms could also be inferred from evidences of aridity and loess deposits. The position of the jet stream might be indicated, as it is in Japan for the lifetime of Mt. Fuji, by the elongation of ash fall deposits.

2. *Atmospheric chemistry*. Geological evidence of past atmospheric conditions includes geochemical information such as rock weathering, and, more rarely, trapped samples of ancient atmospheres themselves.

3. *Albedo*. Variations in vegetation and extent of land, snow, ice, sea, and fresh water as inferred from paleogeographic reconstructions can provide clues to the reflectivity of the earth's surface and its bearing on heat flux.

4. *Thermal mobility in the sea*. Major changes in the distribution of heat in the ocean and the nature of ocean currents can be estimated from paleogeographical maps displaying evidence for sea level stands, oceanic barriers and connections, and paleontological, sedimentological, and isotopic data derived from sea floor sediments.

5. *Thermal mobility in fresh water*. The location of major river systems can be postulated from the paleogeographical reconstructions and sediment types.

6. *Thermal mobility in the atmosphere*. The configuration of land and the distribution of mountain chains can also be estimated from paleogeographical reconstructions and sediment types.

In addition to providing data for the estimation of boundary conditions in model making, paleogeographical and paleoecological maps provide a means of checking the validity of models. Can the observed geological and paleontological features be explained by the model?

We find an understanding of climatic change over the past 100 million years--how the land, ice, oceans, and atmosphere have responded to changing boundary conditions--

to be an important step in the development of a theory of climate that is sufficiently comprehensive for climate forecasting.

THE PAST 5 MILLION YEARS

The history of the cryosphere over the past 5 million years is central to the understanding of climatic change. When we can show in detail what happened and understand why it happened, we will have taken a long step toward an adequate theory of climate and climatic variation. During this part of geological history, the planetary climate experienced a fundamental change, with the onset of a glacial regime characterized as it is today by extensive bodies of permanent ice at both poles. Exactly why (approximately 4 million years ago) the Antarctic Ice Sheet grew to the dimensions it has today is not yet known, however. Nor is it known precisely when the Arctic Ocean froze over or when the Greenland ice sheet developed, although those events clearly occurred within the interval under discussion. They would certainly have increased global albedo, abetting cooling trends, and they may have coincided with the growth of the Antarctic Ice Sheet.

Extensive glaciation at high latitudes began in the northern hemisphere about 3 million years ago. Since then the most striking features of climatic history have been the increase in the average volume of northern hemisphere ice sheets and the tendency, again not understood, for these ice sheets to fluctuate. As time went on, the amplitude of these quasi-periodic fluctuations increased, and the ice sheets extended into lower and lower latitudes during the glacial portions of climatic cycles. The increase in amplitude was accompanied by an increase in the dominant period. For about the last 700,000 years, the dominant cyclical period (also a major unsolved problem) has been about 100,000 years. Although it proves convenient to label these climatic cycles in terms of the extent of northern hemisphere ice sheets, their impact is global. As a result of them, marked changes are known to have occurred in the distribution of animals and plants, the circulation patterns of the atmosphere and ocean, the nature of the land surface, the extent of mountain glaciers, and, in the Antarctic, the extent of sea ice and the volume of the West Antarctic Ice Sheet.

Studies of the past 500,000 years suggest that a portion of the climatic variance over that interval is driven in some way by changes in the geometry of earth's orbit, but the mechanisms by which this orbital control operates are uncertain. A considerable fraction of the variance over this interval remains unexplained, and there is as yet no good explanation for the onset of the glacial regime or of the million-year-long trend of increasing variance.

There is good reason to believe that the systematic investigation of long geological time series inferred from soil and loess sequences, lake sediments, and deep-sea cores, where correlated paleomagnetically, could provide the information needed to attack these fundamental problems effectively. In particular, we need to know what the frequency, amplitude, and phase of oscillation of each major element in the climate system have been.

Knowledge of the synoptic climate pattern before and after the Arctic Ocean freeze-over and before and after the glaciation of Greenland may cast light on the natural sensitivity of this system, including the question as to what would happen to future climate if, as a result of atmospheric warming from CO_2 increases or other causes, the arctic sea ice were to disappear.

To obtain the necessary data, new field programs are needed in the Arctic Ocean, in high latitudes elsewhere, and in the southern hemisphere. To make such programs fully effective we also need new techniques for recovering undisturbed piston cores 100 meters (or more) in length.

