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CAN WE PREDICT CLIMATE FLUCTUATIONS?

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Abstract

The climatic state is defined in terms of the statistics of the complete set of atmospheric, hydrospheric and cryospheric variables over a specified time interval in a specified domain of the earth-atmosphere system. It is established that a certain amount of climatic variability which arises from day-to-day weather fluctuations is unpredictable. The nature and magnitude of this inherent variability is discussed.

Causes of potentially predictable variability are outlined; these include changes in both the external and internal climate system. There are basically three methods of forecasting this variability: wholly statistical procedures, physical-empirical methods and wholly dynamical methods. The advantages and disadvantages of each method are discussed, with particular emphasis on the use of numerical models of the atmospheric circulation. It is concluded that the potential of statistical methods is limited because of lack of data and because ultimately forecasts should be based on an understanding of the system. Climate models are useful tools for understanding the climate system but can not, at the present time, be used for predicting climate fluctuations on an interannual time scale. Physical-empirical methods already show some success but further work is required before we can confidently make reliable interannual climate predictions.

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1. INTRODUCTION

Reconstructions of present and past climate using modern observations and various historical indicators demonstrate that the climate system varies on a wide range of time scales, from the seasonal variations to variations on long geological time scales. Figure 1 gives examples of the kinds of processes involved in climatic fluctuations and the characteristic time-scales of observed fluctuations. This paper will concentrate on the causes and prediction of interannual variations, since it is on this time-scale that interest must focus when the prediction of occurences, such as the cold winter of 1977 in the Eastern U.S., the drought of 1977 in the Western U.S. or the drought of 1976 in Western Europe, are considered. A short paper can not completely review the whole subject of long-range forecasting, as the prediction of climate fluctuations on the interannual time-scale is often called; more comprehensive reviews are given, for example, by Lamb (1972), Barry and Perry (1973) and Namias (1974). Likewise, a detailed discussion of the physical basis of the climate system, the causes of climatic change and the modelling of climate and climatic change is not possible and the reader is referred to the recent reports of GARP (1975) and the U.S. Committee for GARP (1975). The present paper therefore gives a personal assessment of the problem, reflecting the areas of experience of the author.

2. DEFINITION OF CLIMATE

The climatic state is defined (U.S. Committee for GARP, 1975) as the average (together with the variability and other statistics) of the complete set of atmospheric, hydrospheric and cryospheric (snow and ice) variables over a specified time interval in a specified domain of the earth-atmosphere system. The time interval refers to a period longer than the life span of individual weather systems (of the order of several days) and longer than the theoretical time limit over which the behaviour of the atmosphere can be locally predicted (of the order of some weeks). Climatic variation is therefore defined as the difference between climatic states of the same kind, such as between one January and the next January.

3. INHERENT VARIABILITY

Since climatic states are defined in terms of finite time averages they are subject to fluctuations of statistical origin in addition to changes of a physical nature (caused, for example by changes in the amount of incoming solar radiation or the composition of the atmosphere). These statistical fluctuations are a result of day-to-day fluctuations in the weather, they are unpredictable over time scales of climatological interest and are therefore refered to as "climatic-noise" or the "inherent variability of the climate system".

In order to answer the question "can we predict climate fluctuations?", therefore, it is necessary to know the magnitude of the unpredictable climatic noise. It would then be possible to compare any potentially predictable long-range change with this inherent variability in a signal-to-noise ratio (Leith, 1973, 1975; Madden, 1976). Within a climatic record a certain amount of the variability will be unpredictable (i.e. noise), there may exist variations not associated with the day-to-day weather fluctuations which may be predictable.

Madden (1976) has estimated the inherent variability of monthly-mean sea-level pressure using a 74-year data set covering much of the northern hemisphere. Figure 2 shows the standard deviation of January mean sea-level pressure associated with the estimated inherent variability. The highest variability is yearly associated with the location of the Iceland and Aleutian low pressure systems. Madden (op. cit.) used this estimate of the inherent variability to examine the possibility of there being potential long-range predictability. Firstly he tested to see if the actual interannual variance of monthly means is greater than the estimated inherent variability, which, as Madden pointed out, was a "pessimistic" test since it proceeded from the null hypothesis that the actual interannual variability is equal to the inherent variability. Fig. 3 shows the ratios of the actual variance to the estimated inherent variability and areas where the ratio is near unity are those where inherent variability adequately explains actual interannual variability. Those regions where the ratio is greater than 1.5 are ones where it is most likely that potential long-range predictability may be found. From this "pessimistic" test, it is concluded that in the middle latitudes (40-60^{O} N) there is little evidence for variability over and above the unpredictable inherent variability, but to the north and south of this band there is more likelihood of potential predictability.

