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THE PHYSICAL BASIS OF CLIMATE AND CLIMATE MODELLING

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THE PHYSICAL BASIS OF CLIMATE AND CLIMATE MODELLING

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APPENDIX 2.1

CLIMATIC PREDICTABILITY

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Weather is often identified with the complete state of the atmosphere at a particular instant. As such the weather is continually changing. Weather prediction is then identified with the process of determining how the weather will change as time advances, and the problem of weather predictability becomes that of ascertaining whether such prediction is possible.

Climate may be identified with the set of statistics of an ensemble of many different states of the atmosphere. Particularly when the real atmosphere is replaced by an idealized mathematical system, the ensemble is often taken to consist of all states during an infinite time span. In this event the climate, by definition, does not change, and climatic prediction and predictability become meaningless concepts.

Our interest in what we call climatic change has arisen because atmospheric statistics taken over a rather long time span may differ considerably from those taken over a subsequent span. Thus, for example, a region where agriculture once flourished for years or centuries may now be a desert. For our purposes we may therefore define climate in terms of the ensemble of all states during a long but finite time span. Climatic prediction then becomes the process of determining how these statistics will change as the beginning and end of the time span advance, and climatic predictability is concerned with whether such climatic prediction is possible.

The question arises as to the appropriate length for the time span through which a given climate is supposed to last. There appears to be no unique answer — climates defined in terms of widely differing time spans all constitute different aspects of the total problem. Typical conditions over millenia or longer are important in the study of ice ages; conditions over decades are important to agriculture. Personally I find it difficult to think of oscillations which complete a full cycle within a year or two as "climatic" fluctuations. However, this does not detract from the importance of such oscillations to mankind. Moreover, these shorter-period fluctuations may be studied by the same procedures applicable to longer-period variations, and, if numerical models are used, they may offer more suitable subjects for study because so much less computation is needed.

We shall refer to the climatic prediction (and predictability) which we have just introduced as climatic prediction (and predictability) *of the first kind*, because there is another kind of climatic prediction, with its associated predictability, which is of very real concern to us, and which incidentally possesses meaning even when the ensemble defining the climate covers an infinite time span. We may inquire, for example, what would be the effect upon the climate of doubling the concentration of CO_2 in the atmosphere — an event which could conceivably result some years hence from human activity. An answer would not constitute a prediction of the first kind, unless accompanied by a prediction that the CO_2 concentration will indeed double. We shall refer to such predictions, which are not directly concerned with the chronological order in which atmospheric states occur, as climatic predictions *of the second kind*.

We might note that if we really expected the concentration of CO_2 to double in the next century, our chief concern might not be how statistics taken over very long or perhaps infinite time spans would depend upon the concentration. It would more likely be how the climate of the next century would differ from the present climate. The situation is complicated because we feel reasonably certain that the climate will change in the course of a century even without a change in CO_2. What we would desire would be a prediction of the first kind, but, lacking sufficient skill, we might have to settle for a prediction of the second kind.

Before offering any conclusions and speculations regarding climatic predictability, we shall review briefly what is known about the predictability of weather. First of all, most meteorological time series are expressible as sums of periodic and non-periodic components. The periodic components include the normal diurnal and annual variations and their overtones, and presumably other weaker fluctuations, but, when all known periodicities are subtracted out, there remains a strong non-periodic signal. It has been established (1) that, in view of the impossibility of perfect measurements, the predictability of any non-periodic time series, or the non-periodic component of any time series, decays to zero as the range of prediction becomes infinite. This result is independent of the method of prediction being used. The periodic component is, of course, highly predictable by pure extrapolation.

An exception might appear to occur when the non-periodic variation results solely from non-periodic external forcing, and it is true that a hypothetical time series generated by pre-specified non-periodic forcing may be highly predictable. But in nature the forcing, being non-periodic, would itself be unpredictable at sufficiently long range, whereupon the signal would be unpredictable also.

It should be stressed that non-periodicity, although an excellent indicator of unpredictability, is not a cause; it is a result. The immediate cause of the unpredictability of the atmosphere is its instability with respect to small perturbations. That is, in general two or more nearly identical states, obeying the same atmospheric laws, will eventually evolve into widely differing states as time continues to advance. If observations are unable to indicate which if any of the original states is the true one, there will be no basis for saying which of the subsequent states will actually follow.

