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An Overview of Climatic Variability and Its Causal Mechanisms

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A variance spectrum of climatic variability is presented that spans all time scales of variability from about one hour (10^{-4} years) to the age of the Earth (4×10^9 years). An interpretive overview of the spectrum is offered in which a distinction is made between sources of variability that arise through stochastic mechanisms internal to the climatic system (atmosphere-ocean-cryosphere) and those that arise through forcing of the system from the outside. All identifiable mechanisms, both internal and external, are briefly defined and clarified as to their essential nature. It is concluded that most features of the spectrum of climatic variability can be given tentatively reasonable interpretations, whereas some features (in particular the quasi-biennial oscillation and the neoglacial cycle of the Holocene) remain fundamentally unexplained. The overall spectrum suggests the existence of a modest degree of deterministic forms of climatic change, but sufficient nonsystematic variability to place significant constraints both on the extent to which climate can be predicted, and on the extent to which significant events in the paleoclimatic record can ever manage to be assigned specific causes.

INTRODUCTION

Climate is now recognized as being continually variable, on all scales of time. In consideration of the enormous complexity of the behavior of the climatic system (of which our present knowledge is still only rudimentary), it is not surprising that a bewildering variety of theories can be, and has been, advanced to account for climatic variability. We are not yet in a very good position to confidently weed out the valid theories from the rest. In general, however, we can expect that many different geophysical processes are each capable—at least potentially—of contributing to climatic variability on one time scale or another. In other words, the number of valid theories to account for the variability may turn out to be quite large, and it is likely that no *one* process will be found adequate to account for all the variability that is observed on *any* given time scale of variation.

All potential sources of climatic variability may be grouped in three categories:

- Processes internal to the climatic system, that involve interactions (i.e., feedbacks) between the different parts of the system. These will be defined here as *internal stochastic mechanisms.*
- Processes external to the climatic system, that involve forcing of the system (or of the statistical behavior of the system) by environmental events or changes whose occurrences are independent of the state of the system. These will be defined here as *external forcing mechanisms.*
- Processes that involve some form of resonance between internal modes of climatic system behavior and external forcing of a repetitive or cyclical character. Here the time scale of the forcing phenomenon is normally such as to favor resonant amplification of internal system variability on the same time scale, with an appropriate lag. For purposes of this paper, such processes will also be classed as *external forcing mechanisms,* on the basis that any climatic variability attributable to them could not arise in the absence of external forcing.

Here I define the "climatic system" in the conventional way as the following combination: atmosphere, oceans, land surface, ice masses (i.e., cryosphere), and the biosphere. These are the elements of environment that may freely interact, either physically or chemically, such that a change in any one of them is likely, to one extent or another and on one time scale or another, to result in changes in all the others.

The meaning of "internal stochastic mechanisms" may be clarified as follows. By *internal* I refer to any change in the state of the climatic system that is energized by a process within the system, where that process exists apart from any forms of environmental change that may occur outside the system. By *stochastic* I refer to the fact that the process in question, together with its consequences to the overall behavior of the climatic system, is basically a *probabilistic* process in time, rather than a deterministic one. In general, this means that the process, and its consequences, are extremely difficult—and perhaps impossible—to quantify in explicit detail, as a function of time, and that skillful predictions of the evolution of the state of the climatic system, as a consequence of the process, would be feasible only for ranges of time that are comparable to the characteristic time scale of the process itself.

"External forcing mechanisms" (for example, those related to solar variability, Earth-orbital changes, volcanic eruptions, and various human influences on environment) are to be contrasted on the basis that while each external phenomenon may alter (i.e., "force") the state of the climatic system, the resulting alteration of the system is incapable of "feeding back" to influence the later behavior of that phenomenon. Generally speaking, to the extent that an external mechanism is itself a deterministic process in time, and therefore to some degree predictable over a relatively long interval of time, the variations of climate forced by the mechanism would likewise be deterministic, and therefore to some degree predictable over the same long interval of time.

In this paper, my aim is to sketch a (necessarily rather idealized and subjective) bird's-eye view of the spectrum of climatic variability that spans all scales of time from that of billions of years down to that of a small fraction of one day, and to offer an interpretive view of the origins of the climatic variability on each time scale over this broad range. This will provide a tentative basis for assessing the extent to which climatic variability in general may owe itself to internal stochastic mechanisms. Where the observed variability (on one time scale or another) appears to exceed that accounted for by internal mechanisms, I then consider to what extent external forcing mechanisms may be required to account for the additional variability, and to what extent known (or strongly implied) external mechanisms suffice to explain the additional variability. My purpose here is *not* to evaluate the relative merits of different theories of climatic change, but rather to provide the appropriate perspective for synthesizing both theory and observation into a comprehensive framework, to reveal something of the adequacy (or inadequacy) of our collective views on the sources of climatic variability on all scales of time.