A second test compared some potentially predictable signals with the estimates of inherent variability. Figure 4 shows the signal-to-noise ratio for the quasi-biennial-oscillation (QBO). The latter is a feature primarily of the lower stratosphere over the equator where westerly and easterly winds alternate in an oscillation of roughly two years, but analysis of surface meteorological data have also found variability at this frequency (e.g. Landsberg et al., 1959). Madden derived the "signal" of the QBO by taking the difference between January mean sea-level pressure data during the easterly phase of the QBO and that during the westerly phase (as given by Ebdon, 1975). The signal-to-noise ratio exceeds 0.5 over most of the hemisphere north of 30^{O}N, although again there is a minimum in middle latitudes. This is an example of a signal which could be predicted and represents a change in mean value large enough to be of practical importance.

In an analysis of temperature data for North America, Madden (1977) finds that in most regions evidence for the existence of potential predictability on time scales of a year or more is stronger in summer than in winter, partly because the inherent variability is typically greater in winter than in summer.

In summary, it is established that a certain amount of climatic variability which arises from day-to-day weather fluctuations is unpredictable. It is therefore necessary to examine meteorological records for variability, other than the inherent noise, which could be predicted. The next section will briefly discuss causes of such potentially predictable variability.

4. WHAT CAUSES VARIABILITY?

GARP (1975) subdivided the climatic system into an internal system, consisting of the gaseous, liquid and ice envelopes surrounding the earth, and the external system, consisting of the underlying ground and space surrounding the earth. Sufficiently large changes in the external boundary conditions (configuration of the earth's crust, state of the sun, earth-sun orbital geometry) can obviously result in climatic changes. Variation can also be associated with changes in the internal system, such that changes in the large-scale distribution of the internal driving mechanisms of the atmosphere, ocean and ice occur. The changes in the internal system are manifested as feedbacks (interactions) among the variables of the climate system. For example there are feedbacks between the atmosphere and ocean such that sea-surface temperature anomalies modify the transfer of latent and sensible heat to the atmosphere and consequently affect the atmospheric circulation and cloudiness, these changes in the atmosphere will then lead to changes in the ocean surface temperature, either enhancing the initial anomaly (positive feedback) or eliminating it (negative feedback).

As examples of external causes of climatic variability, Manabe (1975) listed changes in:

- orbital parameters of the earth,
- intensity of solar irradiance,
- rate of rotation of the earth,
- orographic features, such as land-sea distribution,
- atmospheric composition (mixing ratio of CO_2, O_3, etc.)
- aerosol loading in atmosphere (due to volcanic eruption or man's activity),
- heat output due to man's activity.

While some of these changes are predictable (e.g. changes in the orbital parameters) the variability associated with such external forcing is generally on a longer time scale than the interannual variability with which this paper is primarily concerned. An exception to the last statement can be made with regard to the recent work of Bryson and Starr (1976), who suggest that there are atmospheric effects at the same frequencies as those of small motions of the axis of rotation of the earth, which are collectively known as the Chandler motion and have periods of 400 to 450 days. Bryson and Starr (op. cit.) mapped northern hemisphere atmospheric tides at the Chandler motion frequencies and state that these tides are of "significant" amplitude. The nature of the response of the atmosphere to the Chandler motion are "not yet known fully", but the authors claim that significant skill scores have been achieved for predictions based on the relationship between the atmosphere and Chandler motion of monthly total precipitation at a variety of stations. It remains to be shown whether the motion of the axis is influencing the atmosphere or vice versa. Rosen _et_ _al_. (1976) have found that during the period 1958-1968 there was a range of 25% in the relative angular momentum of the atmosphere over the northern hemisphere. Unfortunately data for the southern hemisphere are not available so that variations in the global atmosphere relative angular momentum are not known. The order of magnitude of changes in the northern hemisphere would suggest that the atmospheric changes could well be influencing the behaviour of the oceans and/or solid earth.

