Chaos, Spontaneous Climatic Variations and Detection of the Greenhouse Effect

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ABSTRACT. We illustrate some of the general properties of chaotic dissipative dynamical systems with a simple model. One frequently observed property is the existence of extended intervals, longer than any built-in time scale, during which the system exhibits one type of behavior, followed by extended intervals when another type predominates. In models designed to simulate a climate system with no external variability, we find that an interval may persist for decades. We note the consequent difficulty in attributing particular real climatic changes to causes that are not purely internal. We conclude that we cannot say at present, on the basis of observations alone, that a greenhouse-gas-induced global warming has already set in, nor can we say that it has not already set in.

1. INTRODUCTION

In the minds of many of us who are gathered here, the most important question concerning greenhouse gases is not whether they will produce a recognizable global warming, but when will they do so? Probably we take it for granted that, barring some catastrophe that halts or overwhelms the accumulation of carbon dioxide and other constituents, the warming predicted by theoretical studies will eventually occur. The apparent upward trend of global-average temperature during the most recent century, and the unusually warm and dry weather that has invaded parts of the world during parts of the most recent decade, have led some of us to speculate that the greenhouse warming is already being felt. Figure 1, which is transcribed from the cover of a recent report of the National Climate Program (1988), is typical of the graphical documentations of the situation that faces us. In this talk I wish to examine the basis for speculating that the greenhouse effect is not the main cause of what we have been experiencing and, particularly, that the suggested warming is due to processes purely internal to the atmosphere and its immediate surroundings.

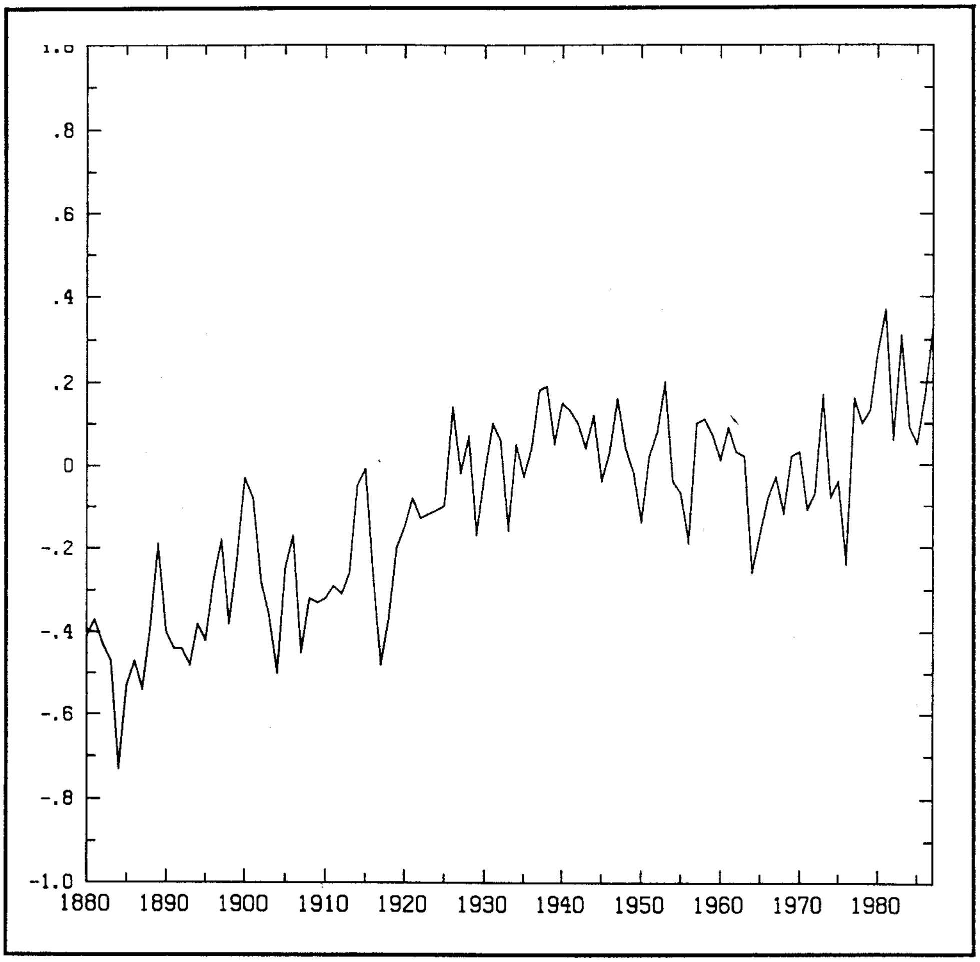

Figure 1. An estimate of the variations of the global-mean annual-mean surface air temperature from 1880 through 1987. The temperatures shown are departures, in degrees K, from a standard value (from National Climate Program, 1988).

