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CLIMATIC DETERMINISM

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ABSTRACT

The often-accepted hypothesis that the physical laws governing the behavior of an atmosphere determine a unique climate is examined critically. It is noted that there are some physical systems (transitive systems) whose statistics taken over infinite time intervals are uniquely determined by the governing laws and the environmental conditions, and other systems (intransitive systems) where this is not the case. There are also certain transitive systems (almost intransitive systems) whose statistics taken over very long but finite intervals differ considerably from one such interval to another. The possibility that long-term climatic changes may result from the almost-intransitivity of the atmosphere rather than from environmental changes is suggested.

1. Introduction

It is indeed a privilege to be allowed to present the opening paper at this symposium on Causes of Climatic Change. For a long time we have been faced with well-nigh incontrovertible evidence that the climate during previous centuries or millenia has differed from the climate of today, and we are presently gathered to ask to what extent we can account for these climatic changes. During the course of this symposium we can expect many alternative and sometimes conflicting explanations to be offered. Some of these will attribute the changes of climate to changes in the properties of the oceans. Others may call upon variations in volcanic activity. Still others will invoke fluctuations in the output of the sun.

The types of explanation which I have chosen to mention have in common the feature that they seek a change in the environment of the atmosphere as the most likely cause of a change in the behavior of the atmosphere itself. Those who advance such explanations might very well assume that if environmental influences long ago had been the same as at present, the ancient climate would have been the same as today's; hence the necessity for invoking environmental changes as an explanation. In short, they might draw the not unreasonable conclusion that the nature of the atmosphere's environment, together with the internal physical nature of the atmosphere, should determine the climate in some more or less unique fashion.

It is this hypothesis, that the physical laws which govern the atmosphere are responsible for determining a unique climate, that I wish to examine critically. I shall assume without further ado that whether or not these physical laws completely determine the climate, they certainly exert their influence upon it. By and large, the physical processes which affect the climate are the same ones which we must take into account if we wish to make the best possible weather forecasts. To be sure, some processes which must have an important bearing upon climate, and upon long-term weather variations, can be virtually ignored in day-to-day forecasting. For example, in preparing a one-day forecast we need not consider the possibility of growth or decay of existing glaciers, and we can probably disregard changes in the present ocean surface temperatures.

2. The mathematical problem

Mathematically, the collection of governing physical laws is most conveniently expressed as a system of differential equations. These particular equations automatically possess a form which renders them suitable for stepwise numerical integration; that is, they express the time derivative of each relevant quantity in terms of the instantaneous overall state of the atmosphere and its environment. As a result, the mathematical problem of weather forecasting is far more straightforward than the problem of deducing the climate from the physical laws. In fact, one of the more promising methods of deducing the climate seems to be to go through the mechanics of weather forecasting, grinding out numerical solutions of the equations for extended periods of time, and then to compile statistics from the solutions (Lorenz, 1964).

More generally, the problem of deducing the climate from the physical laws which influence the climate may be viewed as a special case of an easily stated mathematical problem: Given a closed system of equations, to deduce the set of long-term statistics of the solu-

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tions of these equations. This more general problem has received considerable attention from mathematicians. Questions concerning the existence and uniqueness of long-term statistics fall into the realm of ergodic theory.

Particularly when the equations governing a physical system are linear, a unique set of long-term statistics can often be expressed in analytic form. However, the equations governing the atmosphere are highly nonlinear. The physical process responsible for the most troublesome nonlinearity is advection—the transporting of some property of the atmosphere from one location to another by the motion of the atmosphere itself. Since the motion of the atmosphere is also one of the properties of the atmosphere represented by the dependent variables, those terms in the equations which represent advection will be quadratic, thus rendering the complete system nonlinear.

In the case of nonlinear equations, the uniqueness of long-term statistics is not assured. From the way in which the problem is formulated, the system of equations, expressed in deterministic form, together with a specified set of initial conditions, determines a time-dependent solution extending indefinitely into the future, and therefore determines a set of long-term statistics. The question remains as to whether such statistics are independent of the choice of initial conditions. We define a *transitive* system of equations as one where this is the case. If, however, there are two or more sets of long-term statistics, each of which has a greater-than-zero probability of resulting from randomly chosen initial conditions, the system is called *intransitive*.

So far I have just introduced definitions. Mathematical theory now tells us, however, that both transitive and intransitive systems exist. Moreover, no simple way has been discovered for examining an arbitrary system of equations and determining whether it is transitive or intransitive.

3. Examples of an intransitive system

Since an intransitive physical system, where the physical laws do not uniquely determine the climate, may be a somewhat unfamiliar concept, let me give a few examples. One is provided by the laboratory experiments which have been designed to simulate certain features of the atmosphere [see Fultz *et al.* (1959) and Hide (1958)]. The apparatus consists in essence of a rotating basin, containing water which is subjected to differential heating. The resulting motion of the water is made visible by a tracer. Under suitable conditions a set of waves develops and progresses about the axis of rotation.