A second external forcing mechanism which has been suggested as an important factor on an interannual time scale and which is itself (i.e. the mechanism) potentially predictable is the occurence of sunspots. Summaries of solar-climate relations which have been derived by statistical methods have been given by King (1975) and Wilcox (1975). Mason (1976) points out some of the problems associated with the use of statistics to define relationships of variables over a short period of time. King (1975) found relationships between the yields of various crops and the sunspot cycle using 5-year running means over periods of only 25 years. Mason (1976) shows results of analyses of the data made at the Meteorological Office, which demonstrate that the quasi-11 year peaks contain only a small amount of the variance. It was also found that the antiphase relationship between the sunspot cycle and potato yields cited by King for the period 1935-1959 obviously did not hold over the longer period 1890-1938.

It is quite possible that sunspots have an influence on climate of certain particularly sensitive areas (the area of North America west of the Mississippi is one example), it would be most valuable to establish (a) the physical basis of the relation between sunspots and climate, and (b) the long-term statistical nature of the relationship for the relationship to be of any use for predictive purposes.

The variability associated with changes in the internal climate system is best illustrated by the example of air-ocean interaction. The study of interactions between areas of sea-surface temperature anomalies (SSTAs) and atmospheric circulation patterns has produced interesting results, notably those of Bjerknes (1969) and Namias (1974). Namias (1969), for example, investigated the large-scale atmosphere-ocean interaction which occurred from 1961 through the winter of 1967-68. Namias (op. cit.) concluded that this period was characterized by anomalously warm surface water in the central North Pacific Ocean, which helped to generate atmospheric circulations of a kind favoring the persistence of the warm water. The resultant atmospheric circulation consisted of strong and southward-displayed cyclogenesis which produced a perturbation in the atmospheric long waves downstream resulting in a cooling over the eastern two-thirds of the United States. The primary instigation of the 1962-63 winter which was very cold in the eastern U.S. was believed (Namias, 1963) to be the atmosphere-ocean interactions over the North Pacific.

Similarly, cases in which the sea-surface temperature anomaly distribution in the North Atlantic may serve as a predictor of the behavior of the atmospheric circulation a month ahead have been studied by Ratcliffe and Murray (1970).

Numerical models (see section 6) have been used to investigate the effects of sea surface temperature anomalies on the simulated atmospheric circulation it has been found that anomalies in the tropical ocean (e.g. Rowntree, 1972, 1976) have more influence on the simulated atmosphere than anomalies in the mid-latitudes (e.g. Chervin et al, 1976; Houghton et al, 1974).

Davis (1976) examined 28-year records of sea surface temperature (SST) and sea-level pressure (SLP) anomalies in the Central North Pacific in order to determine the basic scales of variability and the possible causal connections which might lead to prediction of short-term climatic variability. Davis (op cit) found that

1. SST anomalies can be predicted from SST observations several months in advance with measurable skill,
2. the anomalous SLP variability can be specified from simultaneous SST data with significant skill, thus showing that the fields are related, and
3. future SLP anomalous variability cannot be predicted from SST data although previous SLP can be specified.

These results suggested that in the region studied and on the time scales of a month to a year, the observed connection between SST and SLP variabilities is <u>a result of the atmosphere driving the ocean.</u>

Frankignoul and Hasselmann (1977) have also investigated the relationship between atmosphere and ocean and found that in mid-ocean regions away from intense currents or thermal fronts the principal statistical properties of SST anomalies can be explained by a simple model in which the atmosphere acts as a white-noise generator (i.e. random forcing by short time scale weather components) and the ocean as a first-order Markov integrator of the atmospheric input.

It is clear therefore that the internal forcing of changes in the climate system by atmosphere-ocean interactions is an extremely complex matter. Empirical studies have demonstrated that a relationship exists but recent studies of data suggest that the causal relationship is not necessarily in the same direction as previously assumed.