2. CHAOS

Except for those living in special regions of the globe, including some tropical areas, everyone is familiar with the day-to-day and week-to-week irregular alternations between heat and cold, or sunshine and rain, that typify our weather. These fluctuations are one manifestation of what has recently been called "chaos." The term "chaos" currently has a variety of accepted meanings, but here we shall use it to mean deterministically, or nearly deterministically, governed behavior that nevertheless looks rather random. Upon closer inspection, chaotic behavior will generally appear more systematic, but not so much so that it will repeat itself at regular intervals, as do, for example, the oceanic tides.

Before proceeding to an acceptable working definition of chaos, we shall discuss a particular example. Consider the system of three equations

$$\frac{dX}{dt} = -Y^2 - Z^2 - aX + aF$$

$$\frac{dY}{dt} = XY - bXZ - Y + G$$

$$\frac{dZ}{dt} = bXY + XZ - Z$$

in the three dependent variables X, Y and Z, and the independent variable t representing time. This system was originally introduced as a simplified model of large-scale atmospheric flow (Lorenz, 1984a), but our purpose for presenting it here is simply to illustrate some of the properties of chaotic systems in general. We do not claim or intend that it should reproduce atmospheric behavior in any quantitative sense.

The equations have been scaled so that the time unit is 5 days. They may easily be "solved" numerically. We have let a = 0.25, b = 4.0, F = 8.0 and G = 1.0, and have used a fourth-order Taylor-series integration scheme with a time step of 0.025 units, or 3 hours. For initial conditions we have chosen X = Y = Z = 1.0. Figure 2 shows four consecutive one-year segments of the time series for X.