The theory which assures us of the ultimate decay of atmospheric predictability says nothing about the rate of decay. Our first ideas concerning this rate came from the numerical integration of very simple models (1, 2). Fortunately, these models, although very crude, contained fairly good representations of the physical process which seems to be of greatest importance in causing unpredictability, namely advection. This transport of atmospheric properties by the motion of the atmosphere itself, which appears in numerical models as a set of quadratic terms, is the same process which enables the motion of many fluid systems to be turbulent.

Comparisons were made of separate numerical solutions with slightly differing initial conditions. These indicated that small errors in representing the state of the atmosphere would tend to double in amplitude every four days during the forecast interval. More recent studies (3, 4, 5) made with large global circulation models (GCM's) agree almost as well with the simple models as they do with one another, generally favouring a doubling time between two and four days. Of course, the growth rate of errors slackens as the errors grow, and ultimately the errors become no larger than those made by guesswork, i.e., by randomly selecting a realistic atmospheric state as a prediction.

The feature of the advection process which is virtually omitted in the simplest models and inadequately represented in the GCM's is the advection of and by scales of motion too small for the models to resolve. These small scales are transported and distorted by the larger scales, and simultaneously they distort the larger scales. Perfect forecasting of just the larger scales would therefore require perfect representation and forecasting of the smaller scales. It appears (6) that errors in the smaller scales will grow within a fraction of a day to their limiting amplitudes, and while these amplitudes are not large *per se*, they will assure us that after a day or so there will be temperature errors of the order of one degree and wind errors of the order of one meter per second in the *larger* scales. These will then proceed to double every three days, just as if they had been present initially. An absolute limit of a few weeks for forecasting day-to-day weather variations thus seems to be indicated.

We now come to the basic question regarding the first kind of climatic predictability. Accepting the idea that we cannot predict the day-to-day sequence of weather a century or even a season ahead, we may still ask, "Can we predict whether the next winter will on the whole be colder than normal, or whether the next century will be colder than this one?" Here we are concerned not with how rapidly small errors will grow from their initial amplitude, but how slowly large errors will approach their limiting amplitude.

First of all, the theory which tells us that weather cannot be predictable at infinite range, in view of its lack of complete periodicity, also tells us that climate is not predictable at infinite range. More precisely, most climatic elements, and certainly climatic means, are not predictable in the first sense at infinite range, since a non-periodic series cannot be made periodic through averaging. There need not, however, be any uniform limiting range of predictability of climate. For example, annual means could conceivably be predictable two years but not ten years in advance, ten-year means might be predictable twenty years but not a hundred years in advance, etc., to infinity, lack of periodicity notwithstanding.

Again, non-periodicity does not indicate the rate of decay of climatic predictability. We can almost certainly say, however, that the models which appear to give such realistic results regarding the growth rate of small errors need not give much useful information regarding the approach of errors to their limiting values. After all, the processes, notably advection, which render the atmosphere unstable need not be the processes, if any, which hold the errors below their ultimate amplitude for extended periods.

Possible processes of the latter sort fall into two categories. First there are those associated with portions of the "system" which, for physical reasons, behave more sluggishly than other portions of the system. The "system" which governs climate is of course not confined to the atmosphere, and at the very least must include large portions of the oceans and the solid earth. The sea-surface temperature (SST) is perhaps the most frequently cited feature (e.g., (7, 8)) which both influences and is influenced by the weather, but should vary more slowly than the weather. If the ensemble of weather patterns which accompany one SST pattern differs more than trivially from the ensemble associated with another SST pattern, it should be possible to make predictions of positive skill, particularly if the predictions are time-averaged weather patterns, at any range at which the SST pattern is itself predictable, simply by choosing the appropriate ensemble average rather than the long-term climatological average as a prediction. If the SST varies slowly enough, it is predictable at moderate range by pure persistence.

The difficulty in determining whether the sluggishness of SST patterns really leads to extended-range predictability is due to the difficulty in determining how atmospheric ensembles associated with different SST patterns really differ from one another. Presumably the variability within an ensemble is much greater than the variability of the ensemble averages. If small samples are chosen from two ensembles, then, the difference between the sample means may bear little resemblance to the difference between the ensemble means. It is questionable whether enough observations are presently available to process truly large samples, while the computational effort required to generate large samples from models is probably prohibitive.

Another slowly varying feature which should be considered part of the "system", even though it is presumably not influenced by the atmosphere-ocean-earth system, is solar activity. If different ensembles of weather patterns are associated with different intensities or spectra of solar activity, there should be some atmospheric predictability at any range at which solar activity is predictable. Again, the difficulties in establishing the differences between the ensembles of weather patterns may be insurmountable at present.

