Climate models

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To predict future states of the atmosphere one must evaluate the complicated interactions between air, sea, ice, land and powerful external forces.

The great social and economic impact of the weather continues to fuel the age-old quest for a way to predict future meteorological conditions. Enormous payoffs in areas such as agriculture, health and energy use await improved climate forecasting. Greater knowledge of the climate system would also contribute to our understanding of a wide range of phenomena—from the causes of the ice ages to the effects of decreased stratospheric ozone.

Meteorologists have always dreamed of predicting weather and climate in detail on all time and space scales. Beginning in the early 1940s, a steady

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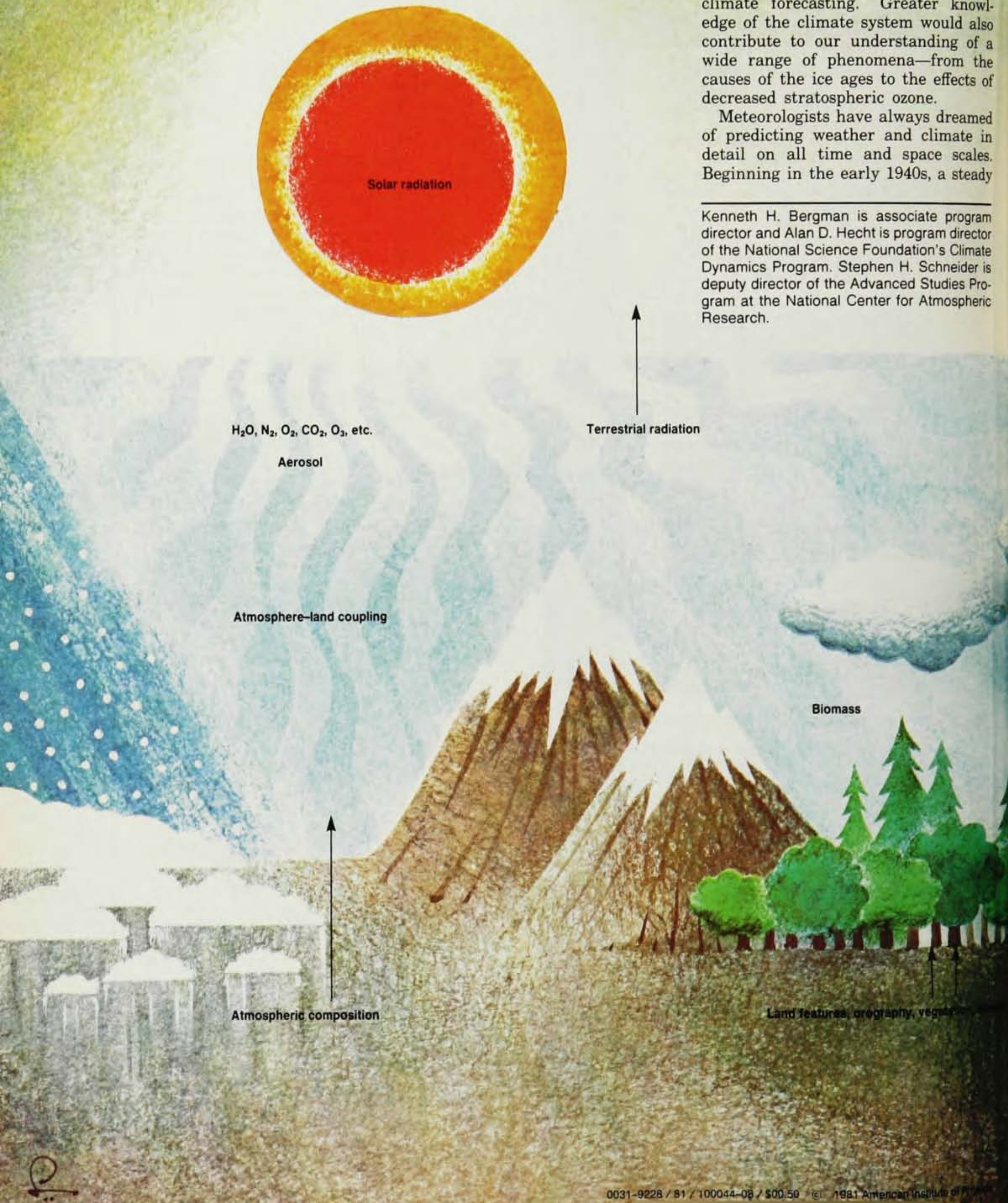


0031-9228 / 81 / 100044-08 / $00.50

stream of scientific observations and research has given forecasters demonstrable skill in predicting daily weather events as much as 10 days in advance.[1] While our ability to extend daily predictions further into the future is not now apparent, there are indications that we may be able to predict prevailing weather for intervals longer than 10 days. The problem of climate prediction is basically one of determining the prevailing weather or, more generally, the prevailing condition of the climate system over an extended interval of time, even though the day-to-day fluctuations are unpredictable.

Although the terms weather and climate are sometimes used interchangeably, there are important distinctions between them. The weather, for our purpose, is the condition of the atmosphere at a particular time, reported as completely as possible with present observing capabilities. Modern weather prediction is the attempt to forecast a future state of the atmosphere from a specified initial state by applying the fundamental physical laws of the atmosphere. Since the current limit of daily weather prediction is ten days or less, we will limit our use of the term "weather prediction" to this period.

Climate is the average state of the atmosphere associated with the weather during a period of time covering at least several days. Thus, we speak of the climate of a month, season, year or decade or even longer period of time. Climate is usually defined by the mean conditions and by some measure of the variability or fluctuation, such as a standard deviation for a time period, but it is not concerned with the details of these fluctuations. In many problems of interest, the difference between two mean climatic states is considerably smaller than the standard deviations of each of them. As a result, the difference between the mean states may be difficult to determine from observational data. Similarly, predictions of small changes in the mean state are made difficult by the presence of much unpredictable "noise."

