Climate and its variations

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Climate and Its Variations

Huw Cathan Davies

Summary

A brief survey of global climate and its variations is presented from a physical standpoint. Thus consideration is given to the character and consequences of the interdependent processes that establish the nature of the present climatic state of the earth-atmosphere system. The review concludes with a summary of some of the major climate variations and a discussion of the possible instigating mechanisms.

Zusammenfassung

In einem kurzen Überblick wird das globale Klima und seine Veränderlichkeit vom physikalischen Standpunkt aus dargestellt. Beschrieben werden der Charakter und die gegenseitigen Abhängigkeiten der Prozesse, die den gegenwärtigen Zustand des Erde-Atmosphäre Systems bestimmen. Dieser Überblick wird durch eine Zusammenfassung der hauptsächlichsten Klimaveränderungen und deren möglichen Verursacher abgeschlossen.

Résumé

Une brève revue du climat global et de ses variations est présentée. On y considère le caractère et les conséquences des processus interdépendants qui déterminent l'état climatique actuel du système terre-atmosphère, en concluant par un résumé de quelques variations climatiques majeures et une discussion de leurs mécanismes possibles.

Introduction

The vagaries of climate influence the living standard and incite the scientific interest of people from every country. For instance Switzerland was, within two years of the ratification of the Confederate constitution in 1815, ravaged by a famine related to a short term climate variation. Likewise the first volume of the records of the Schweizerische Naturforschende Gesellschaft published in 1833 included an observational study of temperature variations in the Swiss Alps. This study provided the necessary evidence to accord the status of theory to the newly formulated Ice-Age hypothesis. This interest and concern in the topic of climate has been intensified with the increasing realization that, in turn, the living standards of today might exert a significant influence upon the climate's vagaries.

The quest for an understanding and appreciation of this complex topic is an issue that is central to the physical sciences. In this brief review an outline is given of global climate and its variation from a physical standpoint. This approach directs attention toward and underlines the significance of, the basic processes that govern the behaviour of the earth-atmosphere system. It is hoped that the adoption of such a strategy will also enable the review to serve as an introduction to, and a framework for, the other contributions to this Symposium.

The succeeding sections seek to illustrate the nature of the present climate, indicate the range of climate variations, and interpret the possible contributions of various mechanisms to these variations.

Nature of the Present Climate

An adequate understanding of our present climate constitutes a highly desirable, if not a necessary, pre-requisite to any attempt to study, interpret or predict changes in the earth-atmosphere climatic system. The fun-

