Zeitschrift: Jahrbuch der Schweizerischen Naturforschenden Gesellschaft. Wissenschaftlicher und administrativer Teil = Annuaire de la Société Helvétique des Sciences Naturelles. Partie scientifique et administrative

Herausgeber: Schweizerische Naturforschende Gesellschaft

Band: 158 (1978)

Artikel: History and Mechanisms of Climate

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DOI: https://doi.org/10.5169/seals-90737

History and Mechanisms of Climate

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Abstract

The modern concept of climate is that of a dynamic physical system in contrary to the classical meaning of "average" weather. Revealing the history of the earth's climate, climate appears to have been variable on all discernable scales of time and in some periods of variation periodic and quasi-periodic movements of climate seem to have occurred. To distinguish these periods from the aperiodic variability the record of climate is stressed in terms of its spectrum. Even this spectrum must be regarded as a crude approximation to reality, the peaks appearing in it can be defensed as probable. For the construction of models of climate system behaviour a number of mechanisms are given that come in mind as possible "drivers" of climatic variability and change. Since the anthropogenic influences on climate are likely to be of rapidly growing importance, the development of realistic models could be a powerful tool to assess the consequences of human activities to future climate and to the stability of the polar ice sheets.

Zusammenfassung

Im Gegensatz zum klassischen Begriff Klima als durchschnittliches Wetter versteht man heute darunter ein dynamisches naturwissenschaftliches System. Im Verlauf seiner Geschichte scheint das Klima der Erde in erkennbaren Zeitskalen geschwankt zu haben, wobei es in gewissen Abschnitten offensichtlich periodische oder quasiperiodische Bewegungen gegeben hat. Um diese von den aperiodischen Schwankungen zu unterscheiden, wird der Ablauf des Klimas durch die Form seines Spektrums verdeutlicht. Obwohl dieses Spektrum nur eine grobe Annäherung an die Wirklichkeit darstellt, können die auftretenden Spitzen als wahrscheinlich betrachtet werden. Im Hinblick auf den Entwurf klimatischer Modelle werden einige Mechanismen angegeben, die als möglicher «Antrieb» bei klimatischen Schwankungen und Änderungen in Frage kommen. Da anthropogene Einflüsse auf das Klima wahrscheinlich rasch an Bedeutung gewinnen werden, könnte die Entwicklung realistischer Modelle eine wertvolle Hilfe sein, um die Folgen menschlicher Tätigkeit auf das Klima der Zukunft und die Stabilität der polaren Eisschilder abzuschätzen.

Résumé

Contrairement au concept classique de «temps moyen», on considère actuellement le climat comme un système physique dynamique. Au cours de son histoire, le climat de la terre paraît avoir été variable à toutes les échelles de temps discernables, et durant certaines époques, des variations périodiques ou quasi-périodiques semblent s'être produites. Afin de distinguer les mouvements périodiques des variations apériodiques, l'évolution du climat est mis en évidence à l'aide de son spectre. Bien que celui-ci ne soit qu'une approximation grossière de la réalité, les pics qu'il révèle peuvent être considérés comme vraisemblables. En rapport avec l'élaboration de modèles climatiques, on mentionne un certain nombre de mécanismes susceptibles d'être à l'origine des fluctuations et des variations climatiques. Etant donné que l'influence de l'homme sur le climat prendra vraisemblablement une importance de plus en plus considérable, le développement de modèles réalistes pourrait constituer un instrument de grande valeur pour l'estimation des conséquences des activités humaines sur le climat futur et la stabilité des calottes glaciaires de pôles.

The concept of climate

There is general agreement among atmospheric scientists that world climate has been fluctuating in recent years. There is no general agreement, however, that it has been changing. Some climatologists would insist that the fluctuations of the past are not fluctuations of climate but rather (weather) fluctuations in the climate. This skirmish over words is not so much a trivial matter of semantics as it is a testimonial to the confusion that exists – even among experts – as to the true nature, of climate and of climatic variability. Whether or not our climate has been changing in recent years, our perceptions about the physical nature of climate have been dramatically changing.

The classical concept of climate involves many physical considerations that we continue to hold as valid today. Chief among these is the long-recognized fact that the geometry of the earth-sun system establishes a global-scale atmospheric circulation regime, which interacts with the contrasting physical properties of the continents and oceans to result in the diverse climatic zones of the world. Yet, in common every-day usage in the past, the term "climate" took little note of physics and referred instead to "average" weather. If climate could be said to "fluctuate" it was presumed that the fluctuations were in the nature of a deterministic response of the atmosphere to extrinsic environmental changes, for example volcanic dust injections into the upper atmosphere, or changes of solar irradiance alleged (but scarcely proven) to be associated with sunspot cycles. Generally speaking, however, climatic "change" was a concept reserved for the geologically remote past and in particular to the great ice ages. Given a constant terrestrial environment, it was widely supposed that the climate does not – indeed, cannot – either change or fluctuate.

The modern concept of climate differs in that it downplays the statistical notion of climate as "average" weather and stresses instead the entirely different notion of climate as a dynamic physical system (fig. 1). The meaning of this concept, and some of its implications, deserve clarification as follows:

In speaking of climate as a system we recognize that the state of the atmosphere at any