Atmosphere-ocean feedbacks are not the only internal forcing mechanisms of climatic variability. Atmosphere-cryosphere interactions are also of importance (e.g. Lamb, 1955; Namias, 1960; Williams, 1975). Feedbacks within the atmosphere itself must also not be neglected when interannual variability is being considered. Green (1977) has examined the physical processes that could have been involved in the creation and maintenance of the drought in Western Europe, which culminated in the summer of 1976. Green's preliminary results have shown that interactions between upper and lower levels of the atmosphere and between eddy motions and the blocking anticyclone which characterized the drought period could be of major significance. Labitzke (1965) showed that there was an interdependence of developments in the troposphere and stratosphere before and after the occurrence of pronounced stratospheric midwinter warmings. The pattern of the observed stratospheric warmings varied in phase with the quasi-biennial oscillation and much interest has focused on tropospheric-stratospheric links with respect to this phenomenon (e.g. Madden,1975;Ramanathan,1977).

The causes of climatic change are summarized in Fig. 1, and have been described in reports such as those listed in the introduction. The above discussion has involved only a few of the causes, clearly there is a wide range of possible interactions among the elements of the climate system. If we wish to use our knowledge of the climate system and the causes of climatic change to make predicitons, the physical basis of the system and especially of the interactions between elements of the system must be well understood.

5. WHAT METHODS ARE AVAILABLE FOR MAKING PREDICTIONS?

If there is potentially predictable climatic variability over and above the unpredictable inherent variability or noise, there are basically three methods of forecasting this variability:

1. wholly statistical procedures;
2. methods in which physical reasoning is important but which also use some statistics and empirical relationships; and

3. wholly dynamical methods, based on physical laws (modeling).

At the present time, the first two of the above categories are used to make long-range forecasts. Statistical methods include the selection of analogues and the study of a number of cycles and oscillations. Barry and Perry (1973), for example, have described the use of such techniques. While it is sometimes claimed that the advantage of statistical methods is that they are objective and do not rely on physical reasoning, which could be complex, the absence of any physical basis for making predictions, using statistics such as correlations or time series analysis, for example, is also their main disadvantage.

van Loon and Jenne (1975) have examined three methods (contingency tables, regression equations and the use of the last few decades if there is a trend at the station) of estimating the level of a coming season's mean temperature for New Haven, where the statistical association between the selected seasons is as high as one can expect in extratropical regions. They found that contingency tables often gave good results because of the association between seasons on long-time scales (trends). van Loon and Jenne (op. cit) concluded that if the association between two seasons is reasonably high, one could give a probability for the second season <u>if</u> the first season not only fell into one of the extreme categories (above or below normal) but also was well removed from the mean. Apart from the tropical regions where the correlation between seasons is often quite high, the expected mean which is obtained by regression is frequently not far enough removed from the long-term mean for an estimate of the next season's mean temperature level to be made which is significantly different from the long-term mean.

Wahl (1977) has reported preliminary results of an attempt at using statistical methods for forecasting large-scale circulation parameters for the northern hemisphere. The work is based on an assumption that there may be some predictability for future states of the circulation in a careful evaluation of antecedent conditions. Wahl, however, points out that the use of statistical methods must only be considered as a first step in approaching the long range forecast problem and that when the physical basis for long-term fluctuations is understood then the statistical methods would be replaced. Wahl concludes, having used a contingency table method and studied lag relationships to predict coefficients of monthly sea-level pressure eigenvectors, that there are some weak but potentially predictable interrelationships over long time spans.

Physical/statistical/empirical methods include those such as the use of sea-surface temperature anomalies to predict atmospheric anomalies and teleconnections. Such methods could be of importance in the development of forecasting capability and are already in use, but the derivation of forecasting "rules" depends on the availability of a good data base and the spatial and temporal extent of the available climate data base is a constraint on the ultimate capabilities of this method.

Wholly dynamical methods of forecasting climate variability are not yet in use but it appears that there is no clear alternative to the use of climate models to study the climate system and its interactions. The following section therefore considers the potential applications of climate models for long-range forecasting.

6. CAN WE USE MODELS TO PREDICT CLIMATE FLUCTUATIONS?

The processes of the climate system can be expressed in terms of a set of hydrodynamical and thermodynamical equations for the atmosphere, oceans and ice, together with equations of state and conservation laws for selected constituents (e.g. CO_2, water in atmosphere). These equations describe the processes which determine distributions of temperature, pressure, density and velocity. Other processes (evaporation, condensation, precipitation, radiation, advective, convective and turbulent transfers of heat and momentum, and biological and chemical processes) can also be described mathematically. The use of these equations to describe the climate system is the basis of climate modeling. However, because our knowledge of the physical system is incomplete and because of computational limitations, certain physical and numerical approximations must be made in the use of the equations and a hierarchy of climate models has been created, with different types of models using different physical and numerical approximations in the equations used to describe the processes of the climate system.