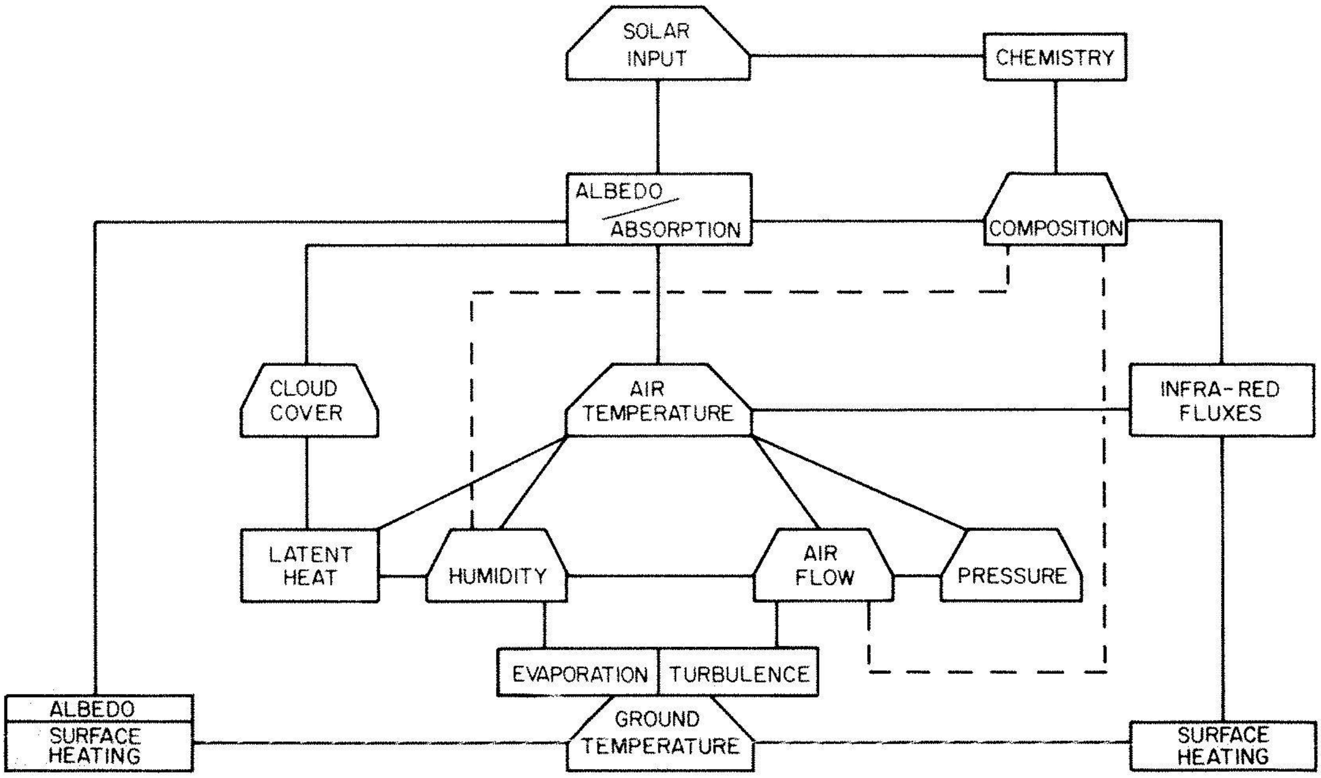

Fig. 1. A box representation of some of the climate variables (⏢), processes (▭) and their interdependence.

damental factors that determine the present climatic state of the system are the input of solar radiation, the rotation rate of the earth, the composition of the atmosphere, and the surface characteristics of the land and sea. These factors together give rise to the myriad of interdependent processes that are the subject of our study.

On a global scale the effect of the incoming solar radiation can be offset by two contributions. The first contribution is the immediate partial reflection of this input by the atmosphere (for the most part from clouds) and from the earth's surface (with albedo values varying from 0.8 for fresh snow to 0.2 for scrub). This reflection accounts respectively for approximately 26% and 4% of the input. These processes correspond to the left side of the schematic (Fig. 1). The absorption of the remaining energy input occurs predominantly at the earth's surface and in the atmosphere by water vapour, dust and clouds. Also of importance is a temperature dependent radiative-chemical process involving ozone in the stratosphere. The second offsetting contribution is the infra-red emission of the system. The atmosphere effects a considerable absorption of the infra-red flux from the surface and reradiates it both upwards and downwards (right side of Fig. 1). A major component of the absorption is attributable directly to the atmospheric water vapour content but smaller contributions arise from CO_2 and other trace gases. This opaqueness of the atmosphere in the infrared maintains surface temperature at a level of the order of 33°C warmer than would prevail in its absence. This has been termed the atmospheric greenhouse effect. Annual average values of the temperature indicate that a quasi-balance is achieved for the global system. However, this balance is not attained locally, neither in the vertical or the horizontal. In the vertical the troposphere is sufficiently opaque in the infra-red that a purely radiatively established vertical temperature gradient gives an intrinsically convectively unstable thermal configuration. This instability is relieved by dry and moist turbulent convection involving evaporation and cloud formation with associated vertical fluxes of sensible and latent heat (Fig. 1, centre). They act to reduce the vertical temperature gradient, and are related to the net radiative heating of the earth's surface and cooling of the troposphere. In comparative terms these