THE PAST 150,000 YEARS

The challenge of the past 150,000 years is to understand how the climate system--including the atmosphere, the continental surfaces, the sea ice, and the surface and deep-waters of the ocean--responded during the last major glacial to interglacial cycle. Deep-sea cores record elements of this response with indicators of the nature of ocean surface waters, the deep ocean, global ice volume, and wind-blown detritus from land areas. Such records are sufficiently detailed to be sampled at intervals as short as 1000 years. A history of the last 150,000 years is also represented in several long terrestrial records recovered from lakes and bogs. The land records can be tied directly to the marine record by means of water-borne pollen found in near-shore marine sediment cores. Together these two histories can provide a comprehensive picture of global climatic change on a time scale comparable to the response times of the more slowly reacting components of the climate system such as ice sheets and the deep oceans.

The climate of this interval encompasses a complete glacial to interglacial cycle. It spans the last full interglacial episode, apparently one of the few times during the last million years when the climate was at least as mild as in modern times. The onset of such warm conditions, their fluctuations and disappearance, and the growth and decay of the continental glaciers are all registered in the sedimentary records.

The delineation of how the various components of the climate system behaved during this cycle is of prime interest. Preliminary studies suggest that a warming of sea-surface temperatures in high southern latitudes preceded the sudden collapse of the northern hemisphere ice sheets, which, in turn, came before warming in the low latitudes and changes in the chemistry of the deep ocean waters. This general picture does not hold for all areas of the oceans, however. In the subarctic Pacific, for example, changes in sea-surface temperature, global ice volume, and the corrosiveness of bottom waters with respect to $CaCO_3$ all appear to have occurred simultaneously.

Such data are sparse at present, but they are fundamental to two important ideas that might guide us in attempts to learn more about how the climate system works. First, because the marine record includes indicators of several different components of the system, all physically contained in the same samples, it provides us with an opportunity to delineate the sequencing of major changes in these components within the system, and therfore the likely hierarchy of interactions. Second, the data suggest a strong geographical dependence on how the various components of the system respond to forcing. Thus, in order to obtain detailed knowledge of how the system operates, the surface waters, deep waters, ice volumes, etc., should be treated as interrelated entities in a global climate model, not as separate variables. The global coverage of both the marine and land records needs to be greatly expanded and used to provide a clear picture of the regional differences in phasing and amplitude of each component's response to climate change. Aspects of such an expansion should respond to the need to fill gaps in existing coverage, guided by consideration of where the climatically sensitive areas are likely to be. Such global studies, moreover, should interact with others involving the use of general circulation models of the oceans and atmosphere in experiments designed to illuminate the mechanics of how such interactions might occur. A combination of approaches involving studies of time series, spatial reconstructions, modeling, and model testing offers much promise for a more basic understanding of the interactions within the climate system and mechanisms of long-term climatic change.

THE PAST 15,000 YEARS

The last 15,000 years encompass the interval during which the earth recovered from the last glacial age and entered a climatic mode similar to that of the present. Climatic extremes during this time ranged from glacial to full interglacial, apparently representing a change in mean global temperature of about 5 to 6°C. About 18,000 years ago continental ice sheets and mountain glaciers were close to their maximum size. But major changes in earth's climatic regime close to 14,000 years ago led to a fluctuating retreat of glaciers worldwide, a corresponding rise of sea level, and revegetation of deglaciated terrains.

Major oceanographic changes also occurred during this interval, among the most marked being the northward retreat of the North Atlantic polar water mass. Following an interval of maximum warmth and dryness in temperate latitudes between about 9000 and 5500 years ago, a series of small-amplitude climatic reversals led to a succession of "little ice ages" marked by minor advances of alpine glaciers, shifts in the boundaries of vegetation zones, and fluctuating lake levels. Radiocarbon dating of glacial deposits and analyses of tree-ring and ice-core records suggest that three widespread culminations of this type occurred at intervals of about 2500 years, implying a possible periodicity of climatic variation in that range.

The kinds of geological investigation that provide the basic data for interpreting paleoclimatic variations and constructing time series for the last 15,000 years include stratigraphic and isotopic studies of glacier, lake, and marine cores, pollen analyses, tree-ring analyses, and glacial-geological studies. Although a general outline of paleoclimatic events can be inferred from existing data, a global synthesis of Holocene climatic variations and evaluation of possible periodicities of climatic variation is hampered by: (a) a paucity of data from certain key areas of the world, especially the tropics, the high Arctic, central Asia, and the southern hemisphere; (b) by our present inability to obtain independent calibration for radiocarbon ages older than 7000 years before the present; and (c) by an insufficient number of local and regional quantitative estimates of past temperature and precipitation to permit broad regional syntheses.