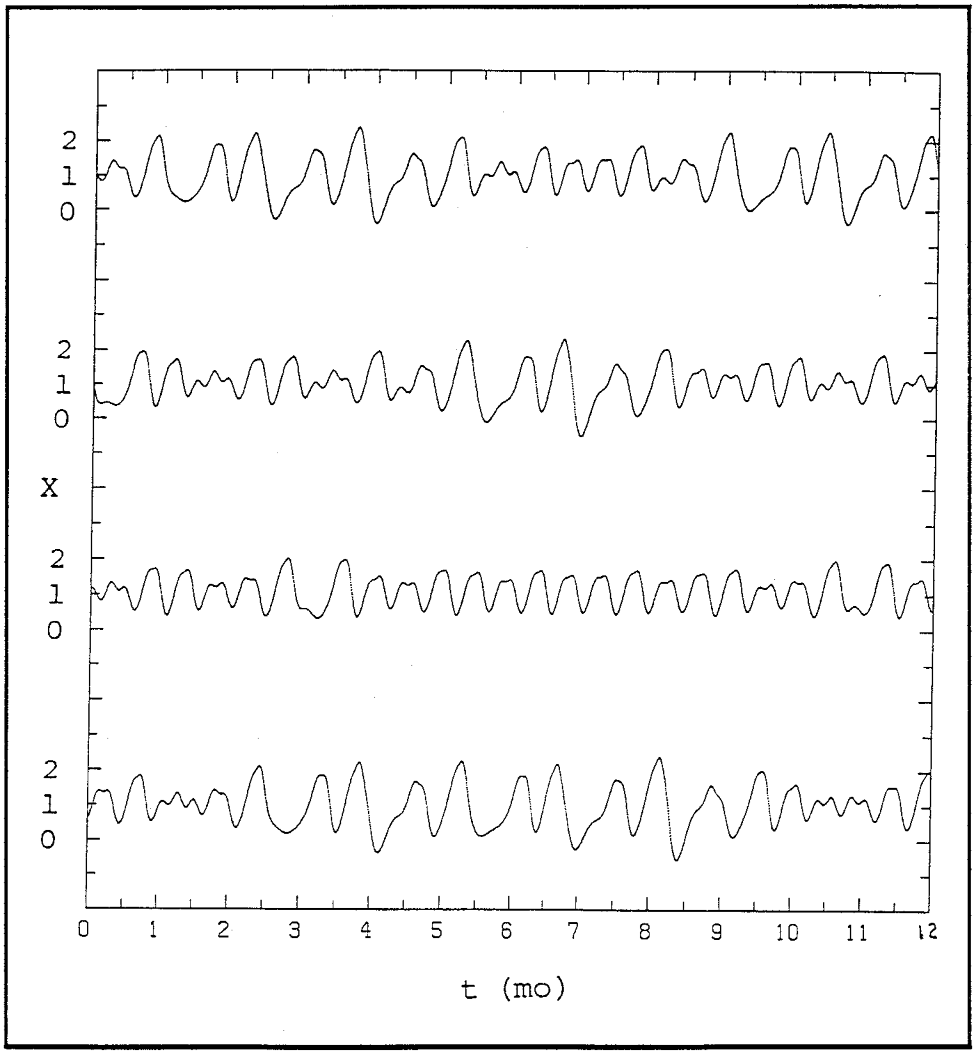

Figure 2. Variations of the variable X during four consecutive years in a numerical solution of the three-variable system. The time scale is in months.

We see that X may behave quite differently during different intervals of several months, but that the types of behavior, or "regimes," are limited in number. Near the beginning and the end of the first year and the middle of the second year, and through much of the fourth year, X undergoes large-amplitude fluctuations with successive maxima or minima typically separated by 3 or 4 weeks. In much of the third year there are weaker oscillations with a period close to 2 weeks. During brief intervals there are still weaker oscillations with maxima about a week apart. Although there is a high probability that one of these three regimes will prevail at any particular moment, changes from one regime to another occur at virtually random intervals, and in no obvious fixed order. Such a combination of short-term regularity and long-term irregularity is shared by many chaotic systems.

The regimes will show up more clearly in a time series of some quantity chosen to reveal them. One such quantity is the standard deviation of X within an interval long enough to include several maxima and minima. In Fig. 3 we show, on a more compressed horizontal scale than in Fig. 2, the standard deviation σ of X within running 45-day intervals, for twelve consecutive years. The regimes of large-amplitude and smaller-amplitude fluctuations show up plainly as periods where σ is near 0.8 or 0.4, while