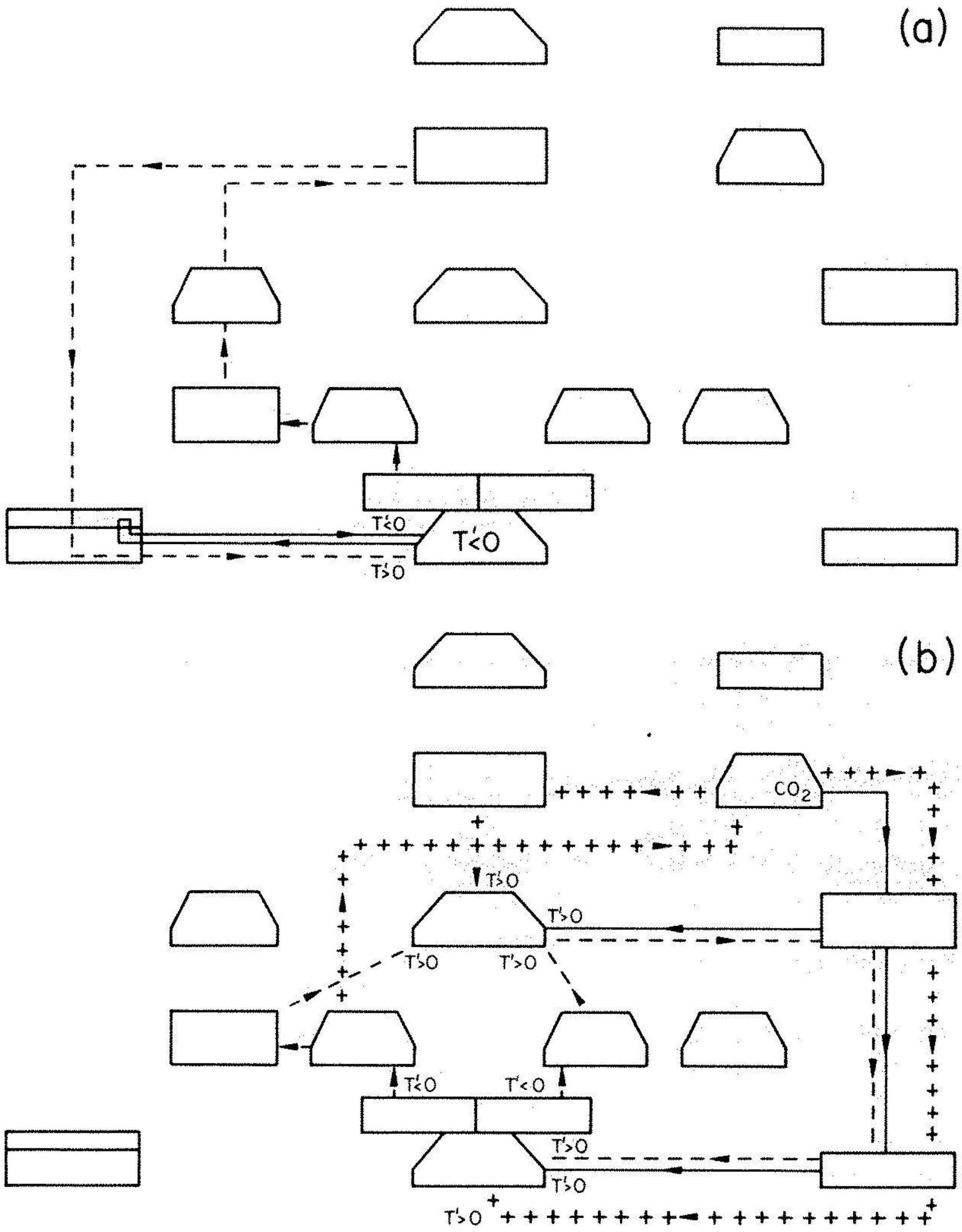

Fig. 2. Possible sequence of effects following:

fig. a) – an increase in surface temperature at the ice-sheet limit.

fig. b) – an increase in the global CO_2 content.
(See text for classification of processes).

imbalances are equivalent to an uniform 0.8°C per day cooling of the troposphere at all latitudes. In the horizontal the observed pole-equator temperature gradient is considerably less than would be established purely by the foregoing radiative-convective process, and there is a concomitant net radiative cooling of the polar regions and heating of the tropics. The necessary compensating horizontal heat flux is achieved to a considerable measure by the sequence of transient eddies that dominate the weather patterns of mid-latitudes (again depicted in the central core of Fig. 1). Oceanic circulation also contributes substantially to this poleward heat flux. The character of the atmospheric eddies is heavily constrained by the earth's rotation while their origin, energy source and vigour is related to the fore-mentioned radiative-convective latitudinal temperature gradient. Again the eddies provide a negative feedback effect in that they act to reduce the pole-equator temperature difference.

A measure of the complexity of the system is apparent on noting that the circulation pattern of these eddies regulate the cloud cover and modify the distribution of the constituents of the atmospheric composition (the dashed lines of Fig. 1). In turn the cloud cover and the distribution of the constituents influence the albedo and radiative properties of the atmosphere.

To illustrate the interactive complexity of the climate system two further examples of the feedback processes and detailed in Fig. 2. The schemata are based on the previous diagram, but now portrayed are a sample of some possible sequences of effects that could follow a change in surface temperature at the ice-edge sheet (Fig. 2 a) and an increase in the global CO_2 content (Fig. 2b). In the former case the solid lines correspond to the positive feedback that is often postulated between ice-cover and the ambient temperature at an ice-sheet edge. A temperature drop is assumed to result in more ice and snow cover with an accompanying increase in albedo, reduction in the absorbed solar energy and a further decrease in temperature. However, the amplitude of this feedback might be modified by the sequences (dashed lines) indicating a decrease in evaporation following the ice sheet extension, leading (say) to a decrease in low level stratus cloud cover and a consequent counteracting increase in the solar radiation incident at the ground. Furthermore the transient eddies discussed earlier might feed on, and reduce, the horizontal temperature gradient established near the ice edge limit.

In Fig. 2b the solid lines denote the increased heating of the surface and reduction of atmospheric cooling as a direct «green-house» response to a CO_2 increase. The dashed line is a positive feedback that relates to an additional surface heating from the warmer troposphere, followed by a further heating of the troposphere via sensible and latent heat flux increases. Again the resulting increase in the atmospheric moisture content will (cross lines) amplify the atmospheric temperature increase by increasing the absorption of solar radiation and provide additional infrared heating of the surface. Yet another factor is that important components of the chemistry of trace gas reactions will also be influenced by the temperature increase.