Major opportunities for paleoclimatic research in this time frame result from the possibility of sampling geological and biological records of past climate at short time intervals with sufficient temporal resolution to permit evaluation of recurring climatic events of short period (<3000 years). Although fluctuations of alpine glaciers, ice cores, tree rings, and pollen-spectra have provided most of the relevant time series thus far, other useful records with comparable time resolution may exist--the racemization (or epimerization) of amino acids, for instance. Because the range of climatic conditions during the Holocene includes climatic states that might be expected to recur within the next few centuries, reconstruction of Holocene climates can provide reasonable analogs of expected future climatic conditions.

Indeed Holocene paleoclimatic data are already sufficiently numerous and reliable, both for some major ocean regions and for some large land masses, that synoptic reconstructions at time intervals of 1000 or 2000 years are now being attempted. Such reconstructions can indicate the direction, character, and magnitude of climatic changes and point out where important paleoclimatic proxy data are missing.

THE PAST THOUSAND YEARS

Although brief by geological standards, the record of the last thousand years is important for the development of criteria for climatic forecasting. It records conditions of the atmosphere, oceans, and cryosphere similar to those now prevailing, but encompassing significant climatic variation on time scales of years to centuries. Because such variations represent the most probable natural climatic states to be expected in the immediate future, better understanding of their causes should be sought. The last thousand years was also a time during which increasingly detailed records of past climatic variations and their impact on man's environment become widely available from a variety of sources, including tree-rings, stratified ice sheets, historical records, and from pollen stratigraphy, geochemical evidence, and sedimentological and other properties of annually layered sediments in lakes and certain near-shore oceanic basins. Because of their high resolution in time, down to individual years or even seasons, such records permit study of variability of the order of 1 to 100 years, and the accurate estimation of rates of climatic change. The end of this interval is also the critical interface between records of contemporary geological events, observations of climatic, other geophysical, geochemical, and astronomical variables, and the data sets that record such variations. This is important for purposes of calibration and for testing hypotheses that require instrumental data unavailable for earlier times.

This wealth of known and potential data calls for assimilation and integration in the form of interpretive climatic models that, on the one hand, can be used for prediction of future climatic trends and, conversely, can be tested against older records of climatic variation.

ROLE OF MODELS IN PALEOCLIMATOLOGY

Scientific models include a very broad range of idealizations of the natural world, both qualitative and quantitative. In this report we use the term climatic model in a more restricted sense to refer to mathematical formulations of the physical and chemical processes which determine earth's climate. Models now being developed range from one-dimensional radiation-convection models that neglect all variations with latitude and longitude to very general three-dimensional models that take account of the redistribution of heat by the motions of the entire fluid envelope of the planet.

A critical evaluation of the results produced by climatic models to date indicates that, although this field is highly promising, it is still in its infancy. Current models tend to be highly biased to the present state of the atmosphere. For example, rainfall distribution predicted by some models is remarkably accurate. A more detailed examination, however, shows that the rainfall is closely tied to sea surface temperature, which is specified as an external condition in the model. In spite of problems of this kind in the interpretation of the results, climate models are widely recognized as one of the best tools available to us to probe the mechanisms that control climate and to predict what changes can occur in response to external conditions.

Examples of the type of practical problems that have been studied by climate models include the effect of changes in aridity of the sub-Sahara caused by changes in surface albedo, the effect of sea-surface anomalies in the Arabian Sea on monsoon rainfall over India, and the expected effect of CO_2 buildup on global temperature and rainfall.

Generally the amplitude of climatic variations increases with the length of time considered. For this reason the geological record of climate offers a unique means of testing climate models. The CLIMAP program is an example of the effectiveness of collaboration between climate modelers, geologists, and paleontologists. More recent and more remote periods of geological time offer similar opportunities. In particular the Late Mesozoic and the Early Cenozoic offer unique problems for scientists interested in ocean circulation because of the very different goemetry of the contemporaneous ocean basins. We anticipate that this field of research will receive a considerable impetus as more students are trained in both geophysical modeling and the interpretation of geological records.

BOUNDARY CONDITIONS

The climate system is driven by energy from the sun that is stored primarily in air, water, and ice. The principal boundary conditions of the climate system are the incident energy (sunlight), the albedo, and the topography of lands and bathymetry of oceans. Geological events (volcanism, continental drift, mountain building) can change some boundary conditions. And evidence for changes in most or all of the boundary conditions can be sought in the geological record. Geology therefore has a role in suggesting geological-geophysical-geochemical forcing functions that can be tested by models and in providing evidence for large past changes in boundary conditions that can, in turn, be used to test the validity of models.