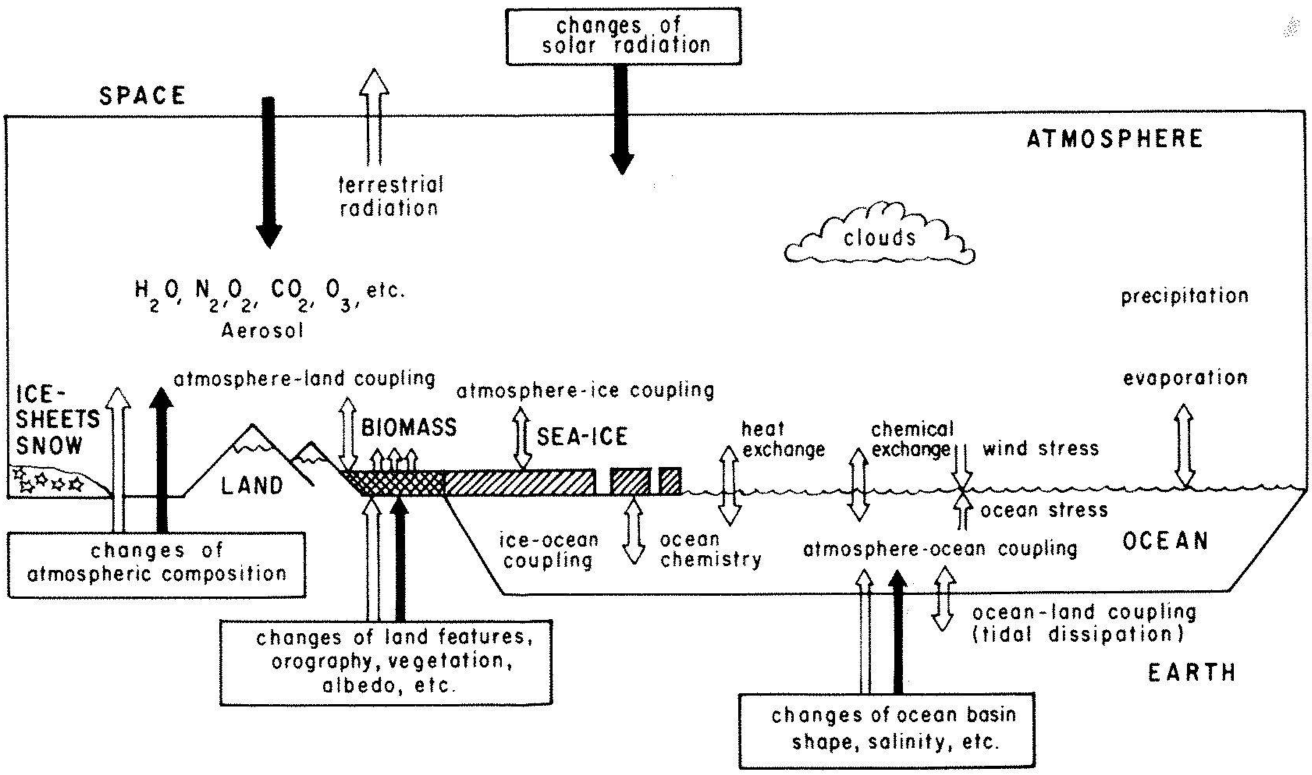


Fig. 1. Schematic outline of earth's climate system (box), showing principal internal couplings between the several parts of the system (open arrows) and extrinsic environmental influences on the system (solid arrows). Source: WMO-ICSU 1975.

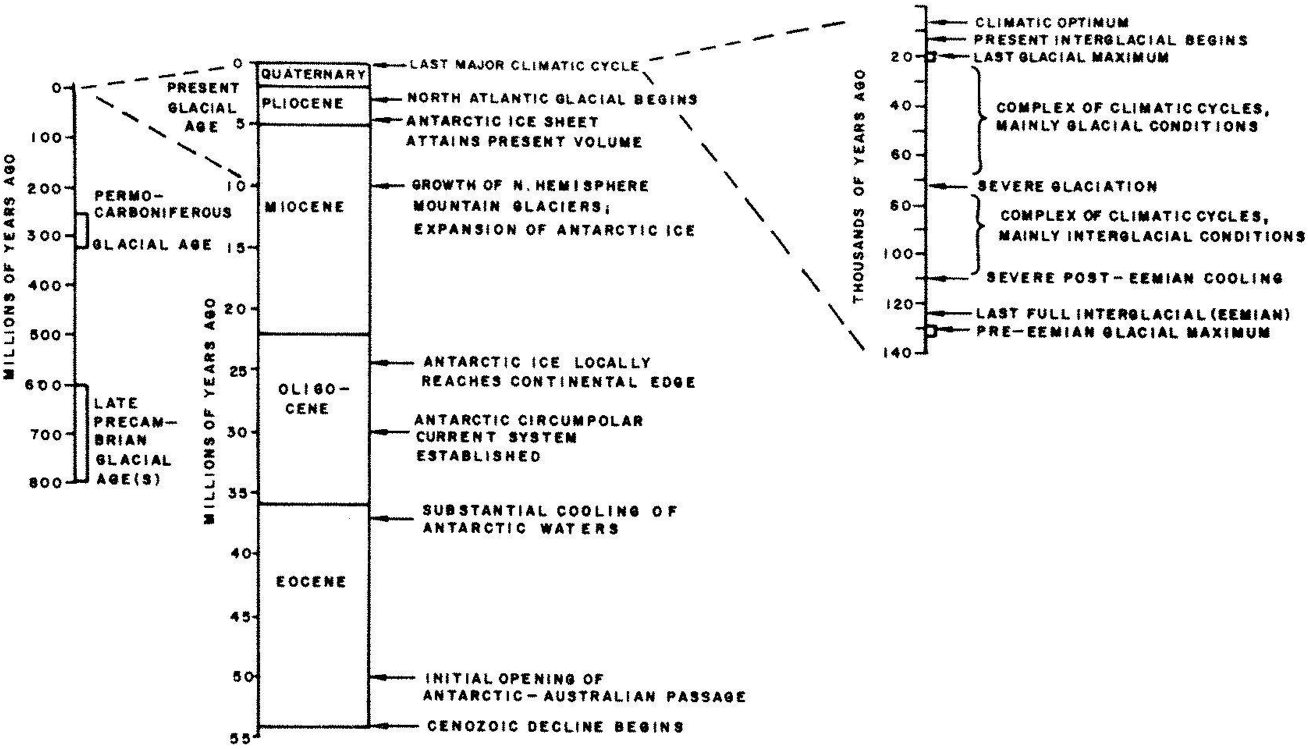


Fig. 2. Climate and climate-related events since the Pre-Cambrian. (Left) major ice age events. (Middle) Events during the Cenozoic cooling phase leading up to The Quaternary Ice Age. (Right) Details of last major glacial-interglacial cycle in the Quaternary. Source: NAS 1975.

given time cannot realistically be considered in isolation of the state of other parts of our terrestrial environment that are coupled to the atmosphere through exchanges of heat, mass, or momentum. For this reason, the climate system is considered to include the atmosphere, the oceans, the land surfaces, the snow and ice masses of the world, and much of the earth's biota (principally continental vegetation).