It is clear from these examples that purely qualitative considerations of these interactive processes is probably inappropriate, and that climate models must incorporate at least the major interactions in a justifiable quantitative fashion. It is also noteworthy to remark, in view of these many feedback precesses, that there is no physical law that requires à priori a global quasi-balance to exist for such an intricate system. Nevertheless our existence is a testimony that it prevails at present, and our continued existence is dependent upon its maintenance.

Climate Variations

The conventional instrumental record of the last 200-300 years and a range of proxy data for earlier periods indicates that the climate has exhibited variations on a wide range of time scales. In Fig. 3 an inferred time history of surface temperature is displayed with the time span of the panels differing successively by one (or two) orders of magnitude.

The schematic suggests that we are living in one of the warmest periods of the past million years - the so-called Holocene interglacial period of the last 10000 years. Several other short interglacial periods with a duration of ~ 10000 years appear to have occured at intervals of ~ 100000 years within the predominantly ice-age climate of the last million years. Within the Holocene period itself the proxy data for the northern hemisphere indicates equally substantial (~ 2°C), quasiperiodic temperature oscillations. Notable features of the last 1000 years in Europe are the warm period of the middle Ages (1150-1350 AD) and the subsequent «Little Ice-Age» of 1500-1850 AD. In the subsequent period there appears to have been an upward trend of global temperature until about 1940. Thereafter, at least poleward of 50° N, there has been until recently a gradual downward drift.

On even shorter time scales the evidence of the last two decades provides ample indication of strong inter-annual and seasonal variations. For instance the unusual and protracted El-Niño event of May 1982 - June 1983 in the equatorial Pacific was accompanied by, or coincided with, many significant anomalous weather patterns e.g. drought in parts of Peru, Bolivia, Central America and the Sahel, severe rainfall in Ecuador and Northern Peru, and some evidence of effects even in North America.

A framework for the further examination of these changes is given by the following conventional definitions,

- the climatic state is the mean or average (together with appropriate higher order statis-