A climate model may be thought of as a complex input-output device. In a model of earth's heat balance the energy received from the sun is the input. Predicted temperatures are the output. For a fluid dynamical model of the atmosphere or the ocean the inputs are the specified boundary conditions, but the exact boundary conditions required depend very much on the details of the particular climate model being considered. The more general the climate model, the fewer the boundary conditions required and the greater the number of fields that can be considered as output. Generality in a climate model, however, involves a concomitant complexity, and there is a need for a wide range of approaches. As a specific example, if the atmosphere alone is included in a climate model, sea-surface temperature must be specified as a boundary condition. If the climate model includes both the ocean and the atmosphere, sea-surface temperature can be an output of the model to be verified against independent data from the geological record.

Joint efforts are needed by specialists in many disciplines to build up the data sets needed and to test the models against the geological record. The data needed for boundary conditions must be on a global scale. Reliable results will require a coordinated international and multidisciplinary effort.

Variables that the model builder might incorporate include the following:

1. *Earth's surface topography and its effect on atmospheric circulation and wind flux.* A primary input to even the most general climatic model is the configuration of the ocean basins, the location and orientation of the lands, and the location and approximate elevation of major mountain chains that affect atmospheric circulation through frictional drag and pressure differences. Methods have been worked out to reconstruct the paleobathymetry of the oceans. The outlines of epicontinental seas and the elevations of highlands are often more uncertain, but fair approximations are possible. Wind directions and force may be approximated for some intervals of time based on sedimentary criteria, given suitable plate-tectonic reconstructions. Assuming that the volume of ocean water has remained the same, detailed records of sea-level changes determined from continental-margin sediments will provide useful cross checks on reconstructions of global bathymetry.

2. *General oceanic circulation and its effect on heat flux.* Large quantities of heat are stored and transported in oceanic currents. Evidence for major past changes in the distribution of the heat and the nature of currents comes from geological evidence of past extent and depth of seas; from paleontological evidence for past oceanic water masses, barriers, and connections (*e.g.*, a Tertiary Atlantic-Pacific connection through Panama); and from paleontological, sedimentological, and isotopic evidence of past ocean temperatures in sea-floor sediments. Ancient marine sediments also contain evidence of sediments rafted by ice.

3. *Runoff of fresh water as a factor in ocean circulation.* Major river systems can in some instances affect ocean circulation and the distribution of global heat, particularly those that discharge into arctic seas. It has been postulated that during recession of the Laurentide Ice Sheet, the Mississippi River discharged much more fresh water into the Gulf of Mexico than is now carried by the Amazon. This could have had a major effect on the density distribution of waters in the Gulf of Mexico and the Gulf Stream.

4. *Paleotemperature.* Global maps of surface temperature are needed as input and also for verifying climate models. Boundary conditions require quantitative data sets, but more qualitative information based on land plants and animals can be very useful. Foraminifera, Radiolaria, and Coccolithophoridae, for instance, have been used by the CLIMAP group to obtain estimates of sea-surface temperature. The relation between sea-surface temperatures and microbiological assemblages is used to reconstruct global temperatures at 18,000 years before the present. Because organisms evolve, this method must be applied with great caution to remote geological times. Oxygen-isotope ratios in calcareous fossils, however, provide a paleotemperature record that should become increasingly more precise with improvements in methods, instrumentation, and base line.

5. *Albedo of land and water surfaces.* Leaving out the effects of clouds, the albedo of land surfaces depends on vegetation, extent of snow and ice, and soil moisture. The albedo of water depends on impurities, temperature, and extent of sea ice. Some of the most general climate models may attempt to predict surface albedo, but most models require albedo estimates as a lower boundary condition for the model atmosphere. For the last 20,000 years, estimates of albedo can be made with some confidence, but in more remote times albedo must be inferred from more indirect evidence and is thus increasingly uncertain.

6. *Particulate matter in the atmosphere.* Sunlight is ordinarily attenuated by particulates in the atmosphere. Dust veils from major volcanic eruptions that discharge ash into the stratosphere reduce sunlight at earth's surface, and some evidence suggests that atmospheric cooling accompanies or follows such eruptions. Volcanic sulfate particulates may cause a significant effect. The geological record can provide a perspective on the relative

effects of natural versus man-caused particulates in the atmosphere.