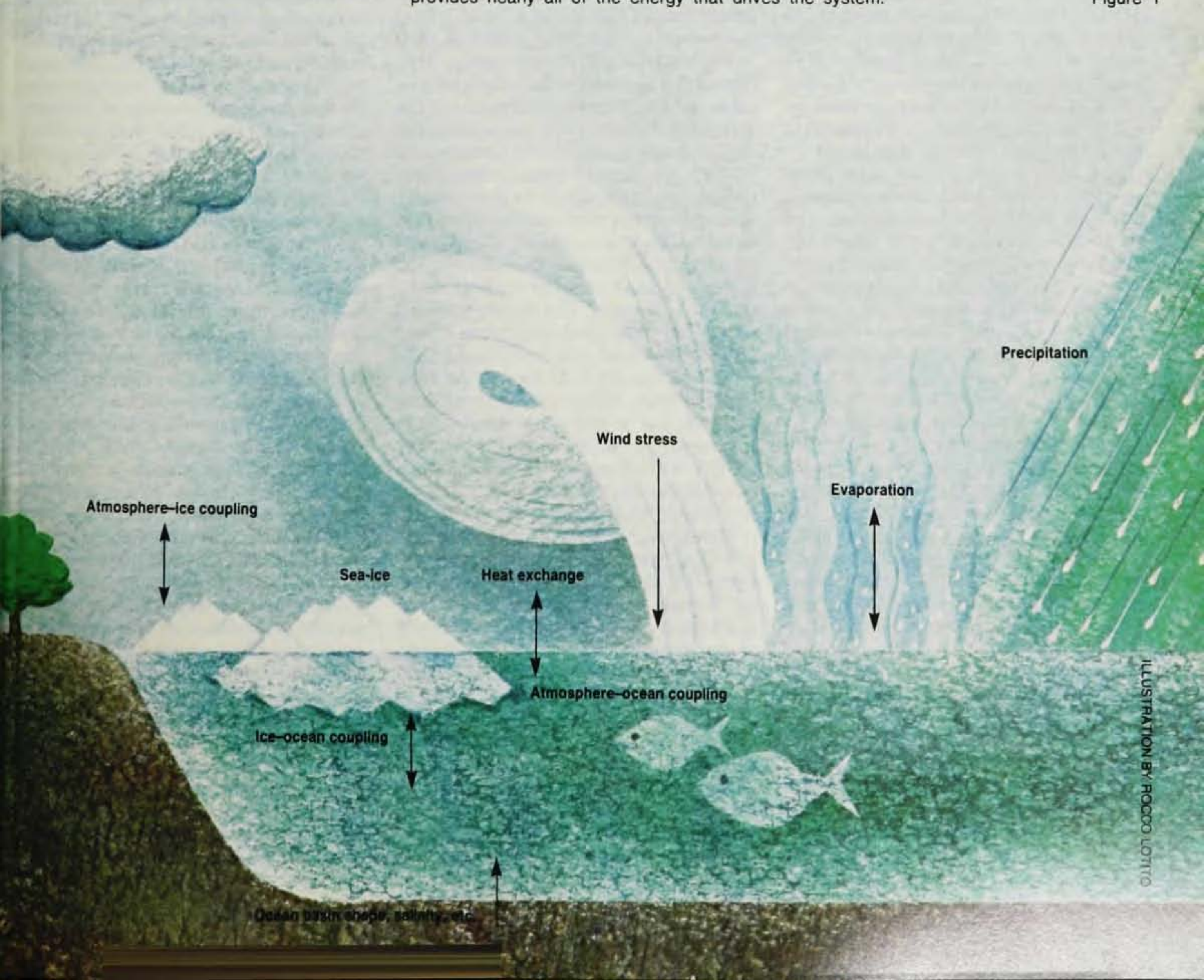
Although the same physical laws apply to both climate and weather prediction, the climate problem is complicated by the need to consider complex interactions between (as well as changes within) all the components of the Earth's climate system—the atmosphere, oceans, land and surfaces of ice and snow (cryosphere). For a successful weather forecast, it is not necessary to consider, for example, the small day-to-day changes in ocean temperature or circulation. But such changes, affecting the lower atmosphere, become important when predicting atmospheric changes from one season to another. Similarly, variations in the geometry of the Earth's orbit occur on a time scale that is important when analyzing climate changes over thousands of years, but these variations are clearly negligible when considering seasonal climate changes.

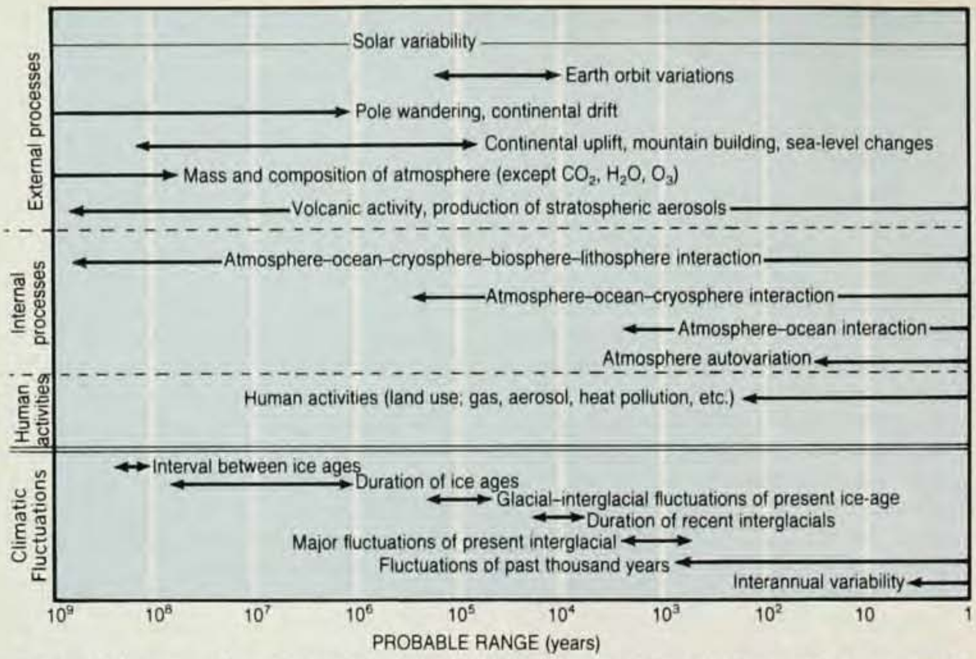
In this article we will describe the components of the climate system and the causes of climate change. Then we will discuss climate prediction, focusing on the use of numerical models.