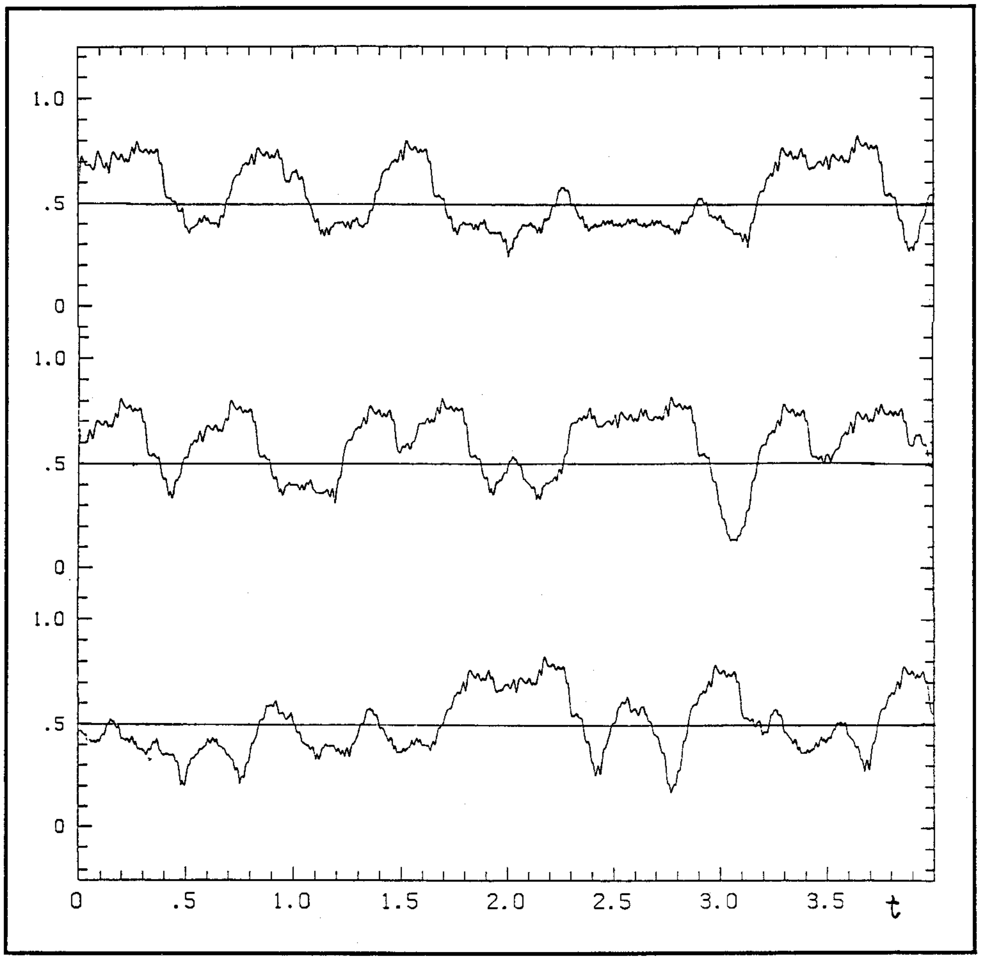

Figure 3. Variations of σ, the standard deviation of X within the 45-day interval centered at the indicated time, during three consecutive 4-year intervals in a numerical solution of the three-variable system. The first four years are the same as those in Fig. 2. The time scale is in years.

the still weaker oscillations correspond to brief minima near or below 0.3. The large-amplitude fluctuations evidently dominate during the second 4-year segment, but become less prevalent during the third.

The cause of the irregularity in Figs. 2 and 3, and of chaos in general, is instability with respect to small-amplitude perturbations, which manifests itself as sensitive dependence on present conditions. This means that solutions originating from nearly identical states will evolve in due time into considerably, and sometimes unrecognizably, different states. In Fig. 2 the behavior during July of year 2, for example, is a close analogue of the behavior during April of year 1. The segments of the solution following these months remain similar for several more weeks, but then go their own ways. Without sensitive dependence, the entire remainder of year 2, and everything thereafter, would have had to repeat what happened fifteen months earlier, and October of year 3 would also have been an analogue of April of year 1. In short, the solution would have been periodic and easily predictable. Our definition of a chaotic system will be one whose general behavior exhibits sensitive dependence.

Note particularly that in the 3-variable system, F and G, which represent external forcing, are constants. The shorter-period fluctuations and the oscillations between regimes are therefore spontaneous. The longest built-in time scale is 1/a, or 20 days, but the regimes can persist for months. Variations with unexpectedly long periods are frequent features of chaos.

3. LONG-TERM SPONTANEOUS VARIATIONS

The regimes appearing in Figs. 2 and 3 are distinguished mainly by the manner in which X oscillates. They show no great difference in the mean value of X, and no tendency to last for many years, and it is not obvious from this example that chaos has much to do with our present problem.

The situation is quite different with another model (Lorenz, 1984b), with 27 variables, also representing atmospheric flow, but incorporating more physical processes. The physical variables include the mixing ratios of water vapor and liquid water. The atmosphere and the ocean exchange heat and water through evaporation and precipitation, and the model produces its own clouds, which reflect incoming solar radiation, while both phases of water absorb and re-emit infrared radiation. Figure 4 shows model-produced sea-level air temperatures, averaged over the globe and over one-year intervals, for 400 successive years (see Lorenz, 1986). We see upward and downward trends lasting through one or several decades, resulting in a total range of about 2°K.

The resemblance of Fig. 4 to records of real global-mean temperature is hard to overlook. Almost certainly, if the real variations had taken this course, we would at various times have been seeking the causes, and would at least have seriously considered the possibility that these causes were external. Yet in the 27-variable model there is no variability of any external feature, or of any atmospheric constituent other than water. The sea-surface temperature field is not prespecified; it is a dependent variable controlled by the model, and its globally averaged variations closely parallel those of globally averaged air temperature.