In referring to the climate system as physical we emphasize that the coupling between the several parts of the system is governed by various, individually identifiable and quantifiable physical, chemical, and biological processes. Through the action of these processes, an alteration in the state of any one part of the system is at least potentially capable of altering the state of all the other parts.

In referring to the climate system as dynamic we go one very important step further by recognizing that the various physical, chemical, and biological processes coupling the several parts of the system require varying lengths of time to run their course, ranging from hours to millennia or longer. This implies that the state of the atmosphere (and of climate in the classical sense of average weather) tends always to be in motion, in the sense that it is always trying to adjust itself toward an equilibrium state that it may never fully achieve before the equilibrium state itself moves on to a new state.

The task facing the climatologist who would try to account for all the climatic variability and changes of the past, or to predict future climate in detail, must begin with the construction of a suitably quantitative and comprehensive "model" of the behavior of the overall climate system. It is by no means clear precisely what such a model would look like, or what level of complexity of physical, chemical, and biological processes would have to be built into the model, to serve such an ambitious purpose. Nor is it clear how soon, if ever, we will gain all the knowledge that may be necessary to construct such a model, and have available the computer power that may be necessary to verify and apply the model as we would like to assure ourselves that it is a satisfactory approximation to real climate system behavior. Yet, significant progress is already being realized along these lines and we have reason to be optimistic that the goal is within human reach.

From what we have already surmised about the nature of the climate system, we can be quite certain that much of the "variability" and "change" that we observe in climate has physical meaning, and that this variability arises from two categories of sources. One category of sources is the response of the climate system to extrinsic environmental changes, of the deterministic sort mentioned earlier. The other category is self-stimulated variability of the climate system, of a stochastic character, which would presumably occur even if the extrinsic environment of the earth were unchanging. We are left with the conclusion that climatic variability and change is as much to be regarded as an inherent attribute of climate as it is to be regarded as something that happens to climate (as a result of extrinsic environmental changes).

I turn now to the record of past climates, to indicate some of the most salient characteristics of climatic variability and change as we have managed to infer them from paleoclimatic investigations. I then propose to consider some implications of the record of past climates for the unravelling of the physical mechanisms of climatic variability and change on a wide range of time scales, and for the appropriate direction to be taken in the development of climate system models.

History of the earth's climate

Geological evidence leaves little doubt that, during the past thousand million years or so, the prevalent condition of global climate was one of relative warmth – as much as 10 °C warmer than now – and almost totally free of polar ice. This warm condition was, however, punctuated by a series of relatively brief ice ages each lasting 10 million years or so and separated by a few hundreds of millions of years. Beginning roughly 60 million years ago, something happened to bring about a gradual deterioration of climate. This deterioration culminated, about 2 million years ago, in the arrival of the new mode of climate, characterized by a long sequence of perhaps as many as 20 major glacial-interglacial oscillations, and many more smaller ice volume changes, which presumably continues to grip the world today (fig. 2).