The climate system

As mentioned above, there are four

The climate system. The atmosphere, oceans, land and ice are the four major components of the Earth's climate system. Various interactions are shown in this sketch. Solar radiation provides nearly all of the energy that drives the system. Figure 1





Time scales at which various forces act to change climate, and time scales of climatic fluctuations.[2] Both natural and anthropogenic processes are given. Figure 2

major interacting components of the physical climate system (figure 1).

▶ The atmosphere and the oceans are two fluid components of the system, each containing organized circulating patterns, less organized eddy motions and comparatively random turbulence. They react on very different time scales to any given perturbation. Interactions between and within them occur on many scales and tend to be concentrated in regions close to their common boundary as well as internally in those zones where gradients of physical properties, such as temperature or density, are large.

The composition of the atmosphere also affects the climate state. Aerosols, dust, amount of carbon dioxide, and ozone distribution directly affect the atmosphere's absorption and transmission of solar radiation, which provides virtually all of the energy for the entire system. Additionally, aerosols and dust may affect the formation of clouds and the processes of precipitation. Similarly, the salinity of ocean waters has a marked effect on their circulation.

▶ A third component of the climate system is the cryosphere, which includes the extensive ice fields of Antarctica and Greenland, other continental snow and ice, and sea ice. Continental snow and sea ice vary seasonally and produce large annual variations in continental heating patterns and upper ocean mixing. The large continental ice sheets do not change rapidly enough to cause seasonal or yearly climatic anomalies, but they clearly play a major role in climatic changes on the scale of tens of thousands of years—changes such as the glacial and interglacial cycles that have occurred repeatedly for at least the last one million years.

▶ The land and the biomass it supports constitute the fourth component of the climate system. This component includes the slowly changing extent, position and orography of the continents and the more rapidly varying characteristics of lakes, rivers and vegetative cover. Thus the land and its biomass are variable parts of the climate system on all time scales.

The climate system thus involves the interaction of the air, sea, ice and land components, with solar radiation providing nearly all of the energy that drives the system. Variations of gaseous and particulate constituents of the atmosphere, along with changes in the earth's position relative to the sun, act to vary the amount and distribution of radiant energy received by the system. The unreflected portion of that energy drives the atmospheric circulation, which in turn is linked by means of wind stress and heat transfer to the circulation of the oceans. The atmosphere and oceans are both influenced by the extent and thickness of the ice covering the land and sea as well as by the land surface itself. Since each of these components has a different range of response times, the whole system must be viewed as continuously evolving, with some parts of the system lagging or leading other parts.

The system also contains feedback loops between the interacting components. These amplify (positive feedback) or damp (negative feedback) perturbations. For example, any increase in the area of polar ice or snow cover will cause more of the incoming solar radiation to be reflected, leaving less to be absorbed by the surface. This will result in a lowered surface temperature, favoring further increase in ice and snow cover in a positive feedback loop, assuming that the availability of moisture for snowfall remains adequate. However, we would expect the increasing snow cover and associated coldness of a continental interior to gradually limit the overlying atmosphere's ability to import moisture into the region. This would eventually result in decreased amounts of snowfall and would limit further growth of the snow cover in a negative feedback loop.

Changes of climate

Several processes that potentially cause fluctuations in climate, and the time scales with which they act, are shown in figure 2. The figure illustrates that climate may be affected by several processes acting simultaneously or in sequence. The large number of factors affecting climate means that the system has a large number of "degrees of freedom." The problem of climate prediction is one of accounting for the effects of the processes in figure 2 and of understanding the relative importance of each process for a wide range of time and space scales.

On the scale of seasonal and interannual variability, anomalous patterns of sea-surface temperatures may be important in affecting atmospheric circulation and producing climatic anomalies.[3,4] Anomalous sea-surface temperatures of the Pacific can be used to predict with some degree of success anomalies in mean seasonal temperature and precipitation in the 48 states. However, the relationships between ocean temperatures and the climate are intricate and contain feedback loops whereby the ocean's effects on the atmosphere, or vice versa, are amplified, suppressed or appear in unexpected ways.

Other climatic variations are correlated to some extent with natural processes, but the actual physical relationships involved are not always clear. For example, the approximately 20-year cycle of drought in the Great Plains region of interior North America appears to correlate with the "double sunspot cycle"—corresponding to one cycle in the reversing solar magnetic field.[5] However, the role of sunspots in affecting solar energy output and the resulting effect on the earth's atmosphere are not well known. Moreover, climatic fluctuations on this time scale in many other parts of the world do not correlate well with sunspots. (See PHYSICS TODAY, September 1975, page 19.)

Variations in solar luminosity not necessarily related to sunspot activity have also been postulated as causing climatic change. However, sufficiently accurate measurements of solar luminescence are a by-product of the "space age" and hence have not yet been available for a long enough time to indicate whether or not they correlate with fluctuations in climate.