7. *Atmospheric gaseous absorption.* Changes in minor components of the atmosphere which can alter its transmissivity (including water, ozone, and carbon dioxide) are affected by geochemical processes such as rock weathering and the combustion of fossil fuels. Geological evidence of past atmospheric chemistry must be sought.

GEOLOGICAL RESPONSES TO CLIMATIC CHANGE

The Problem of Lag

Because many geological and biological processes are controlled to some extent by climate, a significant change in climate can set in motion a host of changes that can occur at different rates. Thus, while different climatic indicators in the resulting geological record may indicate corresponding changes in climate, these changes may not all date back to the same moment in time. This is the phenomenon of retardation, or lag in response. Recognition of this factor is important in the correlation of stratigraphic sequences of different types, or in the definition of subdivisions of the Quaternary based on the geological record of climatic change (*e.g.* the Pleistocene/Holocene boundary).

Perhaps the most "instantaneous" record of climatic change is the oxygen-isotope stratigraphy of the Greenland ice core. Here the only lag presumably involved is the time of travel of air masses from the place of ocean-water evaporation to the location of snowfall in northern Greenland. The spreading of a glacier from its source region to its terminus, however, may take thousands of years, in addition to the preceding time required for the snow to build up to such a thickness that it will flow as glacial ice. The reverse process--the retreat of the ice front in response to climatic change--may be much more rapid, provided the climatic change involves an increase in summer wastage rather than a decrease in winter snow-fall. If the reverse is the case, then the lag factor involved in the flow of ice from distant sources to terminus must be considered. But even in ice wastage an important lag is represented simply by the extra atmospheric heat required to transform ice to water.

In any event, some glacial features may actually date from times considerably later than the time of climatic change. The lag effect is well illustrated by the fact that stagnant glacial ice buried in a moraine or beneath glacial outwash may persist for thousands of years after the retreat of active ice from the region. Thus a lake that might eventually form on the moraine or outwash plain when the buried ice melts out and the surface collapses may contain basal organic sediments much more recent than the climatic change that caused the retreat of the ice and construction of the moraine. Because such sediments often provide the only material suitable for radiocarbon dating, the problem of lag is acute in establishing a glacial chronology.

Eustatic changes in sea level match the growth and retreat of continental ice sheets and are subject to similar elements of lag. Isostatic changes in sea-level and the level of postglacial lakes reflect an additional lag resulting from the slow rate of subcrustal flow that gradually brings about the isostatic adjustment.

Biological factors set in motion by climatic change include the geographical distribution of plants and animals. Numerous studies of the pollen stratigraphy of lake and bog sediments in northwestern Europe have shown that the late-glacial fluctuations in the retreat of the Scandinavian ice sheet were matched by contemporaneous changes in some components of the vegetation. A substantial history has been developed about environmental changes during this important time. But it has been found that a lag is involved in the migration of trees in particular, as the landscape became reopened to vegetation, compared to aquatic plants, which have mechanisms for more rapid dispersal (*e.g.*, by shore birds). Recent work in this area implies that fossils of some of the ground beetles found in these early deposits also record temperate climatic conditions significantly before the upland vegetation shifted to a temperate mode.

Another illustration of the lag effect is seen in the pollen sequence of the Holocene vegetational succession in eastern North America. Here the climatic change at the end of the Pleistocene set off a series of plant migrations from refuges in the Appalachian Mountains. But the trees migrated at different rates, so that southern New England, for example, received successive invasions or population expansions of oak, hemlock, hickory, and chestnut. As far as can be determined from regional studies, these migrations were not controlled by contemporaneous climatic change but rather depended on such nonclimatic variables as seed dispersal, soil conditions, forest disturbance, competition, and other factors. Thus the pollen zones that are recognized in southern New England and adjacent areas are not necessarily a reflection of contemporaneous climatic change.

Recognition of the problem of lags in the stratigraphic record is important in paleoclimatic studies. Quantification of the process depends on two basic approaches. The first requires precise chronological control on numerous sites with well dated and carefully studied sequences. In pollen studies, any attempts to transform pollen-stratigraphic records to a climatic sequence and then to prepare maps of past climates must await full understanding of the regional relations and the possibilities of migrational lag. The second approach calls for a geological record that contains indicators of several elements of the climate system. In this case the requirement for a detailed chronology is less strict. The phasing of changes implied by different indicators can be detected and measured by detailed sampling and study of a single sequence. Spatial variation in this phasing can be delineated by studying similar sections from many different localities.