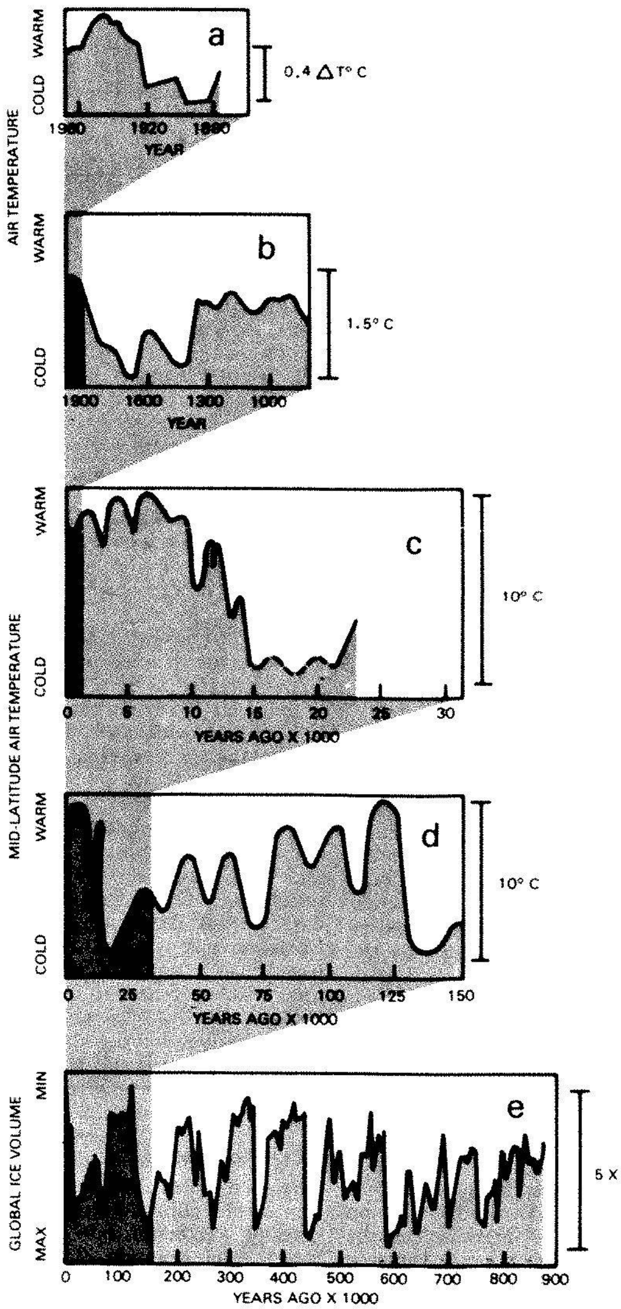
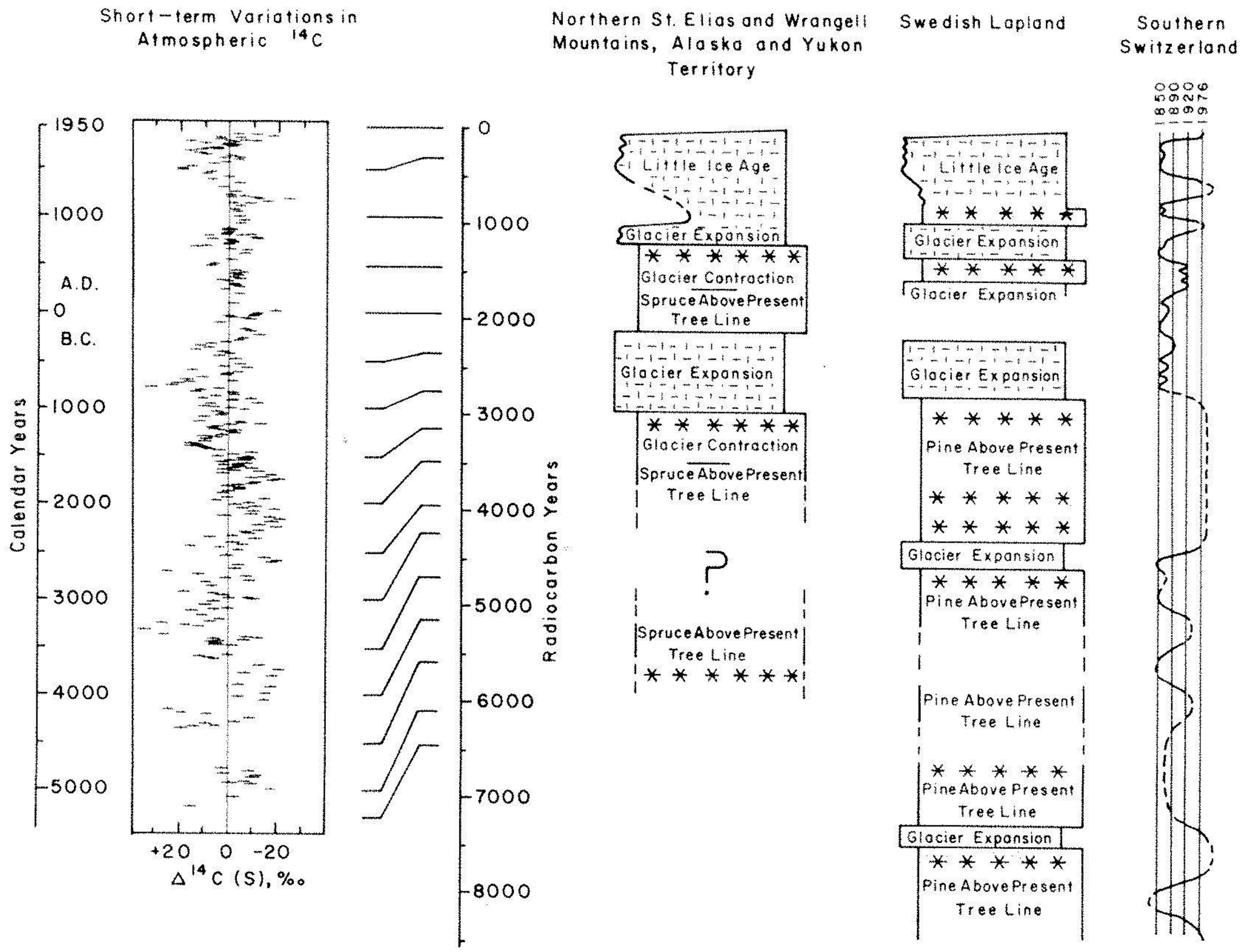


Fig. 3. General trends in global-scale climate on various time scales before present. (a) Northern Hemisphere mean temperature; (b) winter severity index for eastern Europe; (c) generalized air temperature changes, based on fluctuations in Alpine glaciers, tree lines, continental glacier margins, and pollen profiles; (d) generalized air temperature changes, based on fossil plankton analyses of deep-sea sediments, pollen records, and sea-level changes; (e) ice volume changes, based on isotopic composition of fossil plankton in a deep-sea core. Source: NAS 1975.



The history of glacial-interglacial events is revealed in some detail for the past one million years by oxygen-18 analysis of deep-sea sediments and by several other kinds of paleoclimatic indicators. In that period of time, and most particularly during the last half-million years (fig. 3e), the principal variations of ice volume and other conditions of climate appear to have been of a quasi-periodic nature, with a characteristic wavelength close to 100,000 years. Lesser ice volume changes seem also to have occurred with characteristic periods of about 20,000 and 40,000 years (fig. 3d). The world has been in a relatively warm extreme-interglacial phase during the past 10,000 years (fig. 3c), similar to other relatively brief warm phases which have occurred earlier at roughly 100,000-year intervals. In these interglacial phases, ice has been confined primarily to the Antarctic and Greenland ice sheets. In the intervening glacial phases, continental ice sheets have developed primarily in high northern latitudes which covered a maximum of about 9% of the earth's surface and reached a volume of about 75×10^6 km^3 – some three times present-day figures. The variations of ice conditions have been accompanied by mid-latitude temperature changes of the order of 6 to 10 °C, and by sea-level changes of the order of 100 meters.

Fig. 4. Holocene record of ^{14}C fluctuations, alpine glacial events, and tree-line fluctuations. ^{14}C data are from H. Suess. Glacial and tree-line events in St. Elias and Wrangell Mountains are from Denton and Karlén (1977); those from Lapland are from Karlén (1973, 1976) and Karlén and Denton (1976). Glacial variations in southern Switzerland are from Röthlisberger (1976).