The hierarchy of models has been described in detail elsewhere (e.g. Schneider and Dickinson, 1974; GARP, 1975), it ranges from very simple one-dimensional models of the atmosphere to very complex models of the atmosphere-ocean-cryosphere system. The climate models therefore are applicable to a range of time and space scales. For the purpose of forecasting interannual variability, a one-dimensional model of the vertical structure of the atmosphere is clearly inappropriate. Likewise, a model which neglects processes that are potentially important forcing mechanisms on the interannual time scales (e.g. atmosphere ocean interactions) are also not appropriate. Global (or hemispheric) general circulation models (GCM) model the three-dimensional mean atmospheric circulation using a time-dependent set of equations at grid-points usually a few degrees latitudinal and longitudinal resolution and a few kilometers vertically. Such models represent the best tools available at the present time for studying the processes of the climate system, although other models, especially those of a statistical-dynamical nature (e.g. Hasselmann,1976) could become very useful for studies of climate variability and other models, such as zonal atmospheric models (e.g. MacCracken and Luther, 1974) are applicable for certain studies of the climate system (e.g. Potter, et al., 1975) but not for predicting reasonably detailed distributions of climate elements. GCMs, despite shortcomings, which will be described below, simulate quite realistically the basic features of the earth's climate (distribution of pressure, temperature etc. and seasonal differences). The potential for the use of GCMs to predict climate fluctuations will be discussed in the following paragraphs.

Lorenz (1975) has defined two types of climate prediction: climate prediction <u>of the first kind</u> involves the process of determining how climate statistics change as a function of time; climate predictions <u>of the second kind</u> do not look at the chronological order in which climate states occur but rather predict the effect on climate of different forcing such as a doubling of atmospheric CO_2 or the occurrence of a sea-surface temperature anomaly (SSTA) by looking at the difference between predicitons without and with the forcing mechanism of interest.

Studies made with GCMs have shown that small errors in representing the state of the atmosphere grow rapidly because of the non-linear processes in the atmosphere and this implies that there is an absolute limit of 2-3 weeks for forecasting day-to-day weather variations. If GCMs cannot be used to predict the day-to-day weather a season or a year ahead, then as Lorenz (1975) points out, we can still ask whether the models could predict, for instance, whether next winter will be warmer than usual. The latter prediction could be made, if there are some parts of the climate system which behave more sluggishly than others. Lorenz (op. cit) cites the example of SSTAs as features which influence and are influenced by the weather and yet vary more slowly than the weather. To make climate predictions of the first kind using models and accepting SSTAs as the forcing mechanism of climate variability involves the following problems:

1. There is not yet a large enough sample of observations to determine whether the sluggishness of SSTAs really does lead to long-range predictability.
2. GCMs at the present time assume fixed sea-surface temperatures (SSTs) and compute the atmospheric circulation in equilibrium with (or forced by) the given distribution of SSTs. For climate prediction of the first kind the SST distribution must also be predicted, the problems of successfully coupling an atmospheric model with an oceanic general circulation model are not small and have not been solved at the present time.
3. Other shortcomings of GCMs, especially the treatment of clouds, hydrological processes and certain sub-grid scale processes, also will limit the long-range predictive capability of the models. For example, many models either do not compute cloudiness (i.e. assume fixed climatological distributions) or have very crude parameterizations for the cloud processes, if a major part of the feedback loop involving SSTAs and changes in the atmosphere involves cloud interactions then the models will not simulate the feedback realistically and the predictive value of SSTAs may be lost.

4. Lastly, the cost of running GCMs is very high and the cost of predictions of the first kind in which the model would have to simulate at least a season and possibly a year ahead would be prohibitive.