The Case of Carbon Dioxide

The concentration of CO_2 in the atmosphere is increasing today by about one part per million per year. Various estimates have been made of CO_2 level before the current increase began. Most of these estimates assume that the level was essentially constant before the burning of fossil fuels in large quantities beginning about 150 years ago. Estimates of atmospheric CO_2 concentrations for the time before the era of fossil-fuel-burning range between 275 and 290 ppm.

There is no reason to assume that this earlier concentration was constant except the general faith that at this time the natural cycling machine, like a balanced ecosystem, was in a steady state. The question is thus raised: "Was there indeed a steady state, and, if so, what controlled the level of CO_2?"

The chief perturbers of atmospheric CO_2 before man were probably variations in the terrestrial biomass and the rates of burial and erosion of sedimentary carbon. Increase in biomass or burial rates of carbon would remove CO_2. Decrease of biomass or oxidation of sedimentary carbon would add CO_2. The size of the terrestrial plant biomass and the rates of burial and oxidation of fossil carbon are functions of many variables. At the height of a glacial advance the biomass will be much less than that in the middle of an interglacial, a variation that could cause substantial variations in atmospheric CO_2. The situation is complicated because a change in CO_2 could well have feedback with respect to the size of the biomass. According to existing mathematical models of the atmosphere increases of atmospheric CO_2 are expected to cause an increase in average global temperatures, other variables being constant.

So what are the major long-term controls of atmospheric CO_2? Fluctuations of CO_2 storage through time among terrestrial biomass, oceans, soils, sediments, and atmosphere could well take place, but the system is constrained by negative feedbacks. Too much biomass-stored CO_2 would slow photosynthesis and remove CO_2 from the oceans, in consequence of which CO_2 would become a limiting nutrient. Storage presumably has never lowered atmospheric CO_2 below the photosynthetic cut-off of about 100 ppm for most plants, or one-third the present level. On the other hand, limitation of biomass by other nutrients, such as phosphates and nitrogen, would increase CO_2 in atmosphere and oceans. Estimates of the range of fluctuation are not well grounded. For the higher atmosphere they range from perhaps 100 to 2000 ppm, depending on the size of the terrestrial biomass (the oceanic biomass is small relative to the terrestrial biomass).

The controls of biomass fluctuation, as indicated above, are many. What are possible inorganic controls of CO_2? Most obvious is the reaction between calcium-silicates (during weathering) and CO_2 to form calcium carbonate and silica. Continued reaction between atmospheric CO_2 and a calcium-silicate crust would lower atmospheric CO_2 to about 10 ppm, far below the level required for significant plant growth. Thus an earth with an initial charge of CO_2 in atmosphere and ocean might react with the crust to lower CO_2 below the level necessary for life. Obviously the atmospheric CO_2 level has not dropped so low. The only ways out of the dilemma currently suggested are to add CO_2 continuously from earth's interior by metamorphism of limestones to calc-silicates by classical tectonic processes, or perhaps by continuous addition of juvenile CO or CO_2 through volcanism.

A major effort is needed to model the sinks and sources of atmospheric CO_2. Long-term trends of temperature could be related chiefly to balances and shifts of CO_2 consumption in the surface system versus CO_2 additions to the surface from hot zones at depth. Levels of CO_2 before the coming of man are not known, however, nor are the controlling variables understood.

The rate of change in CO_2 concentration caused by the influence of inorganic sinks, such as reactions with calc-silicates in crystalline rocks, is too slow to cause more than a percent or two change in atmospheric CO_2 in a hundred years. On the other hand, under extreme conditions it could influence climate measurably within historic time (a few thousand years).

MODEL EXPERIMENTS

In this section we consider a few problems that are being attacked jointly by mathematical modeling and field studies. These problems are given by way of example only and are not meant to indicate priorities. We also do not wish to make any prejudgements about the best size of efforts, which may be large or small depending on the project.

As an example of a productive effort we have the CLIMAP project. Global data are being combined from several sources to provide surface boundary conditions for climatic models for 18,000 years before the present. These data include estimates of sea-surface temperature based on the fossil record in deep-sea cores, as well as estimates of albedo over land based on evidence of glaciation and the fossil record for land vegetation. Preliminary results of the modeling calculations have now been published. They show that different climate models may give rather different results on the data for 18,000 years ago. This is an important albeit somewhat negative conclusion. Beyond this the models indicate the probably very great influence of sea surface temperature during the ice ages on the precipitation patterns of the tropics and subtropics.