SPECTRUM OF CLIMATIC VARIABILITY

Enlarging on earlier efforts to summarize the spectral distribution of climatic variability over several decades of time scales (Kutzbach and Bryson, 1974; U.S. Committee for GARP, 1975), I present a spectrum of global climatic variability (Fig. 1) that spans all periods (i.e., wavelengths) of change from those comparable to the age of the Earth (4×10^9 years) to small-scale weather variability of the order of 1 hr (10^{-4} years). In order

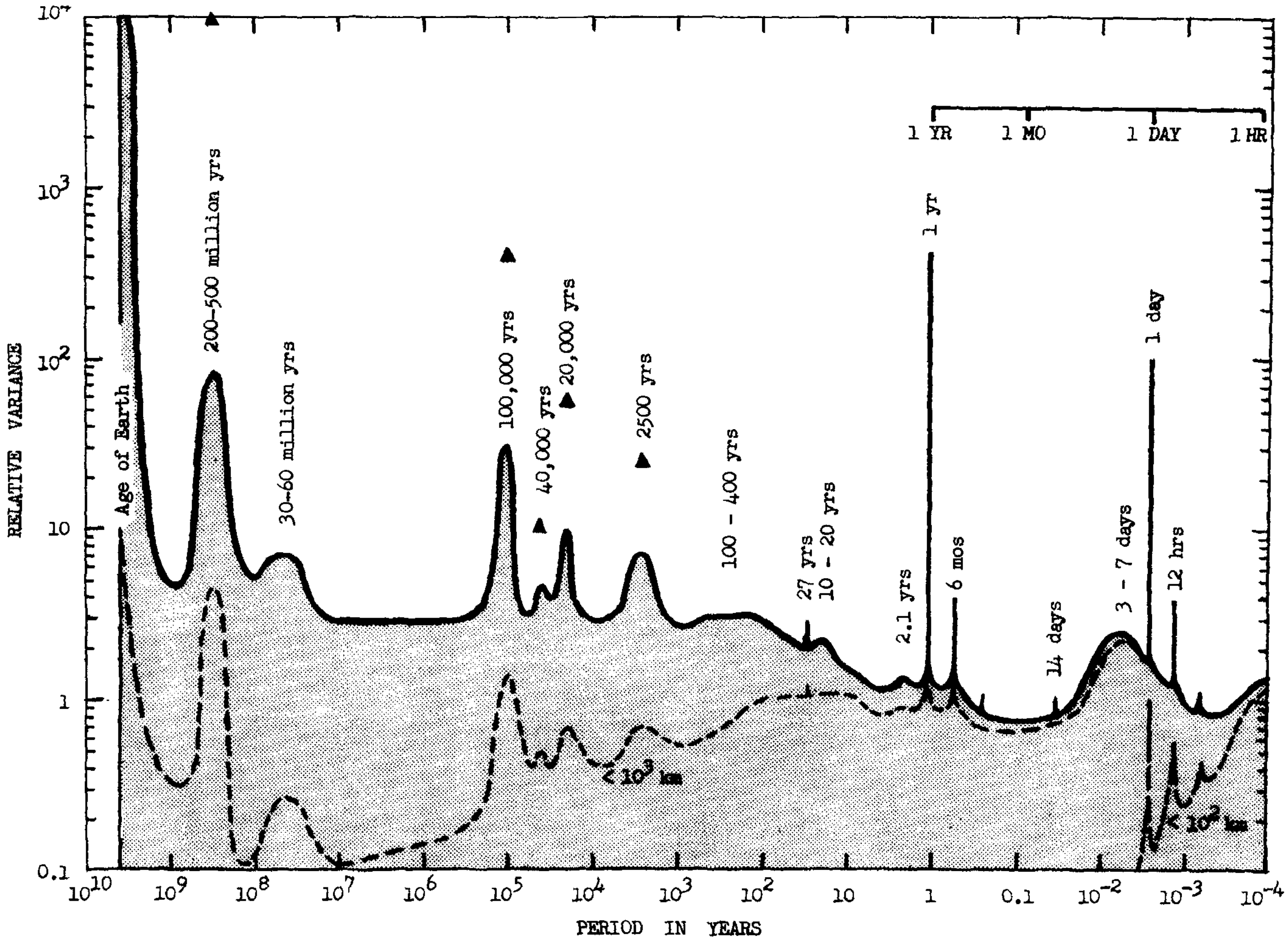

FIG. 1. Estimate of relative variance of climate over all periods (wavelengths) of variation, from those comparable to the age of the Earth to about one hour. Stippled area represents total variance on all spatial scales of variation. Dashed curves in lower part of the figure indicate the contributions to the total variance from processes characterized by spatial scales less than those indicated (in kilometers). Strictly periodic components of variation are represented by spikes of arbitrary width. Solid triangles indicate scaling relationship between the spikes and the amplitude of other features of the spectrum (see text).

to combine information spanning such a wide range of time scales into a single readable diagram, it is necessary to resort to logarithmic coordinates for both variance and time scale. It should be understood that such a coordinate system does not conserve variance, as it would if the ordinate had been chosen as variance divided by the period of variation (see Kutzbach and Bryson, 1974). That is to say, a unit area near the left side of Fig. 1 represents a contribution to the total variance of climate that is many orders of magnitude smaller than the contribution of a unit area near the right side of the figure. The coordinate system used here, however, has a compensating advantage that will become clear in the next section.