Other processes could also be sluggish enough to make long-range predictions of the climate possible, although the above points or variations of them apply in each case. Climate prediction of the second kind with GCMs has already been carried out with several different models and for several forcing mechanisms. The forcing mechanism that has been considered the most is the SSTA (e.g. Rowntree, 1972, 1976 b; Spar, 1973 a,b,c;Houghton et al., 1974; Chervin et al., 1976; Shukla 1975). To consider the SSTA problem as climate prediction of the second kind with a GCM the feedback from the atmosphere to the ocean is neglected. The prediction thus depends on determining the difference between model runs with the SSTA and those without. GCMs have also been used to determine how the atmosphere responds to waste heat input (Washington, 1972; Murphy et al., 1976; Williams et al., 1977 a and b), to doubling atmospheric CO_2 (Manabe and Wetherald, 1975), to removal of mountains (Kasahara and Washington, 1971; Mintz, 1965; Manabe and Terpstra, 1974; Rowntree, 1976a) and to inclusion of ice age boundary conditions (Williams et al., 1974; Gates, 1976), for example.

The shortcomings of GCMs as mentioned above (clouds, hydrological processes and sub-grid scale parameterizations) also represent limitations to the use of models in climate predictions of the second kind. In particular, certain feedbacks may be omitted in models which could be of importance in predicting the real atmospheric response to the forcing mechanism. For example, the use of fixed climatological clouds in a model when investigating the impact of a doubling of atmospheric CO_2 means that any interactions between changes in temperature and humidity and changes in cloudiness and subsequent interactions with the radiation field will not be considered and yet such interactions could be significant.

The second problem involved in the use of GCMs for climate prediction of the second kind is the determination of signal-to-noise ratios. Just as the real atmosphere has a inherent variability, so do models have an inherent variability which is due to the high degree of non-linearity in the models and the consequent growth of small perturbations. Therefore, if we run two experiments with a GCM which differ only because of some small random perturbation in the initial conditions, the results of the two experiments will not be exactly the same. It is necessary to determine the inherent variability of the model so that the difference between a model run with an imposed perturbation (e.g. SSTA) and a control case can be evaluated. That is, it is necessary to evaluate how much of the difference between a perturbed case and a control case is due to the imposed perturbation and how much is due merely to the model's inherent variability.

A series of experiments was run with the six-layer NCAR atmospheric GCM, to examine the response of the simulated atmospheric circulation to SSTAs in the midlatitudes of the North Pacific Ocean (Chervin, Washington and Schneider, 1976). Using a methodology developed by Chervin and Schneider (1976), the authors estimated the inherent variability of the model by finding the standard deviation of a meteorological variable (in the illustrated case, temperature at 1.5 km) in five January control cases (which only differed by small random perturbations in the initial conditions). The differences between perturbed cases and control cases were then compared with the standard deviations in a ratio. Statistical tests, using the Students' t distribution were made to see if there was a statistically significant difference between the perturbed case and the control cases--that is, whether the difference was statistically significantly greater than the inherent variability of the model. Chervin et al. (1976) concluded, after consideration of the values of the ratio, that the pattern of anomalous change over the United States is very small and can be ascribed in the imposed perturbation with only a very low degree of confidence. Moreover, even if it could be accepted as statistically significant it is so small that it would provide only a marginal improvement in forecast skill over climatological means.

The fact that the experiments described by Chervin et al. (op. cit) did not show significant downstream effects from the SSTAs in the North Pacific does not mean that these downstream effects do not occur in the real atmosphere. The experiments emphasize, however, the problems involved in the use of GCMs to predict climate fluctuations. Firstly, of course, the GCMs are not perfect replicas of climate. Secondly, the predictability experiment should really be carried out by comparing a large number of control cases with a large number of perturbation cases so that the model variability can be accurately assessed and the "signal" can also be evaluated with less risk of sampling error. In most predictability experiments made to date the number of experiments made has been very small. Many predictability studies have compared only one perturbed case with one control case, some have compared one perturbed case with three control cases (Murphy et al., 1976; Williams et al., 1977 a,b) and the maximum number of control cases used in the five cases used by Chervin et al. (1976). It is possible to maximize the amount of information about the model variability contained in a small number of cases (e.g. Williams et al., 1977 b) but the fact remains that a large number of model runs is really required. There are two main reasons why this large number of runs is not available. The first is no doubt the one of cost: the amount of computer time required to run 30 control cases each differing only by small random perturbations in initial conditions would be prohibitive. Secondly, GCMs are in a continual state of development and each new or improved parameterization or treatment of a particular process within the model will mean that a new set of control cases is required if the change is large enough to have caused an alteration of the model's inherent variability.