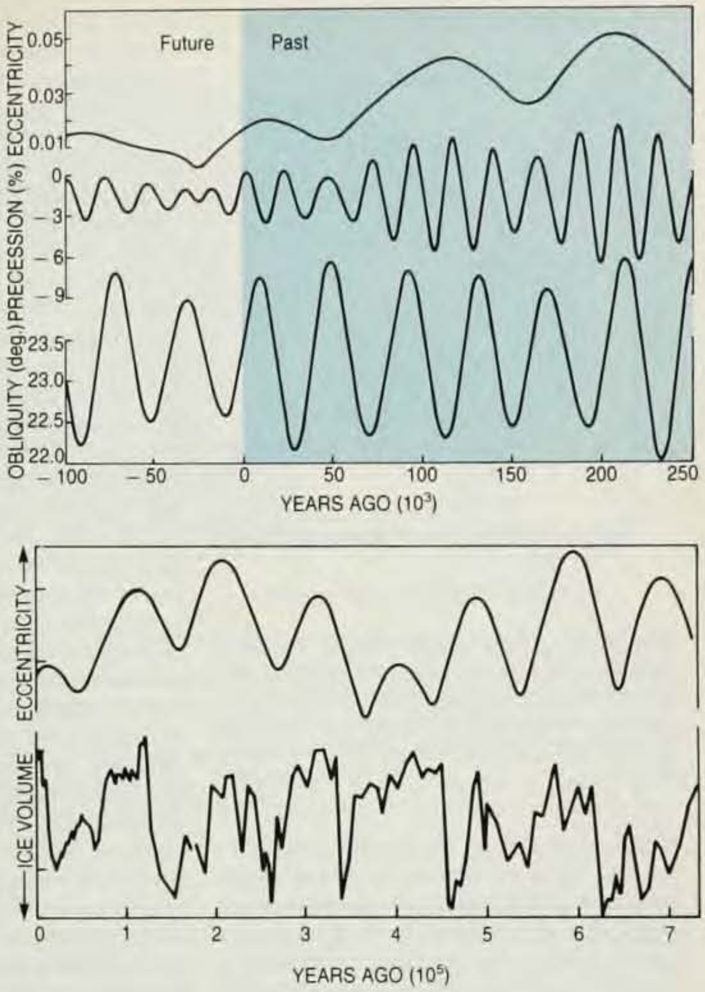
Researchers have attributed climatic variation on scales up to hundreds of years to long-term variations in solar sunspot activity[6] and to changes in atmospheric opacity, mainly due to injection of dust from explosive volcanic eruptions,[7] though the evidence for these causes is not clear.

In addition to these "natural" causes, scientists now suspect that human activities may be altering climatic patterns in significant ways. For example, some suggest that overgrazing in the marginally arable Sahel region of Africa has increased the reflectivity of the surface and lowered the absorption of solar radiation, causing reduced surface temperatures and rainfall in that area and perhaps aggravating the persistent drought conditions of recent years.[8] A similar process of "desertification" may have occurred in the Indus River valley of Pakistan, where an area formerly occupied by a great civilization is now empty desert.[9]

Of concern for the immediate future is increasing evidence that atmospheric concentrations of the trace gases ozone and carbon dioxide are being changed by human activities. Although these gases are present in very low concentrations, they are extremely efficient absorbers of solar radiant energy (ozone primarily in the ultraviolet and carbon dioxide primarily in the infrared), thus any substantial changes in their amount are very likely to have a significant effect on the atmosphere's radiative balance and hence on climatic conditions. Current projections of fossil-fuel consumption suggest that a doubling of atmospheric carbon dioxide may occur by the year 2050 or thereabouts.[10] What effect would this have on world climate?

In an attempt to answer this question, researchers have run numerical climate models with atmospheric absorptivity corresponding to present carbon dioxide levels and also to doubled and quadrupled levels. Comparisons of the results indicate warming of the atmosphere, although the predicted temperature increase varies considerably among the models. On the average, the models suggest an increase of 2 or 3 °C in the globally averaged surface air temperature for the doubling of carbon dioxide. However, primarily because of the melting of sea ice, some models predict temperature increases of as much as 10 °C in portions of the Arctic region. The models also suggest that the temperature changes will be accompanied by changes in atmospheric circulation and regional precipitation patterns. Clearly, there will be significant changes in the world's climate if such predictions come true.

However, a high degree of confidence in the preditions of these models is premature. The model results differ widely in magnitude, mainly because of differing assumptions about the physical processes and interactions being modeled. Also, the present models contain known oversimplifications and inaccuracies, due partly to incomplete understanding of some of the physical processes and partly to inability to include all relevant physical details realistically in a model of manageable size. Finally, the verifiable ability of models to reproduce current climatic conditions is no guarantee that they will successfully predict changed conditions. In order to improve climate model predictions, more realistic numerical descriptions of climate processes are needed, as are improved methods for indirect verification of the predictions.



Orbital characteristics and climate. The upper three curves show variations in the eccentricity and obliquity of the Earth's orbit, and variation in the precession of the equinoxes expressed as a percentage deviation from the mean 21 June Sun–Earth distance. The lower curves compare the Earth's eccentricity with climate of the last 730 000 years, as deduced from isotopic measurements of ocean sediment core samples.[12] Over the last million years, ice ages have recurred with an approximate period of 100 000 years. Figure 3

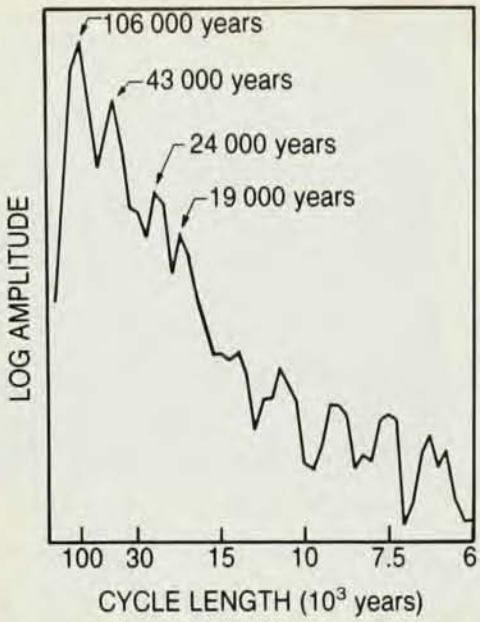
The most dramatic climate changes of all, the "ice ages," have recurred approximately every 100 000 years over the past one million years or so (figure 3). Although much climatic variation remains unexplained, one of the success stories is the identification of episodes of glaciation with changes in the earth's orbital and axial characteristics, which determine the seasonal and latitudinal distribution of solar radiation intercepted by the earth. Variations due to precession of the earth's axis, changes in the obliquity (tilt) of its axis and eccentricity of its orbit occur with periods of 23 000, 41 000, and approximately 100 000 years. James D. Hays and coworkers have identified these frequencies in the paleoclimatic record shown by the time series of geologic data preserved in ocean core sediments[13] (figure 4). Clearly, orbital variations have played an important role in causing these major oscillations in climate. (See PHYSICS TODAY, May 1977, page 17.) However, feedback between glacial ice and the other components of the climate system has undoubtedly modulated the glacial oscillations in their magnitude and rate of growth.