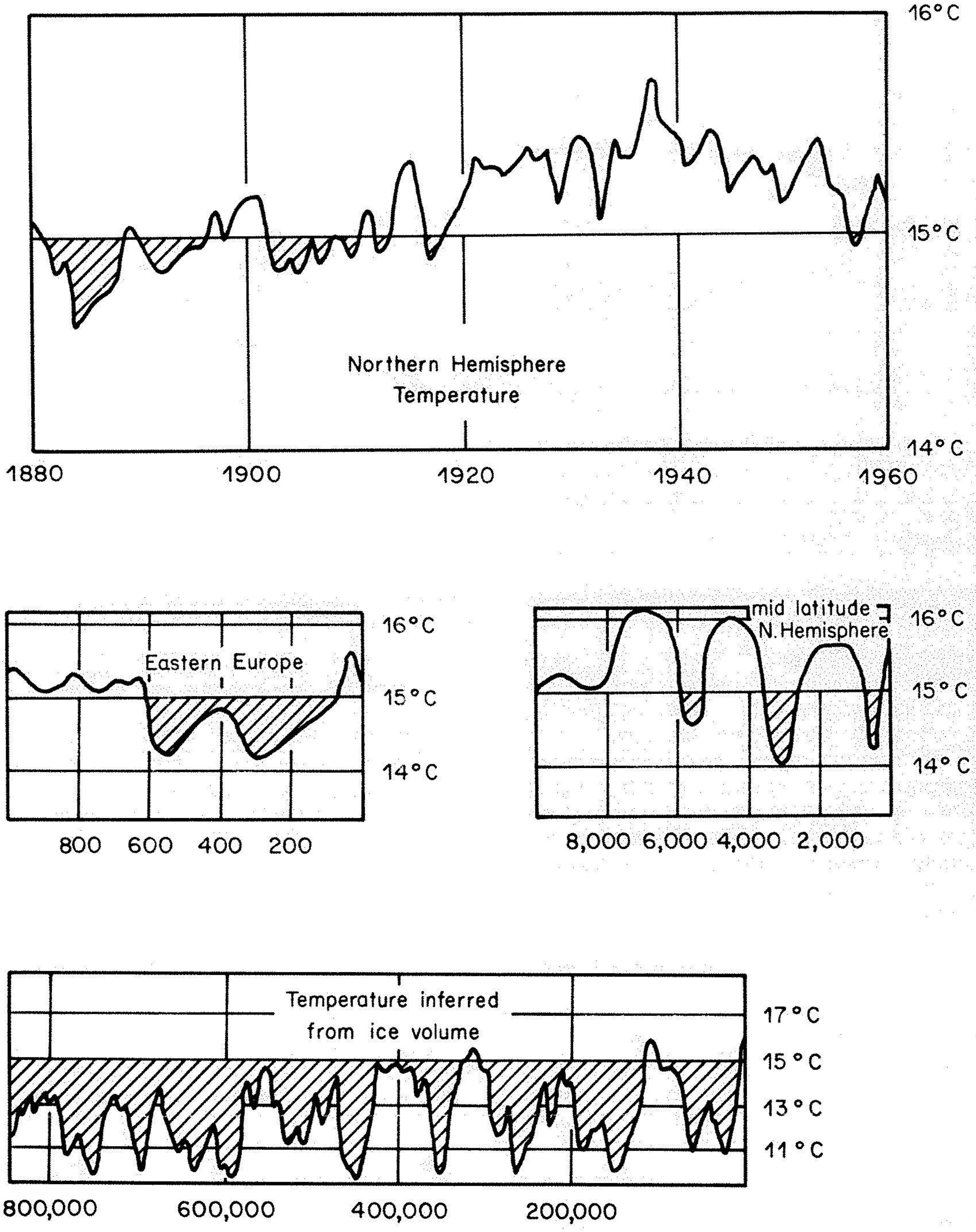

Fig. 3. Schematic time-trace of inferred or measured surface temperature. Note time span of successive panels differ by one (or two) order of magnitude and also differ in geographical extent.
(Adapted from NRC Report, 1975).

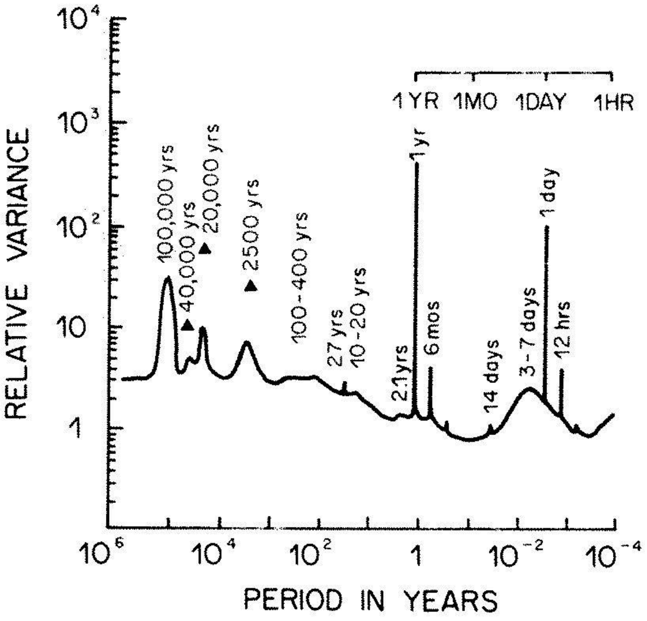

Fig. 4. Highly schematic depiction of the spectral distribution of the relative variance of the temperature record.
(Adapted from NRC Report, 1982).

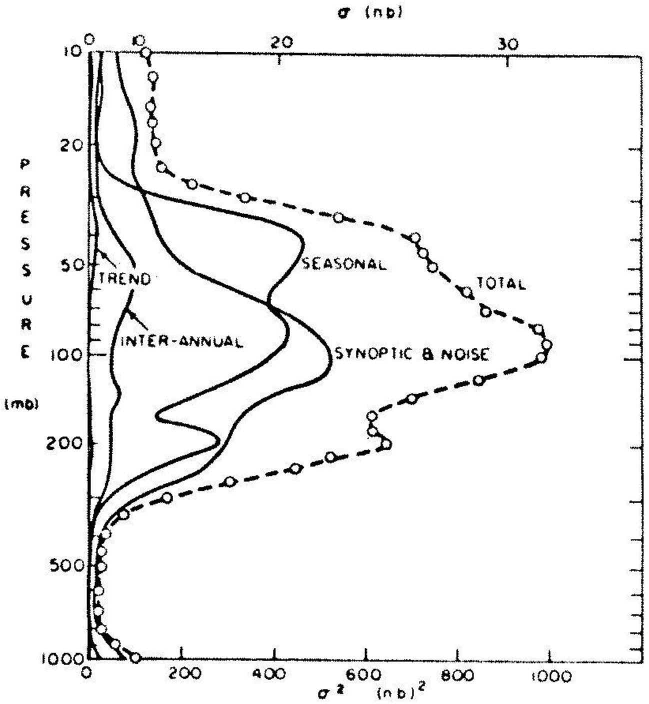

Fig. 5. Vertical distribution of the total and specified sub-components of the variance of ozone partial pressure over Aspendale, Australia for an eight year series of weekly measurements.
(NCR Report, 1982).

tics) of the complete set of atmospheric and related variables over a specified time interval (month, season, year, decade).