In summary, GCMs will continue to be a very useful tool for studying the physical basis of the climate system and the sensitivity of the system to perturbations (SSTAs, changes in atmospheric constituents, changes in land surface characteristics etc). it it unlikely that GCMs will become useful for real-time forecasting of climatic variations on an interannual time scale. If the perturbation is very large so that the signal is correspondingly large, GCMs could be used for forecasts, though this is more likely for variations on a longer time scale than the interannual scale (e.g. doubling of CO_2 level in atmosphere).

Nevertheless, the models could be valuable to those people involved in making long-range forecasts by indicating the magnitude and direction of the response of the atmosphere to certain forcing.

7. CONCLUSIONS--CAN WE PREDICT CLIMATE FLUCTUATIONS?

The climate system is a complex, non-linear system consisting of the atmosphere, ocean, cryosphere, land and biosphere. The ultimate ability to predict climate fluctuations on time scales ranging from interannual to geological will depend on a basic understanding of all of the components of the system and their interactions.

A certain amount of variability within the atmosphere, a result of day-to-day weather fluctuations, is unpredictable. Much more work (and data) is required to determine the magnitude of this inherent variability ("noise") and the implications for the predictability question.

If there is variability over and above the unpredictable climatic noise, it is forced by changes in the external or internal climate system. At the present time the nature of the interaction between the forcing mechanism and the climate or of the feedback mechanisms is generally not well understood--e.g. how can changes in the orbital parameters of the earth, which are associated with only small changes in incoming solar radiation, be related to the large climatic changes between glacial and interglacial periods <u>or</u> how does the atmospheric temperature profile influence cloud distribution? It has been suggested that variability of climate is not forced by internal feedbacks or external forcing but can be attributed to internal random forcing by short time scale "weather" components of the system. It has also been suggested that the system is "intransitive" or "almost intransitive" (Lorenz, 1968). In an "intransitive" system there are two or more physically possible climates or more than one set of solutions to the equations governing the system. In an "almost intransitive" system, different sets of statistical properties may persist for long periods but not forever. These possibilities obviously require further investigations since they relate to the question of climatic predictability.

There are three ways that predictions could be made of climatic variations: statistical, physical-empirical and dynamical. The potential of statistical methods is limited because of lack of enough data (temporally and spatially) and because, ultimately, forecasts should be based on an understanding of the system. Climate models, in particular atmospheric GCMs, are useful tools for understanding the climate system and for estimating its sensitivity to perturbations, but can not at the present time be used to predict climate fluctuations on an interannual time scale.

While our understanding of the climate system is increasing, through analysis of climate data and through the use of climate models, we do not, in general have enough knowledge of the system to make useful predictions of interannual climate variations. Some physical-empirical relationships have been determined and proved useful but further work in the analysis of data and model results is required.

ACKNOWLEDGEMENTS

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Figure 1. Examples of potential processes involved in climatic fluctuations and their characteristic time scales. Adapted from GARP (1975).