The orbital-parameter variations indicate, and the deduced temperature trends of the last 10 000 years suggest, that the earth's climate has already experienced the warmest temperatures of the present interglacial period and for the last 6000 years has been gradually cooling toward a new ice age. Barring man-induced climatic change, this long-term cooling trend is expected to continue for several thousand years and to eventually result in a reestablishment of extensive continental glaciers in the Northern Hemisphere.

Prediction of climate

We have discussed some of the known or suspected causes of variation in climate. We have also mentioned that a significant portion of climate variability is inherently unpredictable. Why is this so?

The atmosphere–earth–ice–ocean system is highly complex. Although in principle we can describe this system by known physical laws, in practice it is virtually impossible to do so in any complete sense. First, the possible



Frequency spectrum of climate variations over the last 500 000 years, as deduced from ocean sediment cores. Three of the spectral maxima correspond closely with frequencies of variation in the Earth's orbital characteristics.[13] Figure 4

scales of motion in the system (and here we are thinking primarily of the atmospheric and oceanic components) range from the submolecular to the global. Second, there are interactions involving energy transfers among the many different scales of motion. Finally, many scales of disturbance are inherently unstable; small disturbances, for example, grow rapidly in size if conditions are favorable. The result, at least for the atmosphere and oceans, is that seemingly small differences between two very similar atmospheric states can lead to widely divergent conditions later.

Thus, to make reliable long-term predictions of future atmospheric behavior, even on the larger scales, initial conditions in the entire atmosphere would have to be known in excruciating detail and with great accuracy. In practice, this is not possible. Consequently, scientists are resigned to the fact that they will never be able to predict atmospheric behavior exactly. The basic limitations on numerical weather prediction are the resolution and accuracy of data that describe initial conditions and the fact that numerical models can predict the larger scales only approximately in the absence of accurate information about the smaller scales. Similar limitations apply to detailed modeling and prediction of oceanic circulations. Numerical predictions based on approximated initial conditions thus have a component of uncertainty ("noise") that gradually becomes dominant as the prediction is extended in time.

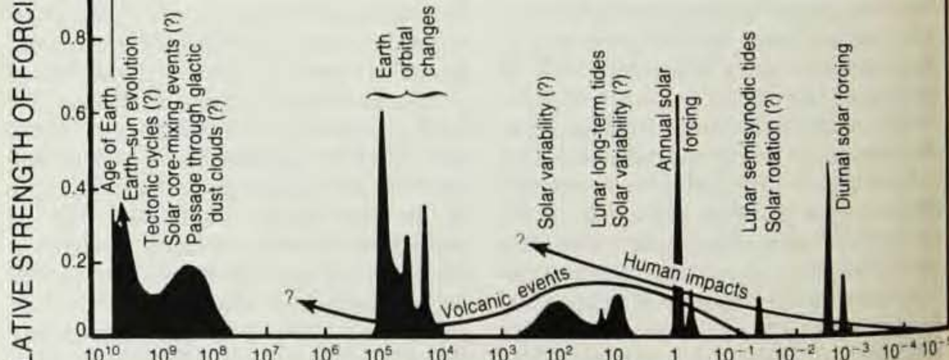
As mentioned earlier, meteorologists have found from theoretical considerations and from practice that useful prediction of day-to-day weather beyond about 10 days is not possible using currently available observations. Does this mean that climate prediction is a hopeless task? Interestingly, the answer is no. There are several reasons why prediction of climate, in contrast to weather, is feasible for comparatively long time periods in spite of the above limitation.

For one thing, although day-to-day weather is not predictable very far in advance, it turns out that we can have some success in predicting average conditions for an extended period. Similarly, we can predict some measure of the day-to-day variability within the time interval. The situation is approximately analogous to the statistical-mechanical theory of gases: Although we cannot predict the behavior of individual molecules, we can predict quite accurately the expected mean state and variance about that mean of an ensemble of molecules. It so happens that, although the movement and development of individual weather systems are highly variable and difficult to predict very far in advance, the global-scale wavy pattern of atmospheric circulation (the "jet stream" and its meanders) frequently shows a high degree of persistence or predictable change over periods of a few weeks to a month or more. Similarly, the broad-scale circulation of ocean currents shows a high degree of persistence even though the movement of individual eddies within these currents is highly variable.

The fact that the climate system is subject to forcing processes that may be of overriding importance for some time scales is another reason that climate predictions for longer periods may be possible. An obvious example is the annual variation in the global distribution of incoming solar radiation. Because of the great strength of this forcing, the seasons follow each other in a highly predictable manner, though differences (anomalies) in the character of a season are noted from year to year. (It is these anomalies that are most economically important and most difficult to forecast.) Less obvious but nonetheless important sources of forcing include the relatively slowly changing (compared to the atmosphere) ocean surface temperatures; the geographical distribution of land, sea, mountains, and ice-covered surfaces; changes in solar energy input due to solar variation and the previously mentioned orbital variations of the earth; changes in the gaseous constitution of the atmosphere or solute constitution of the oceans; changes in atmospheric turbidity associated with vulcanism or other sources, and changes in reflectivity of the earth's surface and atmosphere.