- Climatic variation is the difference between climatic states of the same kind (e.g. between two Januaries or two decades).

In terms of these definitions it is useful to examine the spectral distribution of the relative variance of the time trace of the surface temperature. A schematic of such a plot is given in Fig. 4. There are the expected peaks at the semi-diurnal, diurnal and annual period. The broad peak in the 3-7 day band is the contribution of the large-scale mid-latitude transient eddies, and the well-documented quasi-biannual oscillation accounts for the 2.1 year peak. However, there are several additional significant peaks e.g. the contribution at the 100000 year location is the spectral counterpart of the major glacial-interglacial epochs.

Our earlier assertion that climate variations occur on a very wide range of time scales is reemphasized by the content of Figures 3 and 4. This wide range of scales is also a salutary indicator that the search for an unified and comprehensive theory of climate might be a formidable task.

Measurements, Mechanisms and Models

Instigators of climate variations of the earth-atmosphere system must induce a change in the energy input or the energy output of the system, or be related to a self-sustained internal change.

The predictable astronomical factors that alter the earth's orbital parameters, and a change in the solar emission itself constitute direct changes in the solar radiation input to the system. A change in the atmospheric composition or the nature of the earth's surface that would induce changes in the albedo or the radiative properties of the system would correspond to output changes. Examples in this category are an increase of atmospheric CO_2 or other trace gases, increasing dust content due to volcanic activity, and albedo changes arising from deforestation or over-grazing. The remaining category, self sustained changes, refers to intrinsic fluctuations of the system. For short time scales these fluctuations constitute the day-to-day weather changes but it has been argued that there are contributions to this category on all time scales.

The actual time development of the system is influenced by all these factors. Hence the observed climate variability is composed both of the natural variability, or climatic noise, associated with the intrinsic fluctuations, and the climatic signal associated with specific climate change mechanisms. It follows that the detection of an external (i.e. independent of the existing climatic state) influence requires it to be evident in the climate signal above the noise. Further an unequivocal identification of a specific external cause requires it to be, to some measure, quantitatively related to the observed effect. The magnitude of the climate change detection problem can be gleaned from Fig. 5 which shows a trend of less than 4% of the total variance in a one station, eight year series of weekly measurements of the vertical distribution of ozone.

In fact there is a discomfortingly low value for the signal-noise ratio for most climate variables. This remark applies particularly to the mid-latitude troposphere, and it also implies that a long record of measurements will usually be required to validate the results of detection studies.

In the following sections a summary is given of salient features of the above mentioned possible instigators of climate change.

a) Astronomical Factors

The distribution of insolation is determined by three parameters of the earth's orbital motion: eccentricity, obliquity and precession. These factors specify respectively the deviation of the earth's orbit from circularity, the tilt of the earth's equatorial plane from its orbital plane, and the direction of the earth's axis of rotation in space. These three parameters vary in a quasi-cyclical manner with respective periods of approximately 100000 -, 41000 -, 22000 - years. Their variation during the last 250000 years is shown in Fig. 6. Also shown is an estimate of the global ice volume inferred from deep sea sediment data. There is an evident strong correlation of the ice volume with the eccentricity. Further climat-orbital parameter links are revealed by power spectrum analysis of a longer time series of sediment data. Results show (see the 10^4-10^5 year spectral band of Fig. 4) a dominant contribution at 100000 years and also smaller but significant peaks at approximately 40000 - and 20000 -years.