Other comments helpful to the proper interpretation of Fig. 1 are the following. Astronomically dictated variations of climate—in particular the annual and diurnal cycles—are portrayed in the figure as sharp spikes (of arbitrary width) at periods of 1 year and 1 day, and other harmonically related spikes at 6 and 3 months, and at 12 and 6 hr. Such spikes are appropriate to strictly periodic components of climatic variation. With a few exceptions (see later), all other "peaks" in the spectrum of Fig. 1 are shown as broader maxima, as appropriate to variations that are either quasi-periodic, or aperiodic with a preferred time scale of energization (e.g., turbulence). The amplitudes of the spikes that represent strictly periodic variations, and those of the peaks that represent quasi-periodic or aperiodic variations, can be related to one another by reference to the solid triangles shown above some of the spectral peaks. For example, if the 100,000-year variation of climate were to be approximated by a simple sine wave having the same total variance (at one discrete wavelength) that it actually has over a range of periods centered at the same wavelength, then the 100,000-year variation could be represented by a spike with an amplitude given by the solid triangle shown at that wavelength in the figure.

Information as to the geographical scale of climatic variation is also shown in Fig. 1 by the dashed curves near the bottom of the figure. The heavy curve (stippled area) represents the variability of climate on all spatial scales of variability, up to and including strictly global scales. This is the spectrum that might be derived from the record of a rapid-responding thermometer at some representative location on the Earth, were such a thermometer to have been in continuous operation ever since the creation of the planet more than 4 billion years ago (assuming however that the higher-frequency variations of climate had, throughout the aeons, always resembled those of modern Quaternary and postglacial times for which we have quantitative information). The dashed curve labeled "$<10^3$ km" represents the estimated contribution to total variance of climate processes characterized by *spatial* scales of variation less than 1000 km. The dashed curve labeled "$<10^2$ km" similarly represents the contribution of processes with spatial scales less than 100 km. Together, these curves are an indication of the important fact that most climatic variation on time scales shorter than one year is regional, rather than global, in extent.

Lest Fig. 1 be uncritically examined through a magnifying glass by anyone unfamiliar with the sometimes severe limitations of paleoclimatic data, it is to be emphasized that the spectrum portrayed there is little more than an educated guess as to many details shown, especially those for periods longer than 10^5 years. The most that I would wish to claim for the veracity of Fig. 1 is (1) that spectral peaks appear to belong everywhere that they are shown in Fig. 1, whether or not they are shown correctly as to relative shape, magnitude, and width; (2) that the spectrum between periods of 10 and 10^5 years is consistent with the general picture of Quaternary climatic history published in Fig. A.2 of U.S. Committee for GARP (1975); and (3) that the spectrum for periods shorter than 10 years is consistent with instrumental observations of atmospheric variability in the 20th century (see, e.g., Griffith, Panofsky, and Van der Hoven, 1956).

INTERPRETATION OF THE SPECTRUM

If all variations of atmospheric state owed themselves solely to internal atmospheric processes having characteristic time constants of minutes or hours (e.g., turbulent and convective buoyancy effects), with no slower-acting processes or external forcing present, then the spectrum of climatic variability would appear in the coordinate system of Fig. 1 as a featureless, horizontal line across all wavelengths longer than minutes and hours. Such a rectangular spectral shape is appropriate to "white noise," in which all wavelengths of variation contribute equal shares to the total variance. Inasmuch as some extent of variability of atmospheric state does in fact originate from processes with time constants as short as this, it follows that a part (albeit a very small part) of the variance of climate on time scales of hundreds, thousands, even billions, of years can be explained as the result of extremely short-term weather variability. In fact, of course, additional contributions to the variability of climate come from various slower-acting processes internal to the climatic system, as well as from slower-acting forcing of the climatic system by external environmental processes. In each case, the time constant of the process is different (see the next section for an elaboration of this). Whatever the process, and the time scale of the process, it is generally the case that the process simply adds "white noise" to the variations of climate on time scales that are substantially longer than the time scale of the process, but not to those on substantially shorter time scales.

As regards the aggregate contribution of all internal stochastic mechanisms of climatic variation, to the spectrum of climatic variability, the following situation therefore applies. As we scan the spectrum from the short-wave end toward the longer-wave regions, at each point where we pass through a region of the spectrum corresponding to the time constant of a process that adds variance to climate, the amplitude of the spectrum increases by a constant increment across all substantially longer wavelengths. In other words, each stochastic process adds a "shelf" to the spectrum at an appropriate wavelength.