Under certain fixed external conditions, a pattern containing four waves, once established, will persist indefinitely, but a pattern containing five waves, if established instead, will also persist indefinitely. This is a truly intransitive system. Such external tampering as stirring the water with a pencil may change the flow from a four-wave to a five-wave pattern, or vice versa. Under slightly different fixed external conditions, such as a slightly higher rotation rate, only the five-wave pattern will occur. In this case the system is transitive. Transitivity is a qualitative feature of the experiment, but it depends very definitely upon quantitative features of the input.

Another example is afforded by simple numerical models which simulate the gross features of atmospheric motion [see, e.g., Lorenz (1963)]. Both transitive and intransitive systems are easily constructed. The difference between them may be simply the numerical value of one preassigned parameter.

How about the real atmosphere? Is it transitive? We do not know. The atmosphere is neither a laboratory experiment nor a set of numbers in a computer, and we cannot turn it off and then set it in motion again to see whether a new climate develops. Neither does current mathematical theory give us the answer.

So far, I have been tacitly identifying "climate" with the set of long-term statistics, and in addition I have been assuming that "long-term" averages mean averages over infinitely long time intervals extending forward from the present. This is not the universally accepted concept of climate. In fact, if climate were defined in this manner, climatic change would by definition be impossible. A concept of climate more compatible with the purposes of this symposium would be the set of statistics taken over a long but finite interval of time.

4. The almost intransitive system

This leads us to the concept of a special type of transitive system which, for want of a standard mathematical term, I shall call *almost intransitive*. In an almost intransitive system, statistics taken over infinitely long time intervals are independent of initial conditions, but statistics taken over very long but finite intervals depend very much upon initial conditions. Alternatively, a particular solution extending over an infinite time interval will possess successive very long periods with markedly different sets of statistics.

I am not aware that the mathematical theory of almost intransitive systems has been very highly developed, but the existence of systems having the proper qualifications is well established. I do not know whether the experimentalists in the laboratory have found occasion to seek or study such systems. The simplest numerical models simulating the atmosphere may, however, be made almost intransitive through suitable adjustments of one or more of the preassigned parameters. As the models are made more complicated, it seems possible that almost-intransitivity may become the rule rather than the exception.

A few years ago I had occasion to work with a model in which the instantaneous state of the atmosphere was represented by a set of 28 numbers (Lorenz, 1965). The solution of the system of 28 equations was extended over a four year simulated period. Even such basic quantities as mean overall westerly wind speed and pole-to-equator temperature contrast assumed markedly different averages during different years; at times the instantaneous departures from normal would retain one sign throughout periods as long as four months. This was despite the fact that the time steps in the numerical solution were only 3 hr. The model did not include any heat storage in the underlying ocean or ground surfaces nor any seasonal variations in the forcing. On a suitable time scale, this system was almost intransitive. Whether the model could have produced century-to-century differences in average properties is another question.

More recently, together with Dr. Eric Kraus of the Woods Hole Oceanographic Institution, I have studied a model in which seasonal variations of external heating are included (Kraus and Lorenz, 1966). We extended the solution over a simulated period of 100 yr. Although the separate summers were very much alike, they differed enough so that the ensuing winters were ble to differ considerably from one another; a single winter would not suffice for the determination of long-term climatological statistics.

How about the real atmosphere again? It was not my original intention to put in a plug for almost-intransitivity as a major cause of climatic change. However, almost-intransitivity is too important a phenomenon to disregard altogether, and, in examining the program for this symposium, I gained the decided impression that no one else would put in any such plug. Let me say, then, that I find it conceivable that almost-intransitivity could be a principal cause of climatic change, although I would not be prepared to say that it is the most likely cause. Perhaps more can be said when we have had the opportunity to extend the solutions of much larger numerical models over much longer time intervals, to see whether almost-intransitivity on the scale of centuries rather than years can occur.

A word of warning may be needed here. The mathematical theory which I have quoted applies to systems where environmental influences, if present at all, are not affected in turn by the system. The atmosphere by itself is not a system of this sort; the theory is more appropriate if all parts of the environment which e influenced by the atmosphere are included as part of the system, and equations for the time derivatives of properties of this portion of the environment are included in the complete system of equations. The sun, and presumably those layers of the earth from which volcanic activity arises, may still be regarded as part of the external environment, but the oceans, and also the glacial ice, should be part of the system. Perhaps almost-intransitivity of such an augmented system is less difficult to visualize. Nevertheless, almost-intransitivity of the atmosphere of a hypothetical earth devoid of oceans, ice and dust remains a theoretical possibility which may some day be verifiable by an extensive mathematical model.

5. Conclusions

Despite our meager knowledge of almost-intransitivity, we can draw a few conclusions. For one thing, the mere existence of long-term climatic changes cannot by itself be taken as proof of environmental changes; alternative explanations are now available. Finally, what about the not unlikely possibility that the atmosphere would be almost-intransitive if the environmental influences were constant, while at the same time external environmental changes actually are taking place? The effect of these changes will then be harder to detect, and causative connections will be more difficult to establish. For example, an environmental change which ought to bring about a 2C temperature rise might occur just at the time when the temperature was in the process of falling 2C as a result of almost-intransitivity. The environmental change might then go unnoticed simply because no one would see any reason to look for it.

In summary, climate may or may not be deterministic. We shall probably never know for sure, but as further mathematical theory is developed, and as more realistic models are constructed, we may become more and more confident of our opinions.

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