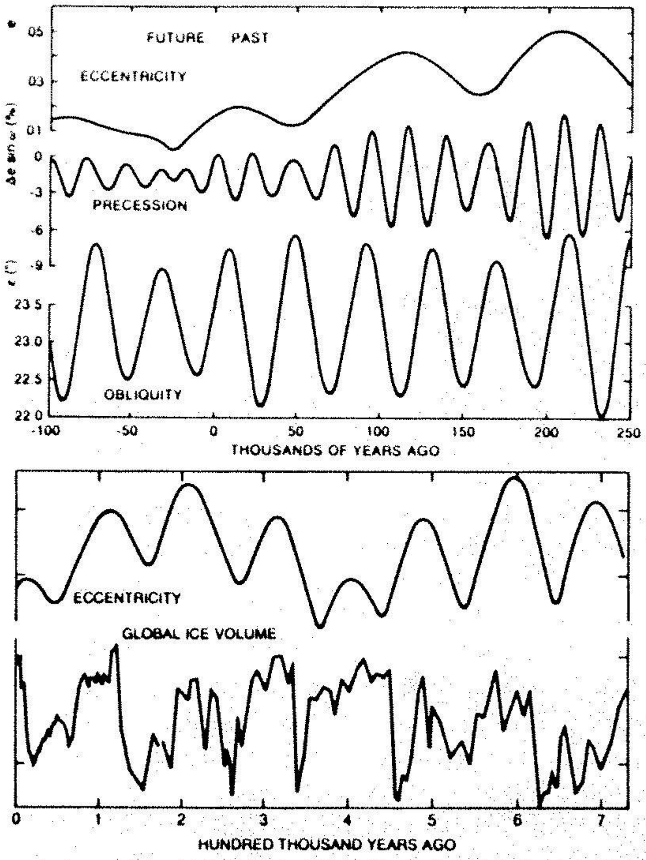

Fig. 6. Variations of the eccentricity, precession and obliquity parameters of the earth's orbital motion over the last 250000 years. Bottom panel indicates the global ice volume changes during a longer time period.
(Adapted from Imbrie and Imbrie, 1979).

The global net value can change only with eccentricity variations and the greatest range is only about 0.1%. However, for the latitudinal distribution there is: in the net annual values a strong response to obliquity, and in the summer mean values there is an eccentricity related trend. Also there is an obliquity signal of about a 1% and 4% insolation change in respectively the temperate and polar latitudes, and a comparable precession signal in the tropics.

The summer mean values are of particular interest because the Milankovitch Ice-Age hypothesis proceeds from the premise that the magnitude of these values in the higher latitudes is a key factor in determining the growth or decay of the ice-sheets. It follows that the hypothesis would be sustained by a 40000 year obliquity related climate change. However, the observed 100000 year cycle does not directly substantiate the hypothesis. Simple energy balance models that incorporate crude representations of the ice-albedo feedback effect and the atmospheric

heat transport also produce a weak Milankovitch effect, but not a 100000 year cycle.
The further elucidation of the influence of astronomical factors is of considerable significance because it promises tantalisingly both an emirical estimate of climate sensitivity to changes in the incident solar radiation and also a bench mark validation criterion for climate models.

b) Solar Influence
Solar variability is known to exist on various time scales (minutes to decades), and these variations cover a broad band of spectral irradiance (from X rays and ultraviolet to cm wavelengths). However, the variable parts of the solar constant constitute certainly less than 1 % of the total solar energy input to the earth-atmosphere system. Furthermore the main contributions to this variation occurs predominantly on the wings of the maximum in the spectral distribution (Fig. 7), and at these wavelengths most of the incoming solar energy is either absorbed or dissipated in the upper atmosphere. One of the most notable impacts is that variations in the 200-310 nm radiation (containing 1.75% of the total solar power) would modify the temperature of the upper stratosphere due to absorption by the ozone layer centred around 50 km. The available observational evidence for a solar cycle influence upon stratospheric ozone and temperature is suggestive rather than definitive. Recent satellite measurements have revealed solar constant fluctuations at the 0.1 - 0.3 % level persisting for a few weeks. These variations have been quantitatively related to radiative deficits proportional to the area of the solar disc covered by sunspots.
The dearth of physical hypotheses to underpin solar-climate links is related both to the low level of the solar constant fluctuations and to the inference that the largest direct effects would be at altitudes of 50-80 km. The systematic low values of the atmospheric energy density at these elevations effectively rules out a direct dynamical influence upon tropospheric climate. However, a temperature-wind related change in the stratospheric transmissivity to upward propagating planetary waves from the troposphere is a possibility. However it has yet to be shown to be significant. Radiative coupling in the vertical would occur if there was a perturbation of stratospheric ozone. An ozone increase would reduce the direct solar heating of the troposphere and increase the downward emission of infra-red from the stratosphere. The net effect would depend upon the vertical ozone distribution.

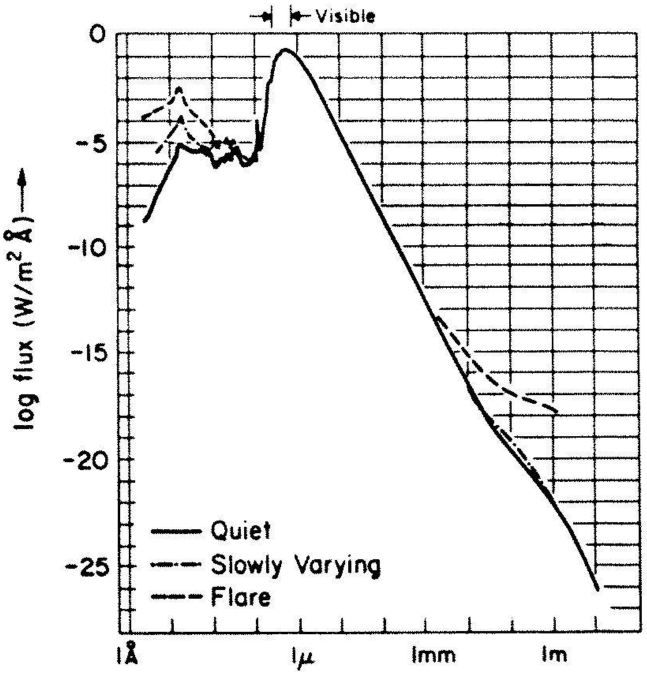

Fig. 7. Solar output displayed as a function of wavelength. Range displayed corresponding to periods of high and low solar activity.