One of the most important problems in climate involves the transition from the relatively mild climates of 80 to 100 million years ago to the cold climate of the last few million years, in which significant portions of the globe are covered with ice even during interglacial times. One of the most significant lines of evidence is a new and growing body of oxygen isotope data from the deep sea. Although these data are subject to problems of interpretation, which are only gradually being cleared up, cross checks with previous qualitative estimates of temperature from the fossil record are encouraging. The oxygen isotope and other data point to the startling conclusion that the deep ocean was much warmer than now during most of the last 100 million years. This suggests that the deep ocean circulation and the role of the ocean in the heat balance of this older earth was dramatically different from what it is today.

If, as some evidence suggests, the general chemistry of the earth's atmosphere varied little over the last 400 million years, the very different ocean of 80 to 100 million years ago would probably be attributable to the different configuration of continents and oceans of that time, and particularly the relatively small amount of then emerged land relative to water. This hypothesis can be tested using climate models, and a small-scale effort has already begun. If repeated numerical experiments with climate models do produce the warm ocean noted in the fossil record, then the hypothesis that continental drift alone can explain the major shifts in climate observed is probably correct. If, on the other hand, the models are *not* able to produce a warm ocean for this 80 to 100 million year interval, we may be forced to look for other forcing factors such as a changing composition of earth's atmosphere or variations in solar radiation.

As a third example, we can cite the problem of ocean geometry and the climate of the southern hemisphere. Deep-sea drilling is producing evidence for the gradual evolution of the Antarctic Circumpolar Current as blocking continents gradually moved out of the way and the Drake Passage opened. The Circumpolar Current is the closest analog in the ocean to the atmospheric jet streams. The strong thermal gradient that forms along the Circumpolar Current suggests that it acts as a barrier that climatically isolates the Antarctic Continent from lower latitudes. Studies of the geological record which define the position of past water masses, the development of oceanic fronts, and the nature of circulation can be coordinated with model studies to provide a possible means of assessing the causal factors. Such a study, aimed at reconstructing past oceans based on geological data (Cenozoic Paleo-oceanography or CENOP) has recently been funded by NSF. Should it turn out that the resolving power of the geological record is inadequate, however, climatic models that include oceanic as well as the atmospheric variables may suggest where new drilling sites should be located to provide the critical tests.

SOME PRIORITIES IN PALEOCLIMATOLOGICAL RESEARCH

The nine priorities proposed below are intentionally general rather than specific and selected rather than comprehensive. Although some specific suggestions are also made our intent is only to provide some broad guidelines for interim action and study pending completion of a more comprehensive and more deeply probing analysis of needs and opportunities by a more representative group than ours. The demand for climate forecasting, nevertheless, has become urgent under the pressures of increasing populations and the ever-growing industrialism, expansion of mechanized agriculture, and burning of fossil fuels. At the same time the potentiality of geology for understanding climate is limited by deficiencies in methods and support to which attention should be drawn now. Being aware of a developing interest in paleoclimatological research and support within the National Science Foundation and some other federal agencies, we commend the suggestions below to their attention.

1. *A greater degree of multidisciplinarity and international cooperation is essential in realizing the maximum scientific and practical benefit from paleoclimatological studies.* The subject is global in its data base and applications and extremely broad in scope. Paleoclimatologists and climate dynamicists need to meet and work together and with associates in the many other relevant disciplines. Nations and regions need to integrate their efforts. Climate dynamicists and oceanographers should be involved in the study proposed in the recommendation below and paleoclimatologists and geochemists should be represented on the Climate Research Board. International efforts in paleoclimatology should be fostered through the International Council of Scientific

Unions and the National Research Council's Commission on International Relations.

Workshops or other means should be considered to promote an effective interchange between theoretical modeling groups on the one hand, and investigators gathering and interpreting paleoclimatic data on the other. We are impressed with the opportunities that appear to be ripe for evaluating various response mechanisms (*e.g.* the role of sea ice) and for testing possible forcing functions (including volcanic, orbital, and resonance effects).

2. *Improvement of the time calibration of paleoclimatological events is urgently needed.* Convenient and inexpensive routine methods of higher precision and resolving power are needed, particularly for events older than 40,000 years and younger than 250,000 years ago. Resolution down to the individual year or shorter is available over the last few thousand years from varved sediments and tree rings, but additional methods for giving similar resolution to a larger and longer range of climatic events would vastly improve rate determination and the prospect of valid climate forecasting.