The long-period variations produced by the model can be traced to a positive cloud-albedo feedback process, which can be eliminated by replacing the variable albedo by a constant. In the model, higher temperatures tend to suppress some of the cloudiness, thereby allowing the solar heating to raise the temperature still more. The heating does not, however, cause the temperature to run away, or to level off at an extreme value; the migratory synoptic systems, which fluctuate chaotically with periods of weeks or months, act as a sort of random forcing for the globally averaged conditions.

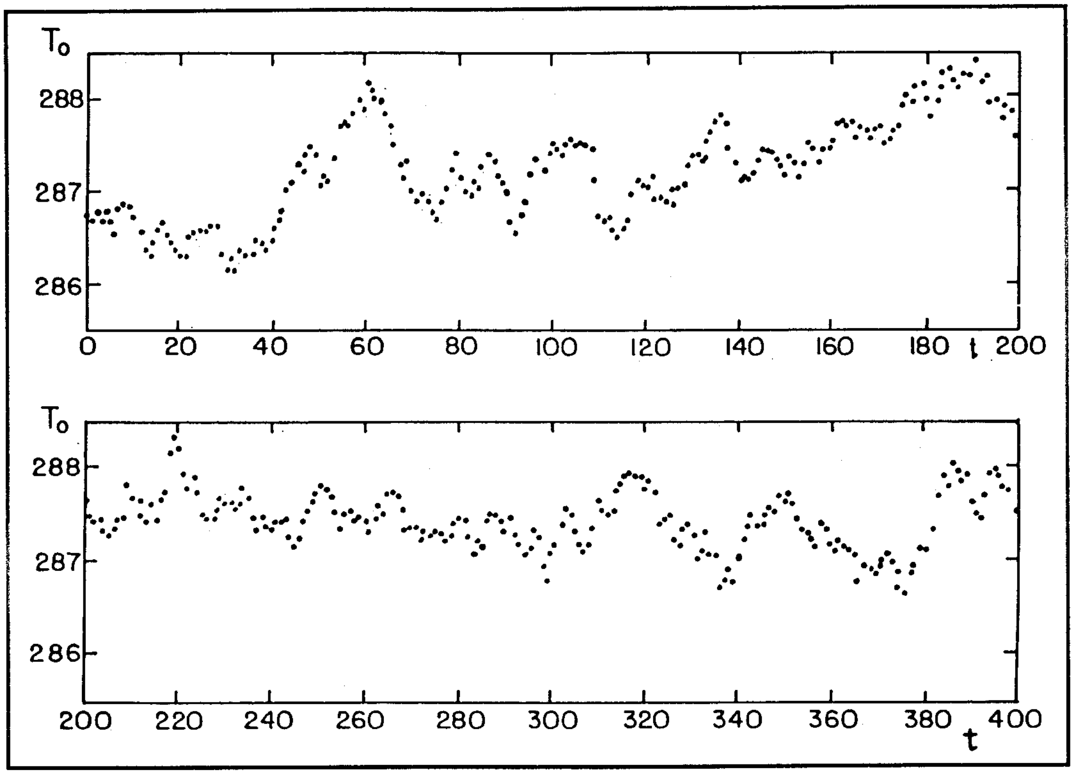

Figure 4. Variations of the global-mean annual-mean sea-level air temperature for 400 years in a numerical solution of the 27-variable model.

The point is not that the model is a good representation of the atmosphere. It is not. In particular, the real atmosphere may very well not possess an important cloud-albedo feedback process. The point is that, in chaotic dynamical systems in general, very-long-period fluctuations, much longer than any obvious time constants appearing in the governing laws, are capable of developing without the help of any variable external influences. The atmosphere and its surroundings constitute a chaotic dynamical system, and we cannot without careful investigation reject the possibility that this system is one where spontaneous long-period fluctuations occur.

Computers have now reached the point where long-term integrations with rather large models are economically feasible. As one example, we show in Fig. 5 a 100-year series of annual-mean global-mean temperatures produced by the GISS Model II (Hansen *et al.*, 1988) in a control run with no variable external influences. Again the solution is patently chaotic, and bears a reasonable resemblance to recent real-world events (compare Figs. 1 and 5). Of special interest for the present discussion, the model consists of nearly 100,000 equations. Spontaneous climatic-scale variations are evidently not restricted to models with only a few degrees of freedom.