At this point we may refer to Fig. 2, in which the lower part of the figure identifies in more specific terms the extent to which the spectrum of Fig. 1 is built up by variance "shelves," in each case by a specific stochastic process, as indicated. The processes identified in Fig. 2 are explained more fully in the next section. To the extent that this view of the contribution of internal stochastic processes to the total variability of climate is a valid one—and once again I emphasize the tentative nature of this analysis—we may focus next on the features of the spectrum marked by stippling in Fig. 2. These features represent variance that conceivably may also derive from internal stochastic mechanisms of climatic variation, but that, for the most part, is more likely to derive instead from external forcing mechanisms. Keeping in mind the logarithmic scale of the ordinate of Fig. 2, it is apparent that in certain parts of the spectrum the variance in question represents a very substantial fraction of the total variance of climate at those wavelengths. In other words, to whatever extent we are unable to account

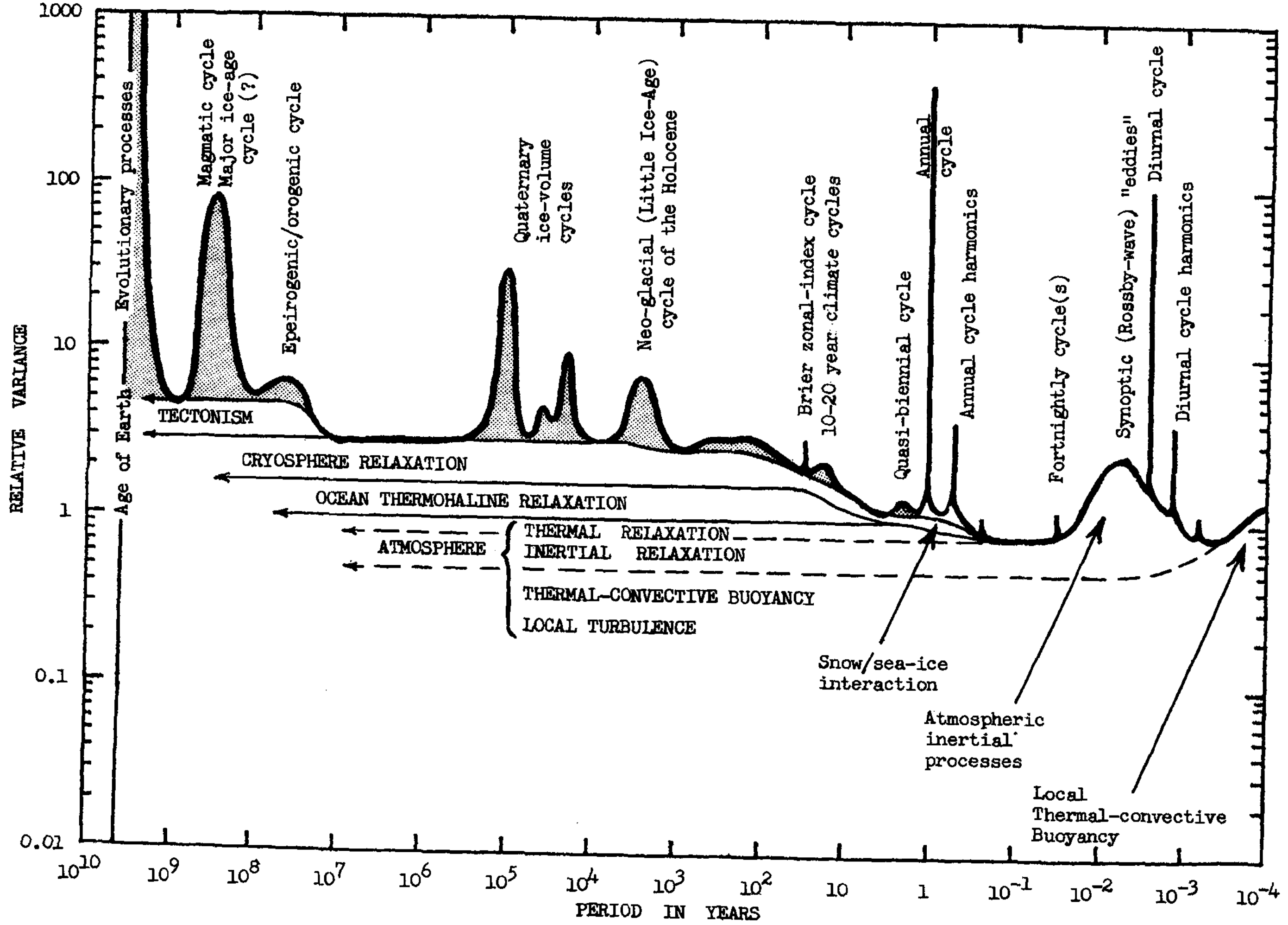

FIG. 2. The spectrum of *Fig.* 1 annotated to indicate the estimated contributions to total variance from various internal stochastic processes (below curve). Features of the spectrum which may or may not also be accounted for by internal stochastic processes are identified phenomenologically (above curve). The excess variance associated with each of these features is emphasized by stippling.

for these features of the spectrum, we must admit to being unable to account for a very important share of the total variability of climate, on a number of different time scales.

In the upper half of Fig. 2, each spectral feature, which internal stochastic variability of the climatic system seems at least tentatively inadequate to account for, is identified phenomenologically. I shall return to each of these features for a closer examination later.