Since recovery of the earth from the last major glacial stage about 10,000 years ago, global climate has been found from a variety of paleoclimatic indications to have varied within narrower limits (fig. 3a–3c). An intercontinental survey of mountain glacier

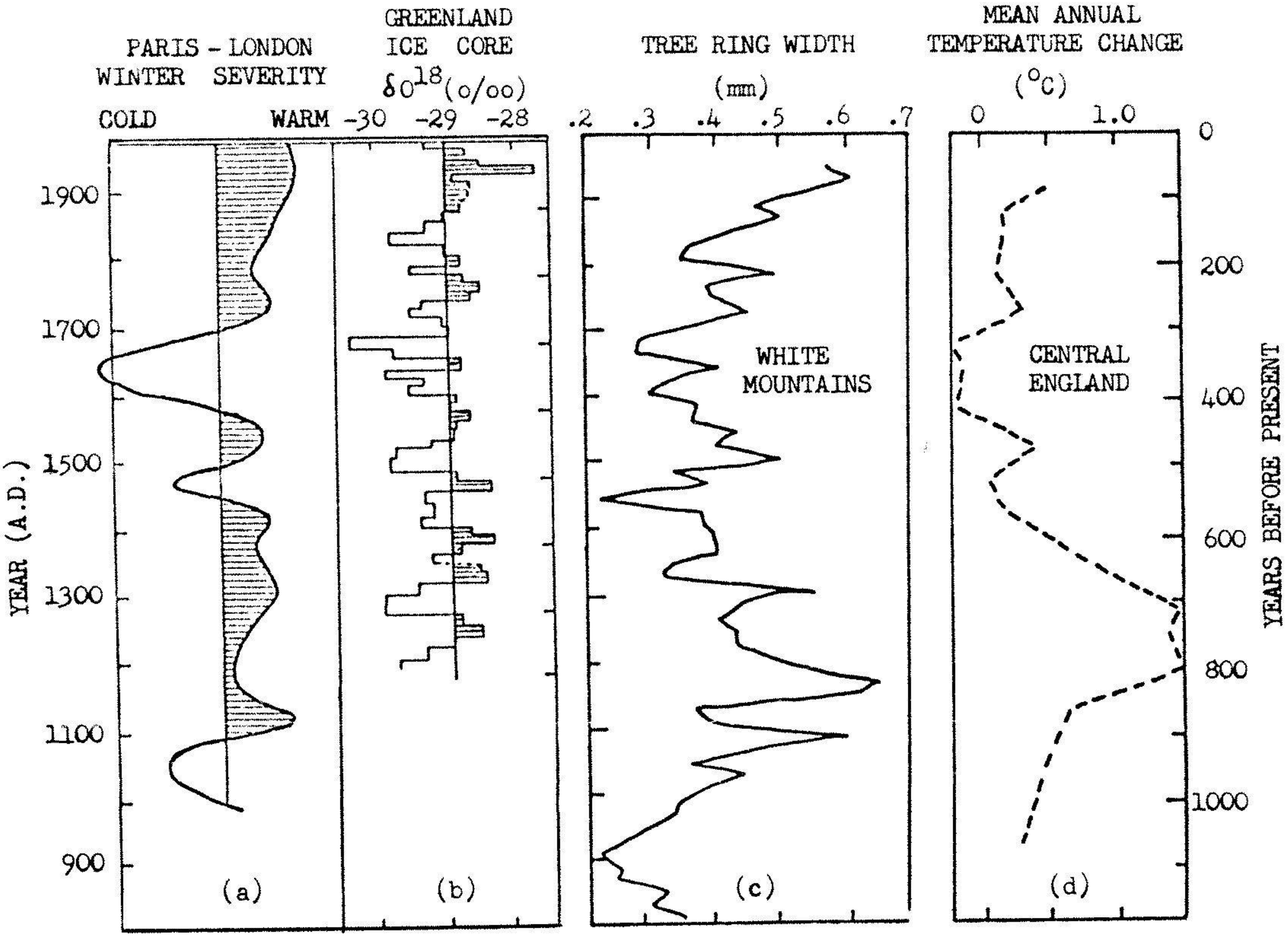


Fig. 5. Climatic indicators of the past 1000 years. (a) Index of winter severity (50-yr moving averages) from documentary evidence for the region of Paris and London, from Lamb (1969). (b) Oxygen-18 variations in ice core from Camp Century, Greenland, from Dansgaard et al. (1971). (c) Mean treering thickness (20-yr averages) at upper tree line of bristlecone pines, White Mountains, California, from LaMarche (1974); reflecting temperature during growing season. (d) Estimated and observed annual mean temperatures (50-yr averages) for central England, from Lamb (1966).

moraines and tree lines has revealed three periods of glacier expansion (each of about 1000 years duration) alternating with three periods of glacial contraction (each of 1000 to 2000 years duration) in the past 8000 years (fig. 4). There is evidence, derived primarily from pollen analyses of lake and bog sediments, that significant shifts of the earth's vegetation zones accompanied these glacial variations, in what is sometimes referred to as the "neoglacial cycle". General temperature levels are believed to have varied by about 1 or 2 °C during the course of this cycle.

Narrowing our attention to the past millennium, we can begin to call into play various additional climatic indices such as human chronicles, tree-ring sections, and annually laminated ice cores from Greenland and Antarctica, to add further detail to our reconstruction of climatic history (fig. 5). The period from about 1530 to 1850 A.S. was one of comparatively cold climate and expanded mountain glaciation. A member of the "neoglacial cycle", noted above, this cold period is commonly referred to as the "Little Ice Age". Earlier centuries were milder, although probably not everywhere as warm as the climate of today. From long instrumental records and human chronicles, typical fluctuations of 30-year averages of climatic variables over the past several centuries can be characterized as follows: Major circulation features, such as the centers of sub-polar lows and sub-tropical highs, and the position of the Intertropical Convergence Zone, have varied by 2 or more degrees of latitude. The positions of mid-latitude troughs and ridges have shifted east or west by 10 to 20° longi-