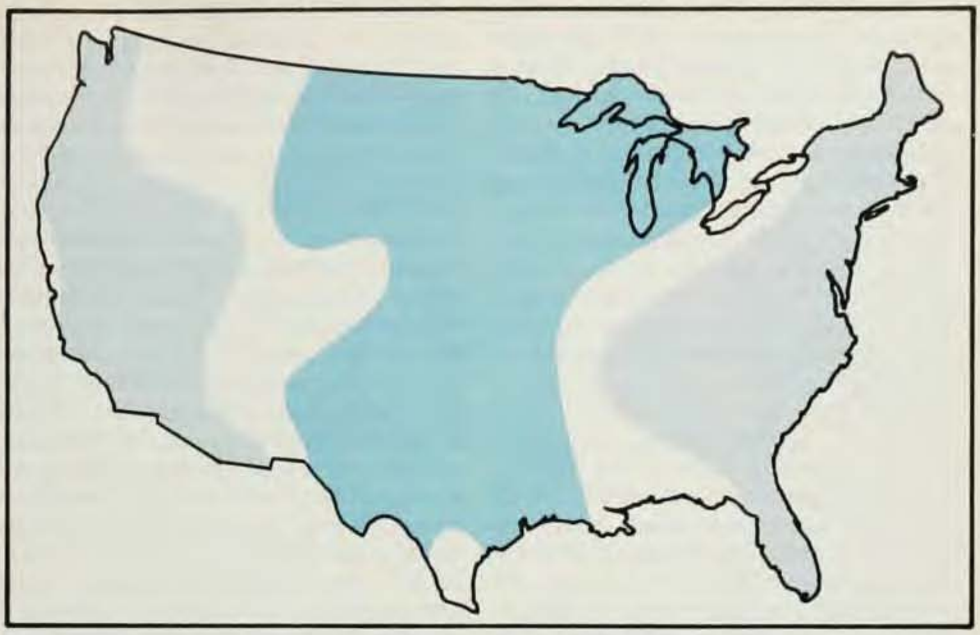
Some of these forcing mechanisms are highly predictable whereas others, such as volcanic activity, are largely unpredictable given the current state of knowledge about them. Also the atmosphere is forced by some mechanisms, oceanic surface temperatures for instance, that themselves respond gradually to atmospheric forcing, resulting in compicated feedback processes. These kinds of interactive processes are commonly referred to as internal forcings, in contrast to the relatively straightforward external forcings by mechanisms acting independently of the climate system. External forcing mechanisms and the time scales on which they act are illustrated schematically in figure 5.

In any event, the presence of forcing implies that some aspects of climate may be predictable on those time scales where the forcing and its effects are important. In fact, one would expect the degree of climate response, hence predictability, to be closely related to both the amplitude and the period or, for aperiodic cases, the time-scale of the forcing. This is true for external forcing except for modifications induced by feedback and resonance within the climate system. It is generally less true for internal forcing, where interactions can lead to internal oscillations in the climate system, producing unexpected



Schematic partitioning of causes of climate variation into components associated with external forcing processes. Time-scale of impact on climate ranges from minutes to the age of the Earth.[14] Figure 5 responses.

Finally, for many of the longer time scales, the climate system appears to respond mainly to the currently existing "boundary conditions" and to have little memory of its history. In other words, the climate system appears to be almost in an equilibrium state for these time scales. As a result, climate models that simulate the equilibrium resulting from specified boundary conditions, rather than models that predict future states from initial conditions, are used for many problems.[15] However, the validity of such equilibrium models depends crucially on the existence of a unique equilibrium state for the given boundary conditions, an as yet unproven assumption for the earth's climate system. Theoretical studies suggest that the system may have more than one equilibrium state under certain conditions. One school of thought maintains that some climatic changes, the glacial–interglacial oscillations of the Pleistocene, for example, are at least partly due to transitions between two coexisting equilibrium states.[16]



Map showing seasonal outlook for the expected average temperature in September, October and November 1981. This autumn forecast shows areas where the probability is 60% that the average temperature will be above normal (light color) or below normal (dark color). The unmarked area is indeterminate (that is, as likely to be above normal as below normal). The 1941-1970 seasonal average is taken as the normal temperature. The map was issued on 28 August 1981 by the Climate Analysis Center of the National Weather Service, National Oceanic and Atmospheric Administration. Figure 6

Models of climate

Climate prediction is essentially a process of extrapolation. We attempt to determine the future behavior of the climate system from knowledge of its past behavior and present state. There are basically two ways of doing this. One is to use empirical statistical methods, such as regression equations, with past and present observations to obtain the most probable extrapolation in time. The other approach is to do the extrapolation with equations representing the physical processes that govern the behavior of the climate system. The latter process is what is usually meant by the term "climate modeling."

The statistical approach has its uses, but they are limited. Statistical methods require the existence of an adequate sample of climatic events that can be correlated both spatially and temporally. Thus, for example, since reasonably detailed data on Northern Hemisphere atmospheric circulation patterns are available for approximately the last 50 years, we can generate statistical correlations relating winter circulation to the antecedent autumn circulation.[17] These correlations may have some predictive value when they are applied to independent data on seasonal climatic behavior. However, this is a "black box" approach, in that the statistics do not tell us anything directly about the physical processes involved—although they may suggest that certain physical processes are climatically important. Hence, reasons for the success or failure of such a prediction are difficult if not impossible to determine, making it difficult to improve future predictions. Nevertheless, marginally useful predictions of seasonal climate for the United States (figure 6) are obtained with the aid of statistical methods by the National Oceanic and Atmospheric Administration's Climate Analysis Center, by Jerome Namias of Scripps[3] and by others.

Since the statistical approach is dependent on historical data, it is obviously limited in its ability to predict climatic conditions that have not been previously observed. The statistical method cannot answer "What if?" questions, such as the potential effects of increased atmospheric carbon dioxide on climate. Thus, the more promising approach to much of the climate prediction problem is climate modeling.

Rather than giving a detailed discussion of the various kinds of models and their individual design problems we will discuss some design features that are common to all models. First, the distinction between internal and external forcing may be intentionally different in a model from that in the real climate system. For short-term prediction, for example, slowly-varying quantities such as sea temperature may be assigned fixed values or may be prescribed to vary in some preassigned way. The sea temperature thus becomes either an external forcing quantity or a fixed boundary condition for the atmosphere, and the model is thereby simplified. Even for longer-period predictions, we may want to use such a model in a diagnostic sense by arbitrarily changing one or more climate variables—ice cover and planetary albedo, for example—and determining the response of other climate variables.