STOCHASTIC CAUSAL MECHANISMS

As the starting point for a rational attempt to account for the "lumpiness" of the spectrum of climatic variability, a brief discussion of the physical basis of the internal stochastic mechanisms will be helpful. I have already mentioned that significant variability of the atmospheric state arises through internal atmospheric processes having characteristic time constants measured in minutes and hours. With the aid of Fig. 3a we see that, of the total variability of climate attributable to stochastic mechanisms, the bulk of the variability on time scales of one hour or less derives from local atmospheric turbulence and small-scale convective overturning (thermal-convective buoyancy). As we move toward longer time scales, of a day or so, a different source of atmospheric variability becomes dominant, namely that defined here as atmospheric inertial relaxation. This refers to synoptic- (regional-) scale weather processes, typified by the cyclones and anticyclones, and the undulating upper-atmospheric wind streams, that are routinely charted on daily weather maps. Such weather features are shaped by the course of atmospheric wind currents in the limited period of time (a matter of days) during which the currents are not yet run down (i.e., "relaxed") by frictional dissipation, and are meanwhile behaving as required to conserve their momentum. Inasmuch as considerable kinetic energy is generated (from potential energy) in synoptic-scale weather systems, a major peak in the spectrum of atmospheric variability is found on time scales of the order of the inertial lifetime of such systems (a few days).

Moving toward still longer time scales, of weeks and months, a new source of atmospheric variability appears, namely the relatively slow thermal adjustments in the atmosphere (atmospheric thermal relaxation). The thermal state of the atmosphere is constantly perturbed by shorter time-scale processes. It "relaxes" after each perturbation partly through comparatively slow internal radiative adjustments, and partly through thermodynamic transactions with slowly responding ocean and land surfaces. Since the potential energy of the atmosphere, from which the synoptic-scale weather systems derive their kinetic energy, is itself governed essentially by the thermal state of the atmosphere, this means that slower variations in the day-to-day statistics of atmospheric state (including the *mean* atmospheric state) can arise on time scales (of order weeks and months) commensurate with the time scale of "relaxation" of the thermal state of the atmosphere from any anomalous condition toward equilibrium.

To the extent that atmospheric thermal state depends on thermodynamic transactions with the ocean surface, these very transactions tend to energize motion within the oceans. This motion results in a transfer of heat between the ocean surface and deeper layers, which may, in turn, affect the later availability of heat from the surface to the atmosphere on the still longer time scales that are characteristic of the comparatively sluggish overturning of water in the ocean mixed layer (of order one to 10 years). It is at this point (and this range of time scales of climatic variation) that a major—

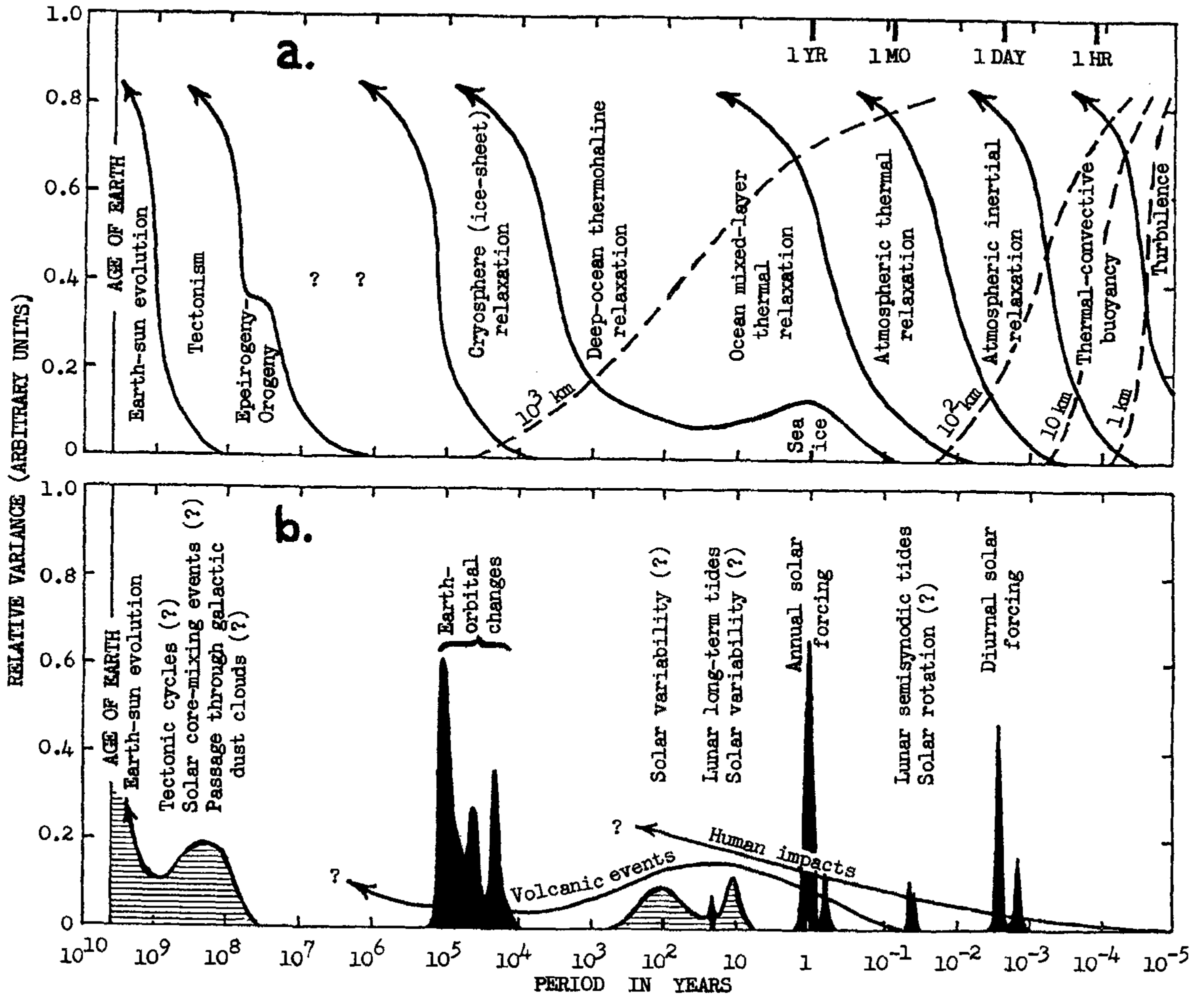
a.
b.
RELATIVE VARIANCE (ARBITRARY UNITS)
1.0
0.8
0.6
0.4
0.2
0
1 YR
1 MO
1 DAY
1 HR
AGE OF EARTH
Earth-sun evolution
Tectonism
Epeirogeny-Orogeny
? ?
Cryosphere (ice-sheet) relaxation
Deep-ocean thermohaline relaxation
Ocean mixed-layer thermal relaxation
Atmospheric thermal relaxation
Atmospheric inertial relaxation
Thermal-convective buoyancy
Turbulence
10^3 km
10^2 km
10 km
1 km
Sea ice
Tectonic cycles (?)
Solar core-mixing events (?)
Passage through galactic dust clouds (?)
Earth-orbital changes
Solar variability (?)
Lunar long-term tides
Solar variability (?)
Annual solar forcing
Lunar semisynodic tides
Solar rotation (?)
Diurnal solar forcing
Volcanic events
Human impacts
?
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
PERIOD IN YEARS