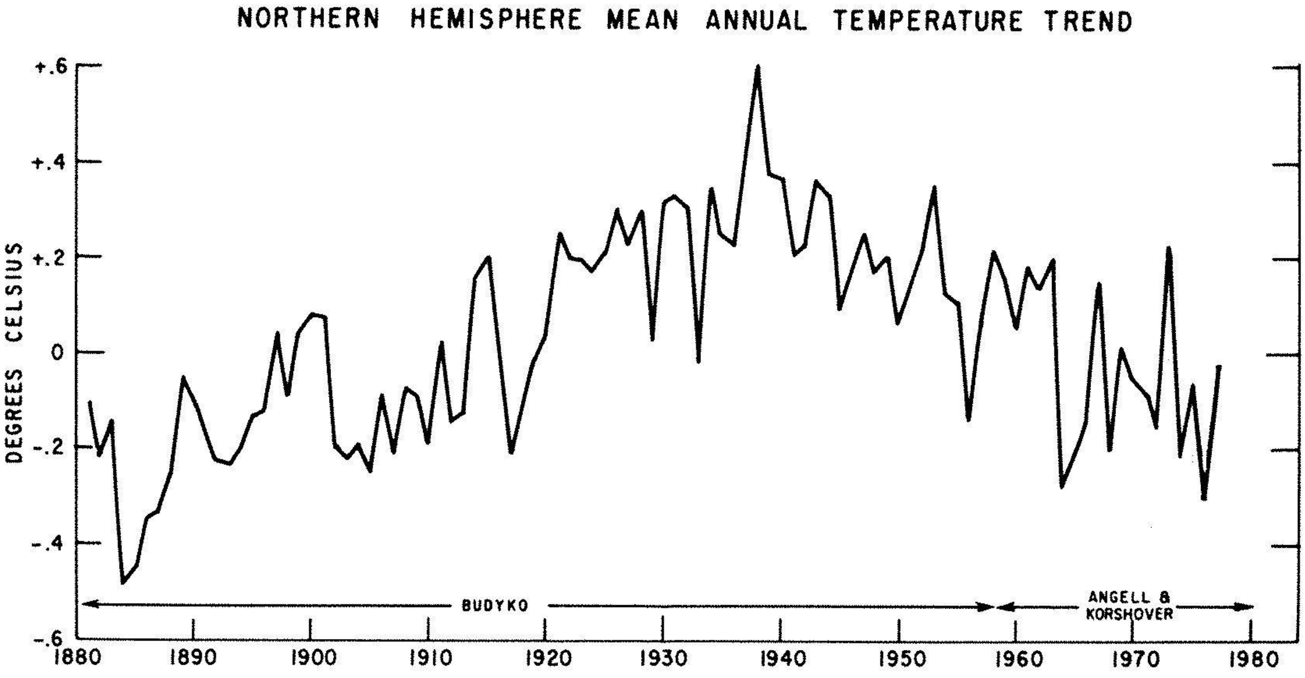


Fig. 6. Changes of annual mean temperature for the Northern Hemisphere, from Budyko (1969) updated through 1977 by J.K. Angell (NOAA, private communication).

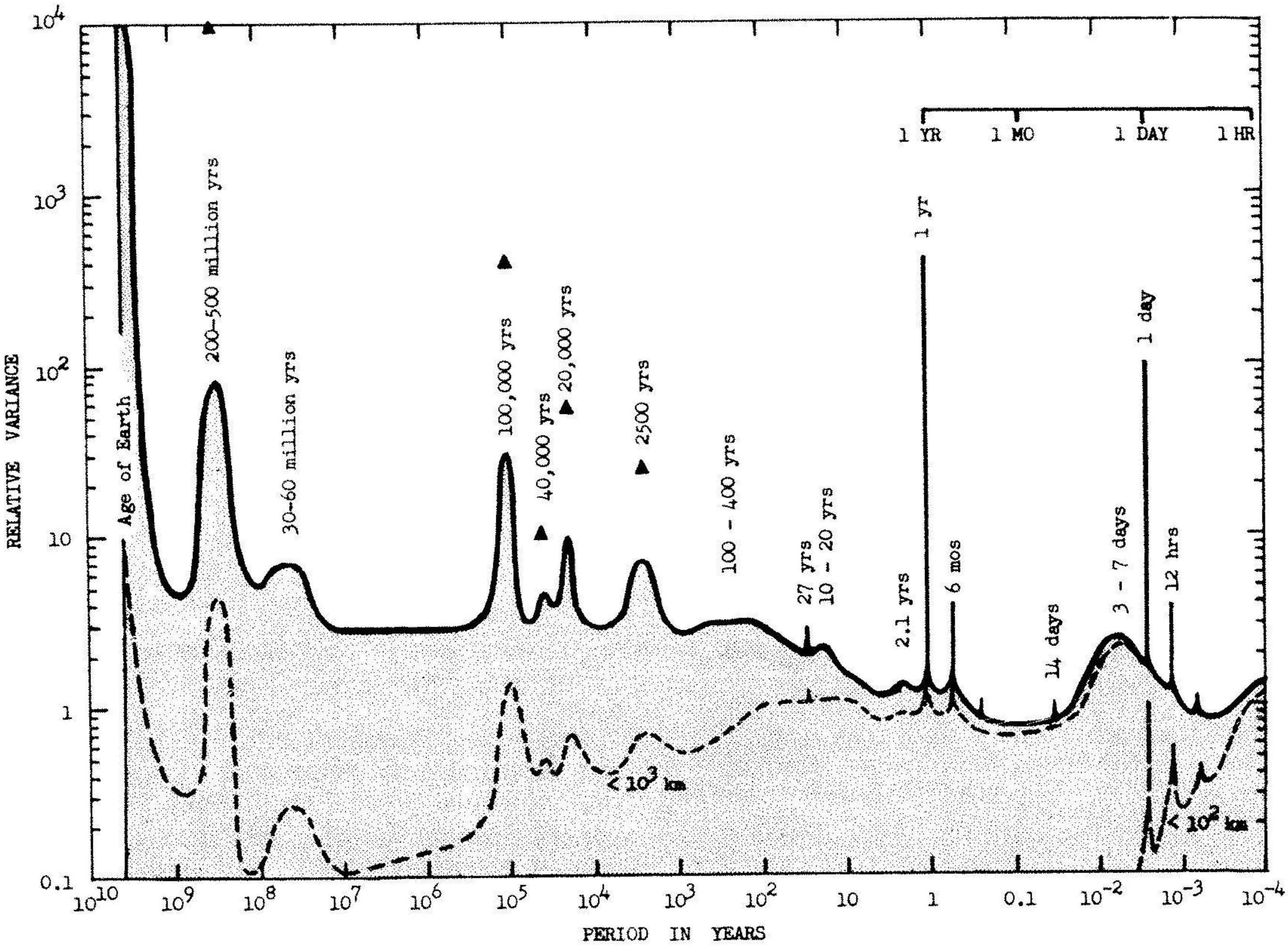
tude. Regional variations of temperature have been of the order 1–2 °C, and those of precipitation, of the order of 10–20%.