Unfortunately, recognizing a system as chaotic will not tell us all that we might like to know. It will not provide us with a means of predicting the future course of the system. It will tell us that there is a limit to how far ahead we can predict, but it may not tell us what this limit is. Perhaps the best advice that chaos "theory" can give us is not to jump at conclusions; unexpected occurrences may constitute perfectly normal behavior.

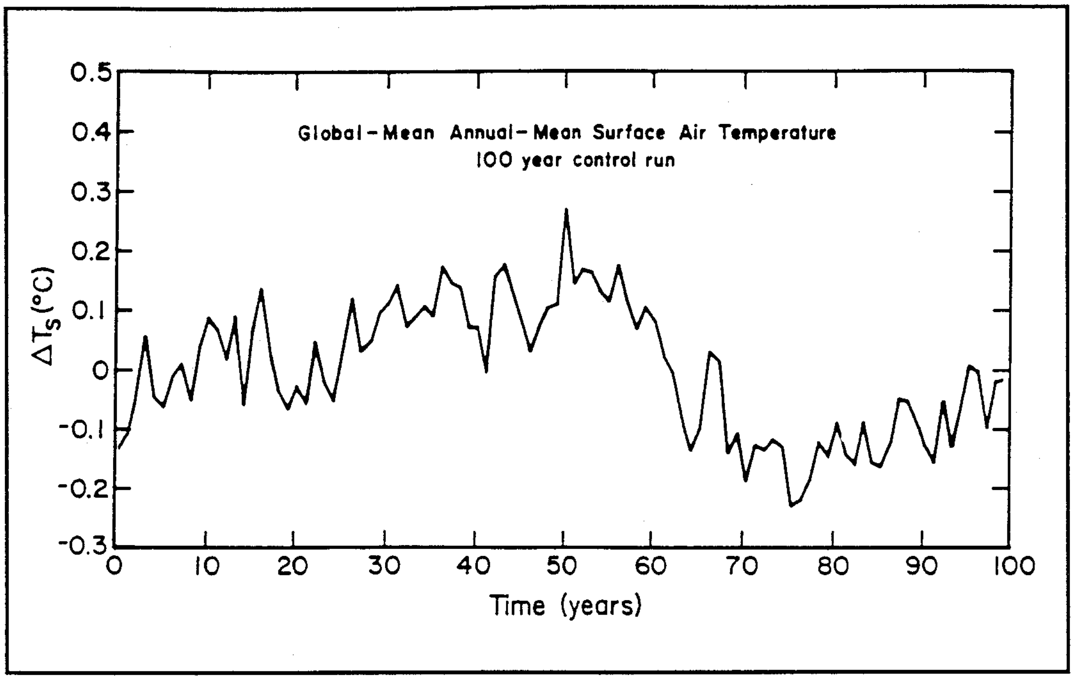

Figure 5. Variations of the global-mean annual-mean surface air temperature for 100 years in a numerical solution of the GISS Model II. The temperatures shown are departures, in degrees K, from a standard value (from Hansen *et al.*, 1988).

4. DETECTION OF GREENHOUSE WARMING

In view of these considerations, how are we to know when a stronger greenhouse effect is finally making its presence felt? First, we must realize that we are not looking for the onset of the effect. Presumably there is no critical concentration of CO_2 or some other gas beyond which the greenhouse effect begins to operate; more likely the absorption of terrestrial re-radiation by CO_2 varies continuously, even if not truly linearly, with the concentration. This concentration has been steadily increasing for many years; hence, if the effect exists at all, its onset must have occurred long ago. What we are looking for is the time when the effect crosses the threshold of detectability.

It has sometimes been objected that in dealing with this problem we have relied too heavily on theory, but I would maintain that the problem cannot be wholly dissociated from theoretical considerations. Imagine for the moment a scenario in which we have traveled to a new location, with whose weather we are unfamiliar. For the first ten days or so the maximum temperature varies between 5° and 15°C. Suddenly, on two successive days, it exceeds 25°C. Do we on the second warm day, or perhaps on the first, conclude that somebody or something is tampering with the weather? Almost surely we do not; we are quite familiar with this sort of behavior, and we take it for granted that this is what the weather often does.