FIGURE 3

perhaps the principal—source of stochastic variability of climate moves from sites internal to the atmosphere to sites elsewhere in the climatic system.

Over a broad range of time scales, from about one month to 10^5 years, the distribution of ice in its various forms plays a more or less major role in giving rise to stochastic climate variability. This situation arises because, on the one hand, different parts of the cryosphere (ranging from seasonal floating sea ice and continental snow cover, to major polar ice sheets) possess vastly dissimilar survival times, and, on the other hand, ice in its various forms on earth can play crucial roles in affecting the pattern of atmospheric heating (through albedo effects), the exchange of heat between the atmosphere and the oceans (through the buffering effects of sea ice), and the long-term thermal state of the oceans themselves (through the control of polar ice masses over bottom water formation).

By the time we have reached time scales of climatic variation as long as 10^3 to 10^5 years, it is likely that three-way stochastic interactions between the permanent ice sheets, the deep oceans, and the atmosphere are those which account for a considerable share of total climatic variability. On still longer time scales, we must recognize that tectonic processes are likely in various ways to contribute further climatic variability. Tectonic processes may affect climate through their influence on the geography of the Earth, the depth and shape of the ocean basins and their submarine interconnections, the height of the continents and mountain ranges, the extent of volcanic activity (as this may affect atmospheric composition and aerosol loading), and possibly other geophysical conditions to which the state of the climatic system is sensitive. These tectonic processes cannot, of course, be viewed as internal stochastic mechanisms of climatic change unless we choose to include the interior of the Earth as part of the climatic system. It is only from a more general geophysical point of view that they may legitimately be regarded as stochastic.

There is a region in Fig. 3a, at time scales of 10^6 to 10^7 years, where the source of stochastic variability is indicated by question marks. At these particular time scales, Figs. 1 and 2 tentatively show a broad spectral "gap." If we consider that all stochastic processes which have time constants shorter than this contribute a substantial "background" level of variability on the time scale in question, we may suppose that the variance there is fully accounted for. On the other hand, there might possibly be additional variance on time scales of 10^6 to 10^7 years that is not yet obvious from the paleoclimatic record. The question marks are intended to call attention to this possibility.