In the first half of the 20th century, the world was enjoying a full recovery, at least temporarily, from the Little Ice Age. There are indications that, at that time, the circumpolar westerlies contracted toward the poles, and that, in the Northern Hemisphere at least, the amplitude of the planetary waves underwent a decrease. Also at that time a general warming of the earth occurred which was most pronounced in the Atlantic sector of the sub-Arctic. A rapid world-wide retreat of mountain glaciers, and a poleward extension of the ranges of many flora and fauna took place then.

Since the 1940's, there is considerable evidence that the climatic changes of the earlier part of this century have undergone a reversal (fig.6). Temperatures have fallen, especially in the Arctic and the Atlantic sub-Arctic where sea ice has been increasing. The circulation of the Northern Hemisphere appears to have shifted in a manner suggestive of an increasing amplitude of the planetary waves, and of greater extremes of weather conditions in many areas of the world. These events have culminated, in the last decade, in the emergence of anomalous conditions in the monsoon belt of the tropics, in widespread drought in the Sahel zone of Africa and in Northwest India, and in a spate of rather extraordinary weather extremes in other parts of the world. To what extent these recent events are related to each other, as manifestations of a globally coherent fluctuation of climate, is not entirely clear. In any event they dramatize the fact that climatic variability, whether globally coherent or not, is to be expected no less on time scales of months and years than on time scales of centuries and millennia.

Mechanisms of climatic variability

The record of past climates is far from complete either geographically or temporally. Interpolations based on educated guesses are necessary to bridge across gaps in our reconstructions if our aim is to develop a chronology spanning all time scales of variability. The further back in time we look, the poorer becomes our knowledge of shorter time-scale events and other details. Despite these failings, two reliable conclusions can be drawn. First, to one extent or another climate appears to have been variable on all discernable scales of time. Second, in a number of ranges of time scale (i.e., periods of



variation) it is difficult to avoid the impression that there have been periodic or quasi-periodic movements of climate.

Elsewhere (Mitchell 1976), I have made an attempt to draw out from the climate record an estimate of the variance spectrum of climate for all periods of variation from the age of the earth to a fraction of one day. I emphasize that this spectrum, shown in fig. 7, tables 1 and 2, must be regarded only as a very crude approximation to reality. I have suggested that all the peaks appearing in this estimated spectrum can be defended as being probably real whether or not they are portrayed with correct amplitude and bandwidth.

Fig. 7. Estimate of relative variance of climate over all periods (wave-lengths) 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.

Tab. 1. The geological clock

Years before present	Event	Relative time before present
$4{,}5 \cdot 10^9$	Age of Planet Earth	1 year
$6 \cdot 10^8$	Cambrian Period	7 weeks
$6 \cdot 10^7$	Cenozoic Era began	5 days
$2 \cdot 10^6$	Quaternary Period began	4 hours
$125 \cdot 10^3$	Last Extreme Interglacial (Eem)	15 minutes
$18 \cdot 10^3$	Maximum Würm Glaciation	2 minutes
$10 \cdot 10^3$	Present Interglacial (Holocene) began	70 seconds
$6 \cdot 10^3$	Postglacial Warm Peak (Hypsithermal)	40 seconds
130-550	Little Ice Age (1430-1850 A.D.)	1-4 seconds
40	Modern Thermal Maximum (ca. 1940 A.D.)	0.3 seconds

It is to be pointed out that should climate vary in a totally random manner, defined as "white noise", the spectrum of climate would be characterized in the coordinate system of fig. 7 as a straight horizontal line across all periods (or frequencies) of variation. The

Tab. 2. Characteristic recurrence intervals of selected climatic and environmental events

Recurrence interval (years)	Event	Relative interval
$4{,}5 \cdot 10^9$	Age of Planet Earth to date	1 year
2 to $4 \cdot 10^8$	Major Ice Age Avents (since Pre-Cambrian)	2–5 weeks
3 to $6 \cdot 10^7$	Orogenic/Epeirogenic Revolutions	2–5 days
2 to $10 \cdot 10^4$	Quaternary Ice Volume Fluctuations	2–12 minutes
2500	Neoglacial Events in Holocene	15–20 sec
100 to 400	Historical Climatic Fluctuations	1–3 sec
11 to 22	Solar Cycles	.08–.15 sec
1	Annual Insolation Cycle	.007 sec (140 Hz)
.01 to .02	Planetary-scale Weather Variations	.0001 sec (10^4 Hz)
.00274	Diurnal Insolation Cycle	.00002 sec ($5{,}2 \cdot 10^4$ Hz)

actual spectrum, as I have reconstructed it, differs from white noise partly in that the variance shows a general tendency to increase with increasing period of variation. This condition is defined as "red noise". Superposed on the red noise are a number of relatively broad-band peaks, each with a characteristic period of variation as shown.

I have chosen to stress the record of climate in terms of its spectrum, rather than as a time series, because the spectrum has special diagnostic value from the viewpoint of clarifying physical mechanisms of climate variability. In particular, the spectrum is well suited for distinguishing between strictly aperiodic variability on the one hand, and either periodic or quasi-periodic variations in certain ranges of period on the other hand. It also tells us at a glance what fraction of the total variance of climate derives from each of these two kinds of variability, in any arbitrary range of periods in which we might have a special interest.

The part of the variance that the spectrum suggests is aperiodic is to be interpreted as that part which originates from stochastic changes of state of the climate system through mechanisms internal to the system. This arises through a hierarchy of physical processes, each process adding to the variability of climate at all periods longer than the characteristic time scale of the process itself.