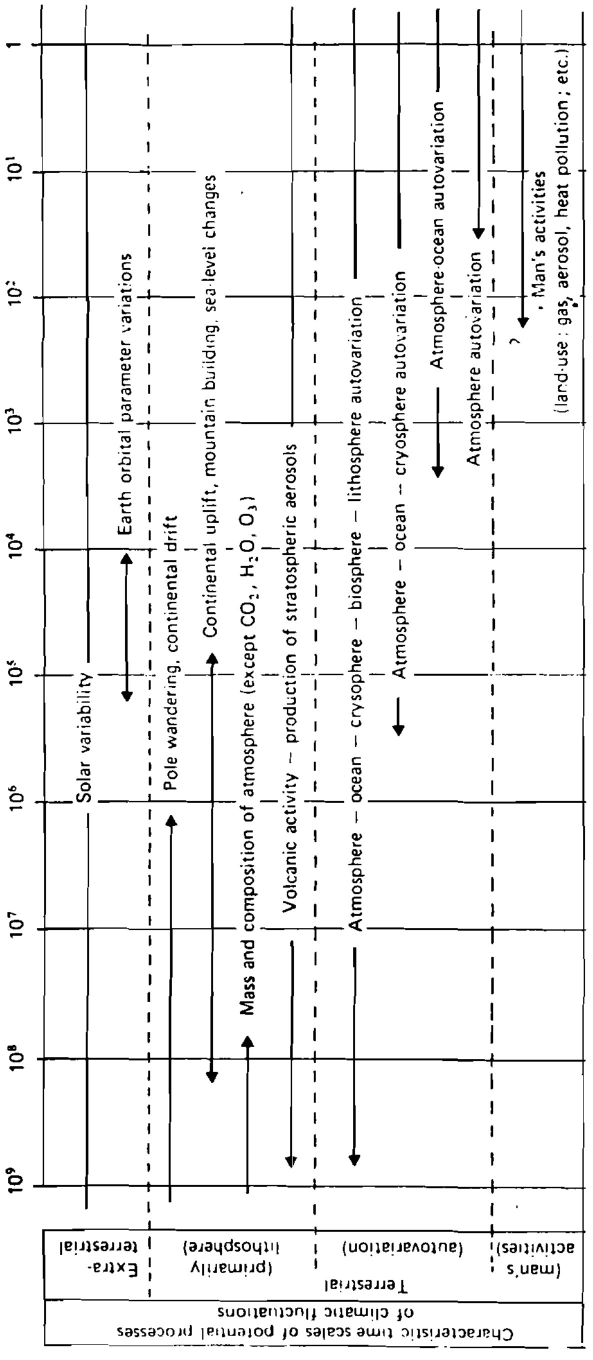


Figure 2. Standard deviation in mbs associated with the estimated natural variability for January. From Madden (1976).

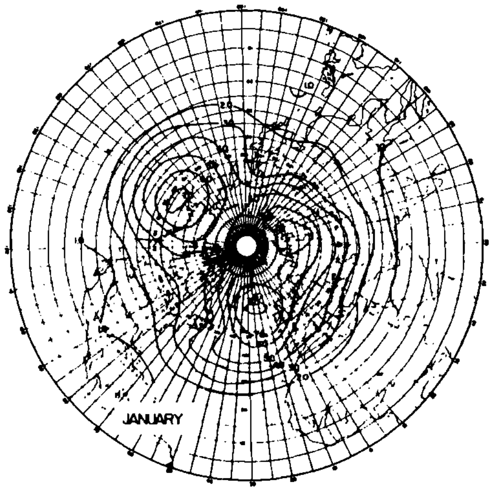


Figure 3. Ratio of actual interannual variance of January means to the variance associated with the estimated inherent variability. Ratio exceeds 1.5 in stippled area. Region "not analyzed" is due to inhomogeneities in the data. Blank areas are ones where non-stationarity in the seasonal spectrum is most likely. From Madden (1976).

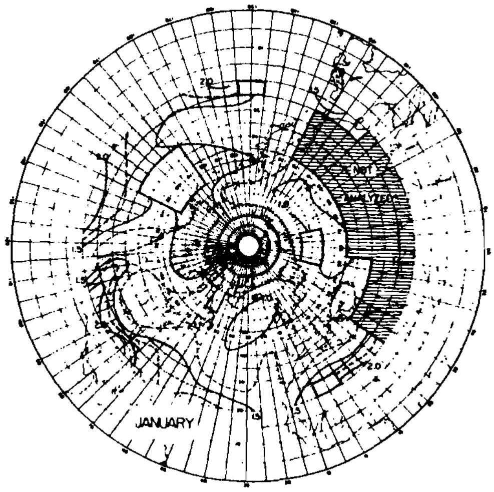
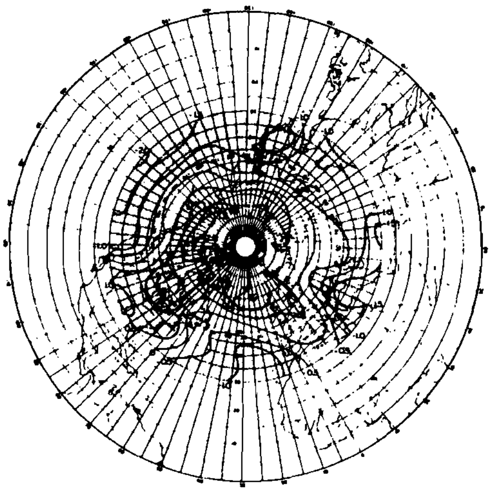


Figure 4. Signal-to-noise ratios associated with the quasi-biennial oscillation: signal is based on Ebdon (1975) and noise is σ_t for January. Stippled regions are ones where absolute value of ratio exceeds 0.5. From Madden (1976).



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