DETERMINISTIC CAUSAL MECHANISMS

There are no known deterministic mechanisms of climatic variability that are internal to the atmosphere, or internal to any other part of the climatic

FIG. 3. (a) Partitioning of total variance (solid curves) arising from internal stochastic processes, contributed by the specific stochastic processes indicated. (Processes indicated for periods longer than 10^6 years are not internal to the climatic system per se.) Arrows at top of partitions are a reminder that some variance at any given wavelength arises from each stochastic process arising at shorter wavelengths. Dashed curves indicate partitioning of stochastically generated variance on different spatial scales of variation (in kilometers). (b) Added contributions to total variance from various known or proposed external forcing mechanisms. Variance that is contributed by well-known periodic forcing phenomena is shown in solid black. Variance that is contributed by less well established or hypothetical forcing phenomena is shown by hatching. Curves labeled "volcanic events" and "human impacts" require special interpretations (see text). Forcing mechanisms of doubtful validity are distinguished from the others by question marks.

system. That is to say, all internal sources of variability are stochastic in form. (While each of these may control the *statistics* of climatic system behavior in deterministically definable ways, none is able to control the *details of the time history* of that behavior beyond the range of its own characteristic time scale.)

On the other hand, the diurnal and annual forcing of climate, arising, respectively, from the rotation of the Earth and from the inclination of the Earth's rotational axis with respect to the orbital plane, are two obvious examples of deterministic forcing of the climatic system from outside the system. Because of the asymmetric geometry of the diurnal and annual radiation changes, and also because of a tendency for asymmetric response of the climatic system to the changes, the spectrum of climatic variability properly reflects both the diurnal and annual forcing not as single spikes at wavelengths of one day and one year, but as two families of harmonically related spikes as shown in Figs. 1 and 2. (Dismiss this as a mathematical artifact if you prefer.)

In Fig. 3b I show the diurnal and annual forcing of climate along with a number of other climate forcing mechanisms (each at its appropriate time scale) that are either known to exist or tentatively postulated to exist. Scanning from right to left in Fig. 3b, the mechanisms indicated in the figure are further identified and described, in three categories, below.

Deterministic solar and lunar forcing. The diurnal and annual forcing by solar radiation have already been noted. In addition, a modest degree of deterministic variability of climate has been detected in meteorological data at periods near two weeks. Part of this variability has been reliably traced to lunar tidal influences, as manifested primarily in a fortnightly (semisynodic) variation of cloudiness and heavy precipitation events (Brier, 1964). Another part may be attributable to solar rotation effects, which may also involve periods of variation near one week, related to the passage of sun-generated magnetically reversing "sector boundaries" past the Earth and manifested in certain qualities of the large-scale atmospheric wind field (Wilcox, 1976). In both cases, there is much evidence to support the reality of the effects, but understanding of the physical linkages involved is totally inadequate.

An apparent relation between planetary-scale redistributions of atmospheric pressure and long-term lunar/solar tidal perturbations has been reported by Brier (1968). This arises on time scales of order 27 years but, as Brier has indicated, the situation is complicated by many factors that further investigation will be required to clarify.

For more than a century it has been known that long-term variations exist in the shape of the Earth's orbit and in the orientation of the Earth's rotational axis, which affect the seasonal and latitudinal distribution of solar radiation reaching the top of the atmosphere. Recently, Hays *et al.* (1976) have convincingly established that these variations are strongly reflected in ice-volume changes on the Earth, and in climate generally, as inferred from oxygen-18 and foram analyses of deep-sea sediments. The periods of climatic variation involved are near 100,000, 40,000, and 20,000 years.

Other deterministic forcing. Other mechanisms of climate forcing (those shown by hatching in Fig. 3b) are potentially significant but as yet inadequately verified. Some of these are really only speculative.

Solar variability is believed to exist on a very wide range of time scales, but principally on those between 10 and 10^3 years. In the absence of a clearer understanding of the nature of solar variability, and in the absence of observational evidence that the solar energy output actually varies on any of these time scales in a manner, and to an extent, that might affect terrestrial climate, it is not yet possible to assess the full extent to which solar variability forces climatic variation. There is a large body of (rather equivocal) evidence that climate varies with either the 11-year sunspot cycle or the 22-year "double" sunspot cycle (see, e.g., Currie, 1974; Roberts, 1975). There are indications that climate may also respond to longer-period solar variations, on time scales of a few hundred years (e.g., Eddy, 1976). If such relationships are real, their behavior would seem to indicate either that the driving solar mechanisms are not as regularly periodic as is generally supposed, or that the climatic response is stochastic rather than deterministic, or possibly both. In any case, a spectrally broad climatic response to solar variability is suggested, as indicated in Fig. 3b.

Epeirogenic changes, and orogenic revolutions, appear to have characteristic time constants of order 10^7 to 10^8 years (Damon, 1971). If so, a significant excess of climatic variability on these time scales can be expected.