When we consider the second kind of climatic predictability, we face similar difficulties. We may, for example, use a GCM to try to determine how the ensemble of weather patterns occurring under the present-day concentration of CO_2 would differ from the ensemble associated with a concentration twice as large. Incidentally, we may also treat the SST problem numerically as a problem in predictability of the second kind, by omitting the influence of the atmosphere on the SST, and seeking ensembles of atmospheric states corresponding to different prescribed SST patterns. Again, the required amount of computation may be prohibitive.

We note in passing that SST and solar activity are only two of the numerous physical features which may vary slowly enough to render the atmosphere predictable at extended range. Large-scale glaciation, for example, should render the climate highly predictable in at least one frequently accepted sense. If we use very-long-term means as a standard of comparison, we can almost surely make an excellent forecast a century ahead simply by predicting that we shall not have yet entered the next ice age. Of course, there remains a bare possibility that such a forecast will be wrong.

The other category of processes which could lead to extended-range or climatic predictability is related to the phenomena of transitivity, intransitivity, and almost-intransitivity. If the dynamics of a system leads to a unique stable set of infinitely-long-term statistics, i.e., a unique climate in the infinite sense, the system is called *transitive*. If, instead, there are two or more physically possible climates in the infinite sense, the system is called *intransitive*. Which of these climates will actually prevail forever in that case may be a matter of chance. It is not known whether our atmosphere-ocean-earth system is transitive or intransitive, but both transitive and intransitive physical as well as mathematical systems can be found which bear more than a superficial resemblance to the atmosphere and its surroundings. In particular, both transitive and intransitive systems are encountered in the familiar dishpan experiments (9).

Of particular interest is a special type of transitive system where different sets of statistical properties may persist for long periods, but not forever. We have called such a system *almost intransitive* (10). Obviously, the climate of such a system, defined in terms of ensembles of suitable length, may be highly predictable in the first sense.

As presently defined, a system might be considered almost intransitive if the long-term fluctuations arise from some sluggishly varying physical quantity, such as SST. We prefer not to regard the phenomenon as almost-intransitivity in this case. We prefer to call a system almost intransitive when the slow variations of some statistic arise from some process which does not obviously demand slow variations. An example would be the dishpan experiments when very slow vacillation is occurring (9).

It has been conjectured that the atmosphere-ocean-earth system is almost intransitive on a rather long scale. The two climates would be the glacial and interglacial climates, while the transitions from one climate to another would presumably occupy but a small fraction of the total time. If we suppose momentarily that these transitions are brought about only by some catastrophic processes, we can say that a numerical model which is correct except for omitting the catastrophes would be intransitive. Intransitive models may of course be much less elaborate. Some of the simplest climatic models (e.g., (11)) are intransitive, and in fact possess two steady-state solutions resembling interglacial and glacial climates.

It is difficult to determine whether almost-intransitivity really plays a significant role in the predictability of climate. Very simple models will probably not yield the answer; it is too easy to convert a simple transitive model into a simple intransitive model by changing the value of some empirical constant, whose appropriate value is in doubt in any case. Large GCM's would probably give us the answer, except that the required length of the numerical integrations, probably many simulated years, would presently be prohibitive. Meanwhile, there is much which can be said about the possible importance of almost-intransitivity.

First of all, whether or not almost-intransitivity is present, slowly varying features such as SST patterns are present, and these may lead to ostensibly similar responses. Suppose that we are investigating the importance of SST variations, either with data or with a model. A climatic fluctuation due to almost-intransitivity might be interpreted as being due to SST effects, and a false positive conclusion would be drawn. On another occasion a fluctuation actually due to SST effects might be nullified by a superposed fluctuation due to almost-intransitivity, and a false negative conclusion would result.

This leads us to a perhaps unexpected general conclusion. *The more readily predictable the climate is in the first sense, the more difficult it is to predict it in the second sense.* Let us see how this situation arises.

Climatic predictability of the first kind would be enhanced by almost-intransitivity, or by slowly varying features such as SST patterns, which could lead to a relatively high probability that the coming month or year or century would depart from the normal one in a known fashion. But to say that subsequent months or years or centuries are predictable is to say that they are not representative of the climate as determined from longer ensembles. Consequently, a numerical integration of one simulated month or year or century, as the case might be, would be insufficient for the purpose of estimating longer-term statistics. To investigate predictability of the second kind, then, our numerical integrations should ideally extend beyond the range of predictability of the first kind.

There are some things which we can do to alleviate this situation. In investigating the effects of doubling the CO_2 concentration, for example, we can hold the SST pattern fixed in our model (unless we believe that CO_2 operates through altering the SST), and we can eliminate other slowly varying features which might enhance the first kind of predictability. We cannot so easily eliminate almost-intransitivity. If we simplify the model to the point where we can readily determine whether or not it is almost intransitive, we have probably oversimplified it for other purposes.