3. *A concerted effort is required to relate marine and terrestrial records of climate and its variation, particularly by means of long, continuous, datable sequences.* This is needed generally, but an immediate and specific need and opportunity exists for comparison of the data obtained by the CLIMAP project (Climate/Long Range Investigation Mapping and Prediction) with data from detailed sequences of the last 18,000 years elsewhere, above all in the interior of North America and in coastal basin sequences where a mixture of marine and terrestrial microorganisms might be found. But even existing cores, from the Arctic Basin, for instance, are short, few, and rather random. A program is needed for obtaining longer cores, more of them, and in paleoclimatologically critical locations--both at sea and on land. An effort is also needed to develop criteria for discriminating between areas formerly covered with sea ice and those covered with ice shelves.

4. *An active program of search for and study of long, continuous data-rich sequences in high latitudes, the tropics, the southern hemisphere, the Asiatic USSR, China, and central Asia generally is essential to fill gaps in*

the global data base. Long paleoclimatic time series are needed that can be correlated and dated by radiocarbon, paleomagnetic, or other methods.

5. *Sampling techniques, instrumentation, and facilities need improvement.* A means for taking numerous continuous, undisturbed, 100 meter cores would be a major step forward, and longer cores would be even better. Finer scale sampling of sediments datable to the nearest year or fraction of a year at the point of sampling should be a goal of high priority. The more the sampling and analytical systems can be automated, the more refined the models can be made and the more time there is to think about their meanings. Better facilities would assist the work of many current workers and will be needed for an expanded paleoclimatological effort. With every extension of the data base and in particular the datable range of time, and with every improvement in precision of dating methods, the resolving power of the models is correspondingly improved.

6. *Upgrading the training and expanding the manpower base available for paleoclimatological research and problem solving is needed.* In addition to a thorough background in the traditional sciences, the paleoclimatologist of the future should have a good operational knowledge of (or work in close association with persons skilled in) climate dynamics, mathematical modeling, solar terrestrial physics, and micropaleontology. If the problem of climate forecasting is to be resolved before the next major climatic change, a much more adequately staffed effort will be needed.

7. *The need for and uses of data banks call for review.* We have an ambivalent feeling about data banks. We are aware that they tend to become data dumps and to remove the pressure for evaluation and synthesis from the eager researcher who fears that funds for field work and laboratory analysis may be cut off at any moment. Nevertheless data banks can serve an important function if intelligently planned, operated, and used. We think it likely that one or more data banks would be a useful resource for climatic forecasting models. But we are not inclined to urge the establishment of such facilities on the basis of our limited collective knowledge. We suggest, therefore, a special study to evaluate the potential uses of and need for a special data bank or banks in

paleoclimatology and to recommend what if any action should be taken.

8. *Time scales of operation should be specified and the limitations, applications, and merits of each clearly recognized.* Despite some emphasis on the special relevance of the record of the last 1 to 15 thousand years in forecasting near-term climatic changes, we strongly endorse active research programs at all time scales here discussed. Each has something unique to say about climate genesis, a process that lies deeply rooted in the past and whose understanding at all levels is relevant to foreseeing the possible courses, rates, and intensities of future climatic changes. Understanding, for instance, how the world warmed up again beginning about 25 million years ago, after the relatively cool Oligocene climates, may well be very germane to understanding how climate responds to processes that take place on time scales of 1000 to 1,000,000 years. The full potential effect of continental drift with accompanying separation, convergence, and flooding of lands and parallel changes in areas and connections of oceans and draining of shallow epicontinental seas is not adequately displayed on a time scale of less than about 100 million years.

RECOMMENDATION

We recommend that a Committee on Geoscience and Climate (COGAC) be organized within the National Research Council. The task of COGAC should be: (1) to assess the state of the art, and to monitor and to stimulate progress in geological aspects of climatic research; (2) to evaluate comprehensively and in detail the research opportunities in, the operational needs of, and the scientific and societal relevance of geological and geophysical processes affecting the understanding of climate and climatic forecasting; and (3) to recommend the appropriate geological content of a national and global climate program.

The membership of COGAC should be appropriately representative within manageable proportions. It should include persons competent in paleoclimatology at a range of time scales. Specialties represented in some way, not necessarily on a one to one basis, should include micropaleontology, dendrochronology, isotopic and other aspects of geochemistry, soils science, hydrology, the geomorphology of terrestrial surface processes, glaciology, volcanology, solar-terrestrial physics, quantitative modeling, meteorology, climate dynamics, and oceanography. It ought also to be reasonably well balanced in the sense of including or in some conscious way providing for discussion with competent representatives of opposing views as well as qualified representatives not only from academia but also from the relevant federal, private, and industrial research institutions.