Models can be ranked in a hierarchy with respect to both type and degree of resolution. Simpler models may compute the spatial distribution at equilibrium of a single key climatic parameter, usually temperature, as a function of latitude, elevation in the atmosphere, or both. Such models are primarily concerned with changes in gross climatic conditions that occur when the climate system's near-equilibrium between energy gain and loss is changed to some other equilibrium state. These models are quite simple in design but give useful information about the sensitivity of the climate system to changes in variables such as solar radiation and planetary albedo. Also, they help in interpreting the results of more complex models.

The most elaborate models depict several climatic quantities for all three spatial dimensions and indicate their variations in time. These models are commonly referred to as "general circulation models," since they explicitly simulate the major features of atmospheric circulation (and, for interactive models, ocean circulation as well) using dynamic principles. General circulation models predict future conditions from given initial and boundary conditions. The expected future climate is the result of averaging over a suitable number of these individual realizations. In predictions extending over a sufficiently long period of time, the model may "forget" the initial conditions and respond only to the fixed or varying boundary conditions, although this is not inevitably the case.

Whatever the resolution of the model, we must incorporate implicit representations of each climate process that is smaller in space- or time-scale than the resolution of the model unless we can determine that such a process is unimportant for the particular model or application. These representations, which link such "sub-grid-scale" processes to those resolved by the model, are referred to as "parameterizations." The realism of the results depends strongly on how successfully these parameterizations are made. For example, the details of radiative energy transfer within the climate system cannot be treated explicitly in even the highest-resolution general circulation models, but their cumulative effect on the resolvable climate variables is nevertheless important. Therefore, we must represent this effect in some statistical or empirical way that is compatible with the model's resolution and, we hope, realistic.[19]

There are several other physical processes that we also frequently parameterize in climate models. These processes include vertical sub-grid-scale convection in the atmosphere, cloud formation and precipitation, vertical mixing in the upper layers of the oceans, some aspects of heat and momentum transfer between atmosphere and ocean, heat and momentum transfers carried out by unresolved eddy circulations in both the atmosphere and the ocean basins, and some aspects of the interaction between the atmosphere and ice or snow surfaces. The simpler models are highly parameterized; nevertheless, these parameterizations, although crude, can lead to useful results that are compatible with the model's resolution and intended capability. More elaborate models, on the other hand, specify the physical and dynamical processes of climate more explicitly. Nevertheless, all models require the parameterization of important processes that occur on unresolved scales.

We have alluded to the fact that a component of the total climate variation is a result of physical processes that cannot or need not be modeled deterministically. Some models take these variations into account by assuming that they are random about their mean values. These so-called "stochastic models" yield probabilistic as well as deterministic predictions about the climate.[20]

Accuracy

In the more elaborate models, the baggage of complicated interactions, detailed parameterizations, stochastic variations and the like may require a formidable amount of computation, even for the present generation of high-speed computers. The modeler may be able to simplify, or even omit, a climate process in a model by first determining the sensitivity of the model (and, we hope, the climate system) to changes in the specification of the climate process.[21] For example, because ocean temperatures and currents respond relatively slowly to atmospheric forcing, the use of mean atmospheric conditions for a period of a month or longer is usually sufficient when modeling the atmosphere's effect on the oceans.

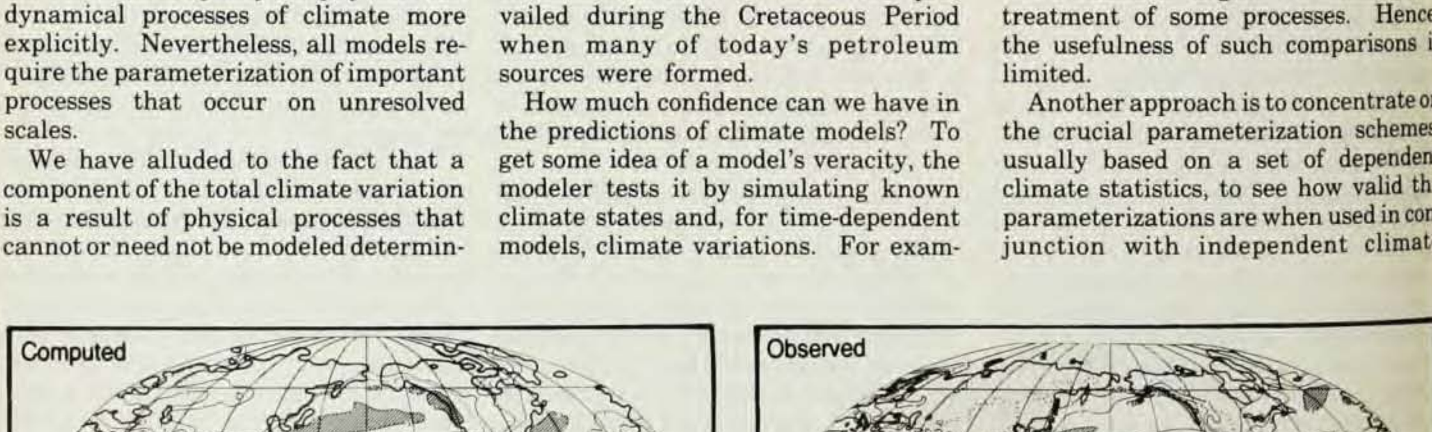
The kinds of problems that climate models are designed to tackle are numerous; we have already mentioned some. They include forecasting monthly and seasonal climate, determining the apparently natural variation of climate from one year to the next and determining the interactions between climate conditions in different parts of the world—such as between the tropical Pacific Ocean and North America. Additional problems include determining the potential effects of increased atmospheric carbon dioxide, volcanic dust and other pollutants on global and regional climate, verifying or disproving current theories about the causes of the ice ages and reconstructing past climatic conditions such as those that prevailed during the Cretaceous Period when many of today's petroleum sources were formed.