The various postulated solar-climate relationships refer to phenomena such as the 11 year solar activity cycle, the Hale 22-year double sunspot cycle, variations in sunspot structures and major flare events. In many of these studies long time series of climate related variable(s) from a single or from a network of stations are compared with some index of solar activity. Most of the apparently highly significant correlations obtained in these comparisons have not been substantiated when tested with different or enlarged data sets. The use of slipshod statistical techniques partly accounts for this debacle. A counterpoise is that the possible non-stationarity and the spatial inhomogenity of natural variability implies that the breakdown in space or time of an apparent correlation of this genre is neither evidence for or against a generalised sun-climate relationship.
However, this failure does underline the desirability of linking these statistical correla-

tion exercises to an accompanying physically based rationale. The absence of such postulates is emphasised in a recent NRC report on «Solar Variability, Weather and Climate», and it accorded the following epitaph to these correlation studies «....none of these endeavours, nor the combined weight of all of them, has proved sufficient to establish unequivoval connections between solar variability and meteorological response.»

c) Atmospheric Composition

The stratospheric aerosols that results from major volcanic eruptions persist for a few years and produce a substantial but temporary reduction in global surface temperature. In this connection note that the famine of 1816-1817 in Switzerland was preceeded by an intense eruption of the Indonesian Tambora volcano in April 1815. The increased albedo effect offsets the infra-red greenhouse effect of the aerosols resulting in stratospheric temperature changes of ~ 3°C, and global surface temperature changes of $\leq$ 1°C. The net radiative effect of an eruption depends upon the size and composition of the particulates that are injected into the stratosphere. It is possible that much of the observed variability of the recent past is attributable directly to volcanic effects.

Other symposium contributions consider in detail the influence of aerosols, CO_2 and other trace gases. Here we note that the atmospheric CO_2 content is expected to double sometime during the next century. The consensus results from a range of models (embracing local radiative-convective representations and global circulation models) is that it will produce a sustained global surface temperature increase of between 1½ to 4°C. This change is larger than any natural change in the historical past. The validation of these predictions is hindered by problem of detecting unambiguously a CO_2 induced climate change signal as a response to the observed exponential CO_2 increase since 1958. The difficulties arise from the possible lag effect associated with the large thermal inertia of the ocean, the masking of the effect by the influence of other climate change instigators and the noise associated with the natural variability. The recent reconstruction of the history of atmospheric CO_2 concentration from information of the CO_2 trapped in large ice-sheets may help in this detection problem.

d) Natural Variability

It has been conjectured that natural variability exists on all times scales. Here we consider some aspects of the inter-annual scale. A likely instigator of variation on this time scale is anomalous diabatic heat supply to the atmosphere. Such effects include sea-surface temperature (S.S.T) anomalies, changes in the air-sea exchange due to variations in the ice-edge limit, and albedo changes due to prolonged or foreshortened snow cover. The most plausible instigator, in terms of extent, persistence and intensity, is an S.S.T. anomaly.

An example par excellance occurs during an El-Niño event. A region of warm surface water (as much as 6°C above normal) covers the central and eastern tropical Pacific Ocean for a period of up to 1 year. The atmospheric response includes a strong local intensification of convection and rainfall in the neighbourhood of the dateline with an accompanying modification of the low level trade winds, and drought events further afield in the tropics. Also striking is the detection from observations of a statistically significant climate response in certain regions of the temperate latitudes. This relationship was first mooted by Walker in the 1930's on the basis of empirical correlation studies. For some regions of North America this effect has now been shown to amount to up to 20% of the winter portion of the inter-annual climate variance. The global scale climate anomaly pattern engendered by an El-Niño event has been incisively interpreted, using a range of circulation models, as an effect of the propagation of wave energy away from the tropical source region. For the large scale atmospheric circulation the wave agency is the so-called Rossby wave.

Thus in these studies of El-Niño there has been an attempt to elucidate the nature of the instigator of climate variation, the amplitude of the atmospheric response, and the atmospheric transmission mechanism. This has provided a firm platform for further study. It is of interest, and irony, to note that this platform was established by the successful amalgam of entrepreneurial correlation exercises, painstacking diagnostic data analysis and dovetailing theoretical studies.

Final Remarks

It has been underlined in this study that the interactive processes that determine the nature of the climate and climate variations of planet earth are numerous and intricate. The scientific task of understanding these processes poses a formidable challenge. Moreover the possible repercussions of man's activity upon the environment adds urgency to this challenge.

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