Consider now a second scenario where a succession of ten or more decades without extreme global-average temperatures is followed by two decades with decidedly higher averages; possibly we shall face such a situation before the 20th century ends. Does this scenario really differ from the previous one? We may feel that it does; for example, we may believe that if the atmosphere is subjected to similar external influences over separate long intervals, say decades, the average conditions should be similar, with the short-period fluctuations tending to cancel. If so, our conclusions have been reached through theory, that is, through what we believe is demanded by the physical laws, even though the theory may be qualitative and not worked out in detail. Certainly no observations have told us that decadal-mean temperatures are nearly constant under constant external influences. If we discard all theoretical considerations, we cannot distinguish between the two scenarios.

At this point we may, in the second scenario, turn to statistical procedures. We may introduce a null hypothesis, which could say that the mean of the population of decadal mean temperatures to which the last two observations belong is *not different* from the mean of the population to which the earlier observations belong. We would then seek the probability that a discrepancy as large as the one that we have observed would occur, if the null hypothesis is true. If the probability is rather small, we would be likely to reject the null hypothesis, and conclude that the populations do indeed have different means. If the probability is large, the populations may still have different means, but we will lack a basis for concluding that they do.

Let us note, then, that we could introduce a similar null hypothesis in the first scenario. We might easily be led to reject the null hypothesis, incorrectly, if we should fail to take into account the high persistence of daily maximum temperatures, which renders the number of independent observations far less than the total number. That daily maximum temperatures are indeed persistent is readily verified from many years of records.

Returning to the second scenario, should we assume that decadal mean temperatures are also highly persistent? Our observations are insufficient to yield an answer, but we may turn to theory. The high persistence revealing itself in Figs. 3–5 suggests the possibility that real atmospheric decadal-mean temperatures are persistent; at least, it indicates that there is no obvious theoretical reason for hypothesizing that they are not persistent, no matter what intuition might tell us. There is a good chance, then, that in a real situation resembling the second scenario, we might not be able to reject the null hypothesis, that is, we might have to say that any change in the climate, including a change brought about by the greenhouse effect, has yet to cross the threshold of detectability.

If our only evidence were observational, we might have to pause at this point, and wait for more years of data to accumulate. However, since we do have theoretical results, and since, in fact, the entire greenhouse effect would have remained unsuspected without some theory, we can put the theory to use. Different models agree reasonably well as to the increase in globally averaged sea-level temperature that would be produced by a prescribed increase in CO_2 concentration. We are therefore equally justified in introducing a second null hypothesis, which would say that the difference between the means of two populations, one to which the earlier decadal mean temperatures belong, and one to which the later ones belong, is *not different* from the numerical value that the consensus of the theoretical studies stipulates. Again, we can ask whether anything as unusual as the difference between the observed sample means would be likely to have occurred, if the new null hypothesis is correct. Again, there is a good chance that we might lack sufficient evidence for rejecting the new hypothesis.

This somewhat unorthodox procedure would be quite unacceptable if the new null hypothesis had been formulated after the fact, that is, if the observed climatic trend had directly or indirectly affected the statement of the hypothesis. This would be the case, for example, if the models had been tuned to fit the observed course of the climate. Provided, however, that the observed trend has in no way entered the construction or operation of the models, the procedure would appear to be sound.

What we would conclude, then, if the second scenario is realistic, is that, although we may lack sufficient direct evidence that an increased greenhouse effect is influencing our climate, we just as surely lack direct evidence that it is not. If the effect is important, we may have to wait a few years to verify that it is, but, by the same token, if it is not important, we may have to wait a few years to verify that it is not. The implications of such a conclusion for future decision making speak for themselves.

What does chaos have to do with these claims? Without chaos, the numerical solutions summarized in Figs. 2–5 would have been periodic, repeating at regular intervals. Unless these periods proved to be extremely long, successive decadal or even annual means would have exhibited very little variability, and the qualitative theoretical conclusion that similar external conditions must produce similar long-term averages could not be so easily refuted. In that event, we might already be able to reject the original null hypothesis, and conclude that we are presently experiencing a climatic change, which in turn might be due to an increased greenhouse effect.

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