The part of the variance that the spectrum suggests is periodic or quasi-periodic might be interpreted in one of three ways:

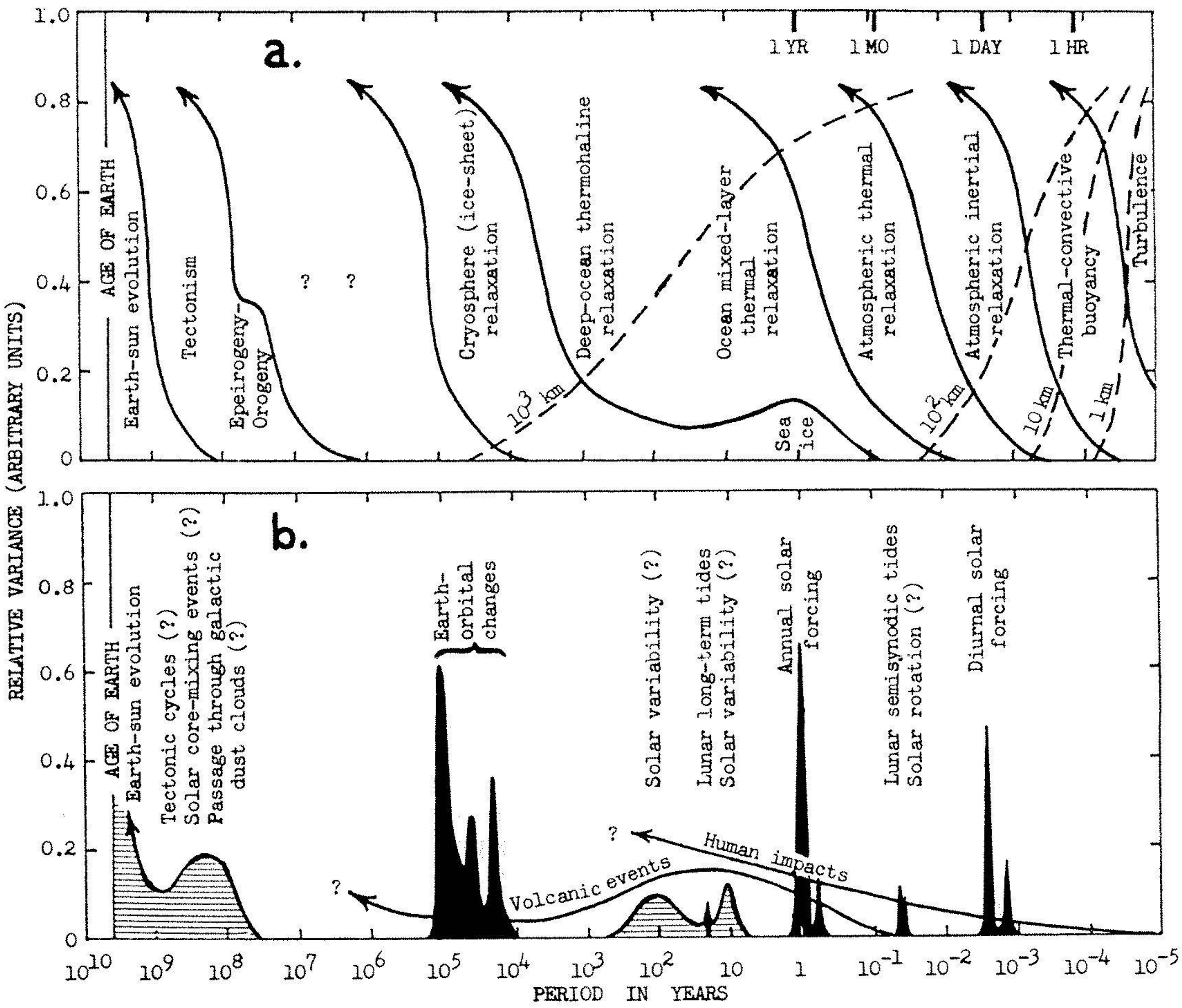
1. It arises through an internal stochastic process that converts potential energy to kinetic energy of motion in some part of the climate system (for example, cyclogenesis on time scales of a few days);

2. It arises through forcing of the climate system by a periodic or quasi-periodic variation of some aspect of the earth's environment outside the climate system, that is able to affect either the solar energy arriving at the earth or the disposition of that energy after it reaches the earth (for example, volcanic dust injections into the stratosphere); or

3. It arises through a resonance between a recurrent or periodic environmental change and a process internal to the climate system that possesses the appropriate response frequency to allow resonance (for example, the long-term changes of the earth's orbital elements in combination with some form of interaction, possibly one between the polar ice sheets, sea level changes, and deep ocean mixing).

In figure 8 (reproduced from Mitchell 1976), I have suggested a number of mechanisms that come to mind as possible drivers of climatic variability and change across all time scales of variation. In fig. 8a I show a hierarchy of "relaxation" mechanisms that are potentially capable of producing internal stochastic variability of climate in various ranges of time scale as indicated. In fig. 8b I show a range of extrinsic environmental phenomena, some of which are only speculative, that are at least potentially capable of "forcing" changes in the climate system from beyond its boundaries.

With regard to the construction of "models" of climate system behavior, figure 8 may serve as a very tentative guide to indicate what general forms of mechanisms must be included in the models if they are to simulate



real climatic variability in all essential respects. If our concern is with climatic variability on time scales of hours and days, then conventional atmospheric general circulation models would suffice for understanding and prediction. If, however, our concern is with variability on longer time scales of weeks, months, or years, then it is necessary to include in our models interactions between the atmosphere and the upper mixed layer of the oceans, snow, and sea ice. Variability on still longer time scales must consider an ever expanding part of the overall climate system, along with a growing number of longer-term extrinsic forcing phenomena. Various chemical and biological processes, that influence the composition of the atmosphere and the properties of the earth's surface, not explicitly shown in fig. 8,

Fig. 8. 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 period of variation arises from each stochastic process at shorter periods of variation. 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. Forcing mechanisms of doubtful validity are distinguished from the others by question marks.

would also need to be brought into consideration.

Looking to the future, it is important to keep in mind that anthropogenic influences on climate are likely to be of rapidly growing importance. The future accumulation of carbon dioxide in the atmosphere from the combustion of fossil fuels is a major concern in this connection. This circumstance lends a special sense of urgency to the development of realistic models of climate system behavior, as a powerful tool to assess the consequences of human activities to future climate and to the stability of the polar ice sheets. To whatever extent man may harbor the potential to drive global climate to inhospitably extreme conditions unknown in the past, better understanding of the climate system may be the only option we have to assess the environmental risk that we as a world society would be taking if we continue for very much longer to rely on fossil fuels as our principal source of energy.

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