What conclusions can we then draw as to the most suitable models to use in studying climatic predicability? The large GCM's appear to be physically the most acceptable, but they suffer from slowness in execution. In general they run no more than two orders of magnitude faster than real time, on the computers for which they have been designed. To extend an integration of such a model from an interglacial to a glacial period would appear hopeless at present.

At the other extreme, the very simple models where even the effects of large-scale baroclinic eddies have been parameterized seem very attractive. To run such models for thousands of simulated years presents no problem. Yet it can be very dangerous to place too much confidence in models whose behaviour depends too strongly upon the details of the parameterizations.

First of all, a parameterization which fits the data rather well may become quite poor when extended beyond the range of the data. For example, in some models the zonally averaged albedo is expressed in terms of the zonally averaged temperature. Of necessity all of our standard meteorological observations have been made during an interglacial period, and the interrelations found between various quantities may not have prevailed during glacial periods. The use of these models for ice-age studies therefore requires caution.

A perhaps even more serious problem is illustrated by the numerous attempts to parameterize the poleward eddy-transports of angular momentum and sensible heat in terms of the zonally averaged wind and temperature fields. It is known from observations that up-gradient transports of momentum are as common as down-gradient transports, so that a simple *Austausch* coefficient cannot be used, and some of the proposed schemes (e.g., (12)) readily overcome this difficulty. However, I find it rather likely that the instantaneous momentum-transport pattern is not determined by the instantaneous zonal-wind pattern at all. When a new zonal-wind pattern becomes established, small-scale eddies, such as those occurring in the turbulent boundary layer, presumably reach a new equilibrium state within a few hours or less, and parameterization seems reasonable. The large-scale eddies, on the other hand, may require a day or two to reach equilibrium, and, before this is accomplished, the zonal-wind pattern will probably have changed to something else. To a lesser extent, similar remarks also apply to the parameterization of sensible-heat transport. Perhaps parameterizations in terms of present and past zonal-wind and temperature patterns, which assume that the eddies always seek but seldom find equilibrium, would be more appropriate.

This suggests that we might look more closely at models of intermediate size, which could perhaps be produced by reducing the horizontal resolution in some of the existing GCM's. A decrease in resolution by a factor of two can speed up a model by possibly a factor of ten. We may note at this time that most of the qualitative verbal arguments attempting to explain climatic change appear on the surface to contain nothing which cannot be duplicated numerically by manipulating a few hundred numbers.

On closer examination, however, we find that many of these arguments assume a basic knowledge of the behaviour of cyclones. To duplicate these arguments numerically, then, our models must handle cyclones properly. One effect of reducing the horizontal resolution in a GCM is to suppress baroclinic activity. In the NCAR GCM, for example, baroclinic activity is unrealistically weak with a ten-degree resolution (13). We must, therefore, if we decrease the resolution, make other adjustments (parameterizations?) which tend to restore the baroclinic activity. We might, for example, artificially reduce the static stability, or introduce some unconventional horizontal-differencing scheme. At some point we should use the high-resolution models to calibrate the low-resolution models. I feel that such models offer considerable promise, but they do not really overcome the need for some sort of parameterization.

A final shortcoming of all the models so far considered, but particularly the simpler models, is that they are too deterministic. We have already noted that the simplest models even possess stable steady-state solutions. One might argue that the atmosphere-ocean-earth system is for practical purposes deterministic, but certainly the portion which is observed, or which is represented numerically in a computer, is not by itself deterministic. I believe that the ultimate climatic models, and perhaps the first ones which will successfully turn ice ages on and off, will be stochastic, i.e., random numbers will appear somewhere in the time derivatives. Random numbers in the parameterization of angular-momentum and sensible-heat transports might even successfully overcome the objection that the transports are not uniquely determined by the zonal-wind and temperature fields.

Such a procedure may seem less than completely satisfying. One might argue, for example, that in due time any desired climate would be reproduced by random numbers. One might even quote the often-heard statement to the effect that a monkey placed in front of a typewriter would eventually reproduce a volume of Shakespeare.

What is not generally added along with this statement is that the probability that the volume will have already appeared within the expected life time of a single monkey, or even of the species, is something like $10^{-1,000,000}$. If we are truly careful in introducing our random numbers, we can likewise assure ourselves that the probability of producing an ice age, when one ought not to form, is some infinetesimally small number.

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