On time scales of 10^8 to 10^9 years, very little is known about the structure of climatic variation, and about the mechanisms available to account for climatic change. Since Precambrian times we can at least recognize what seems to have been a sequence of three major ice ages, at intervals of between 200 and 500 million years. Several competing categories of theories have been advanced to explain this sequence: (1) tectonic processes, involving either the alternate dispersion and reclustering of continental masses or changes of atmospheric composition following pulses of volcanism on the same time scale; (2) deep-seated solar disturbances that produce transient changes in the sun's energy output; and (3) the passage of the sun through galactic dust bands, which may affect climate either by altering the sun's energy output through the effects of infalling material or by altering the radiative transmissivity of interplanetary space. Theories in the first category are indirectly supported by clear evidence of a roughly 400 million year cycle in the age distribution of magmatic rocks and minerals throughout the world (Gastil, 1960; Engel *et al.*, 1965). Those in the second category were developed in recent years as a byproduct of attempts on the part of stellar physicists to account for the unexplained lack of a theoretically expected solar neutrino flux (Cameron, 1973). Those in the third category had their origins nearly 40 years ago in a proposal by Fred Hoyle and are only recently being pursued anew (e.g., Dennison and Mansfield, 1976). Inevitably, not all these categories of theories will withstand the test of time. The most likely survivor, I venture to speculate, will be that involving tectonic processes.

Looking to the future, human impacts on the state of the climatic system are to be recognized as a new and historically unprecedented form of "external" forcing. At present these impacts are thought to be small, and confined to local, and possibly regional, conditions. Nevertheless, important global-scale impacts, including a general warming, may eventually follow from the addition to the atmosphere of carbon dioxide and other pollutants (Broecker, 1975; Mitchell, 1972). Reference to human impacts in Fig. 3b is merely to emphasize such future eventualities, and is not to suggest that they have been important to past climatic changes.

Volcanic activity. Major volcanic eruptions, especially those of paroxysmal class, are the evident source of significant, although transitory, global-scale climatic variation (e.g., Oliver, 1976). The climatic response is to a large extent systematic, and includes a general climatic cooling on time scales of a few years. In the event of a series of major eruptions, the aggregate climatic response may contribute to climatic variability on time scales of decades or longer. There is some evidence that earlier geological epochs differed considerably from the present epoch as to the overall level of volcanism, in which case differences of climate on extremely long time scales might conceivably also be accounted for in the same way. As an external forcing mechanism of climatic variability, volcanism has to be regarded as a special case in that individual volcanic events recur with little or no apparent regularity. While this mechanism is likely to be a significant source of climatic variability on many scales of time longer than about 10^{-1} years (the time scale of the most immediate climatic effects of individual eruptions), the episodic nature of the mechanism makes it very difficult to infer its proper contribution to the spectrum of climatic variability.

CONCLUSIONS

I have suggested that a substantial share of the variability of climate, on essentially all time scales of variability (from hours to aeons), derives from stochastic generating mechanisms that are wholly internal to the climatic system. These mechanisms consist of a hierarchy of individual stochastic processes, each characterized by its own unique time constant and each adding to the variability of climate on all time scales longer than that time constant. In this manner, a "background" level of variability is generated which tends to increase in amplitude toward the longer time scales of variation. The "background" variability has a low degree of order (i.e., a high entropy level), and a correspondingly low degree of predictability.

On top of the stochastic "background" variability, additional band-limited variability is contributed by external climate forcing processes. In the absence of all internal stochastic mechanisms of climatic variability, the spectrum of climatic change might resemble something akin to the sum of the individual contributions to the variability shown in Fig. 3b. A high degree of order in climatic variability (i.e., a low entropy level), and a relatively high degree of predictability, would then be indicated. In the real world, however, we must recognize (1) that some forcing mechanisms included in Fig. 3b, in particular those shown with question marks, are of uncertain validity; (2) that, at best, deterministic (and therefore predictable) forcing mechanisms tend to account for the variability only in a few narrow ranges of wavelength; and (3) that in terms of overall climatic variability, the variability that arises from all forcing mechanisms is well diluted by the background variability that arises from all internal stochastic mechanisms. Together, these considerations imply that there are likely to be rather severe constraints on the ultimate limits of climate predictability. A corollary to this is that there may also be rather severe constraints on our ultimate ability to explain many noteworthy events in the Earth's climatic history, as revealed in the paleoclimatic record.

It remains for us to return to Fig. 2, to point out that there are two significant features of the spectrum of climatic variability that have not been provided a "home" somewhere in this discussion of causal mechanisms. One of these features is the quasi-biennial oscillation, with its period of slightly more than two years, that involves a reversal of the winds in the tropical stratosphere and some extent of general climatic variation over large regions of the Earth (Landsberg, 1962; Newell *et al.*, 1974). The excitation mechanism for the quasi-biennial oscillation is unknown, but the prevailing view is that the mechanism is of an internal stochastic form. The other spectral feature devoid of adequate explanation is the so-called neoglacial cycle of the Holocene, with its characteristic period of roughly 2500 years (Denton and Karlén, 1973; U.S. Committee for GARP, 1975). At this time, it is equally plausible to suppose that the neoglacial cycle is an internal stochastic process, perhaps involving some form of ocean-cryosphere interaction, or to suppose that it is the result of an external forcing phenomenon, not inconceivably solar variability (Eddy, 1976).

I close with a caveat. There are undoubtedly many flaws in the spectrum of climatic variability as presented in this paper, and equally many flaws in the interpretations I have lent to the spectrum. I hope, nevertheless, that the rationale underlying this paper will help others, as it has helped me, to lend perspective to the overall problem of climatic change, with special focus on the physical interpretation of the paleoclimatic record.

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