How much confidence can we have in the predictions of climate models? To get some idea of a model's veracity, the modeler tests it by simulating known climate states and, for time-dependent models, climate variations. For example, a longitudinally-averaged, energy-balance model should be able to reproduce the current latitudinal variation of surface air temperature when given the current climatic inputs and boundary conditions. On the other hand, a time-dependent general circulation model should be capable of reproducing with reasonable fidelity the regional asymmetries and seasonal variations found in almost all climate variables (see figure 7). In general, of course, the "climate statistics" of the model should agree closely with those of the real climate system.

It is not so easy to evaluate a prediction when, because of a change in one or more boundary conditions, the prediction is for climatic conditions significantly different from those that currently prevail. If the prediction is for a past climatic state, say the last ice age, we can compare the prediction with what we know from available paleo-climatic data. Clearly, if the model cannot reproduce at least the major features of the paleoclimate, it is in error; however, a successful prediction may be accidental and by itself does not establish the validity of the model. Therefore, we must perform many such tests in order to establish confidence in the model.

Predictions about future or conditional climate states are even more difficult to evaluate. Comparison of predictions from two or more models with significantly different parameterization schemes or methodologies may be useful. Our confidence in a prediction is higher when it arises from more than one model. However, predictions frequently correlate better with each other than with the verifying conditions. This merely indicates that climate models often have similar errors arising from common neglect or inadequate treatment of some processes. Hence, the usefulness of such comparisons is limited.

Another approach is to concentrate on the crucial parameterization schemes, usually based on a set of dependent climate statistics, to see how valid the parameterizations are when used in conjunction with independent climate



Prediction and observation. General circulation model prediction and observed mean rate of precipitation for winter conditions (December, January and February). (Courtesy of Syukuro Manabe, Princeton University.) Figure 7 data. For example, a moisture parameterization "tuned" to give the observed mean annual cloud cover should also be capable of producing the observed cloud cover for the extreme seasonal months of January and July.[22] The more "universal" the parameterization appears to be over the observed range of climatic conditions, the more confidence one has in using it over a wider range of conditions.

For shorter-term predictions, such as monthly or seasonal forecasts, we can evaluate the capability of a model in simulating real climatic conditions and use the results to improve subsequent performance. We can use recurring nonrandom errors to correct predictions empirically and to suggest ways in which we can improve parameterizations and models of physical processes. However, the validity of the verification of a prediction is dependent on the accuracy and completeness with which actual conditions are observed. There is a need for better global coverage of all the components of the climate system.

In summary, it is difficult to evaluate the performance of climate models, especially for conditional predictions such as those concerning effects of increased carbon dioxide. The fact that a model is successful in reproducing the current climatic situation is no guarantee that it will be equally successful in predicting a climatic state which is a marked departure from current conditions. Modelers are always tempted to "tune" the adjustable parameterizations in their models in order to get a successful simulation for a particular problem. In so doing, however, they may unwittingly make the models less meaningful for a wider range of conditions.

The future of prediction

From the foregoing, it is apparent that it is not realistic to expect meterologists to produce highly detailed and accurate climate predictions that are valid far into the future. On the one hand, climate models are "resolution bound", meaning that many processes occurring on small scales in the climate system can neither be detected by the current or any foreseeable observing network nor resolved by practicable climate models. Because this small-scale activity eventually affects the climatically important large-scale processes, the predictability of climate is limited. Parameterizations and statistical techniques offer only a partial way around this fundamental difficulty. As a result, both the spatial and temporal resolution of climate predictions tend to deteriorate as the time interval of prediction increases. As we mentioned earlier, with strong forcing processes there are important exceptions to this general decay of predictability with time interval of prediction. Thus, situations where the climate is dominated by strong forces are the most amenable to solution.

Another limitation results from insufficient knowledge or inadequate representation of the physical processes involved in the climate system. This problem is linked to that of imperfect parameterizations in climate models. This is an area of much current research, and it likely that better treatment of physical processes, especially parameterized ones, will improve predictions. Another prospect is to combine correlation, regression or other purely statistical prediction techniques with deterministic climate models to enhance the quality of predictions.

The development of increasingly powerful computing systems suggests that climate models of greater complexity and realism will be possible in the future and that we can extend the predictive time range of comprehensive models such as the general circulation models. With more powerful computing systems we will be able to make more elaborate, detailed and realistic specifications of initial and boundary conditions, physical processes and parameterizations. Experience indicates that adding refinements to climate models or improving their resolution does not always lead to better predictions. However, we expect that, at least for some problems, increased computational capabilities will give significant improvement in climate prediction.

A process that certainly has a marked effect on seasonal and longer-term climate prediction is the exchange of heat and kinetic energy between the uppermost part of the ocean and the lowest layer of the atmosphere. Several research groups are currently studying this very complex process. Realistic models for the longer time spans must account for this interaction by coupling separate models of the atmospheric and oceanic subsystems in a way that approximates the climatic effects of the interaction without explicitly computing all details of the process. On even longer time scales we must couple models of the cryosphere to models of the atmosphere and ocean. Currently, such couplings, when used at all, are admittedly crude, but we expect that more powerful computers and improved knowledge of the interactions will lead to more sophisticated and more realistic coupling techniques.

These anticipated improvements will further our goals of useful monthly, seasonal and annual climate forecasts, better understanding of the causes of the ice ages, and enhanced ability to predict the effects of increased atmospheric carbon dioxide or decreased stratospheric ozone. There is no doubt that the cost—now an annual investment of some few hundred million dollars—of the research needed to develop better climate models and the observations needed to verify them will grow, but the possibility of achieving reliable climate predictions makes it worthwhile. An improved ability to predict trends in climate will have large immediate payoffs in areas ranging from agricultural production and water-resources management to energy use and health. Even more important in the long run, an improved ability to detect and predict both naturally occuring and anthropogenic long-term trends in climate will tell us much about the future habitability of our planet for life as we know it.

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