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Sensitivity of the Global Climate System to Initial Conditions

Anastasios A. Tsonis

It is widely known that the concentration of greenhouse gases, particularly CO_2, has increased steadily over the past quarter-century. Despite the fact that the radiative properties of such gases are rather well-understood, a clear consensus has yet to emerge among scientists as to the overall direction that global climate is evolving toward. Over the past decade, our understanding of the global climate system has advanced considerably with the development and application of increasingly sophisticated general circulation models (GCMs). In these models the dynamics, thermodynamics, radiative processes, and chemistry of the global climate system are represented to the maximum extent possible, given limitations in our understanding and computational capability.

The GCMS are used today to address how increased concentrations of greenhouse gases affect climate. Typically, a control run is first carried out, usually 100 years in length, that shows the annual global surface temperature. In this run, the model is started using approximate conditions that describe the state of the atmosphere at some starting point. The thin line in Figure 1 exemplifies such a control run, which was produced using the Goddard Space Science Center GCM [*Hansen et al.*, 1988]. Interestingly, this control run exhibits a positive trend for about 50 years and then a negative trend. Evidently this record displays similar dynamics over very short time-scales (year-to-year) and over longer ones (a decade to 100 years). Then the model is integrated again from the same initial condition, except that one parameter, the amount of CO_2, is allowed to increase in magnitude as time goes on. This new run, shown by the heavy solid line, is then compared to the control run. Based on such studies, it has been predicted that by the end of the century, the Earth will become warmer and will continue warming at least through the mid-21st century.

Whether or not this conclusion is correct, we believe that a very important issue—the robustness of the control run—has not yet been seriously addressed. If we carry out another control run starting from slightly different initial conditions (after all, how accurately can we describe the state of the atmosphere in the 1950s?), will the new run be very similar or completely different from the first? If the control runs are not sensitive to initial conditions, then current conclusions about global warming, based on GCMs, are justified. If the control runs are sensitive to initial conditions, as expected for highly nonlinear chaotic systems, then such results should be interpreted within the limits over which the runs do not diverge significantly. *Hansen et al.* [1990] carried out work along these lines, starting from different initial conditions. The runs did not differ significantly, but as we will see later, this might have been because the runs are approximately 35 years long.

Testing the sensitivity of GCMs to initial conditions, using 100-year-long runs, is not an easy task. One such run may require months of intensive supercomputing, making a complete study not feasible. In addition the uncertainty inherent in the initial condition is rather great. Probably the greatest and most important uncertainty is over the initial condition of the oceans, which cover 70% of the planet [*Washington and Meehl*, 1989].

For these reasons, we are forced to employ a statistical approach to demonstrate the importance of the climate system's degree of sensitivity to initial conditions. Such an approach, outlined by *Tsonis and Elsner* [1989], begins by modeling the 1881–1988 global temperature series (see Figure 2) with an optimum autoregressive model, using the approach described in *Katz* [1982]. This record is assumed to represent the global climate system for the last 110 years, and the approach is a parametric modeling of a given time-series. The time-series is viewed as the realization of a stochastic process that is taken to be stationary, with a Gaussian

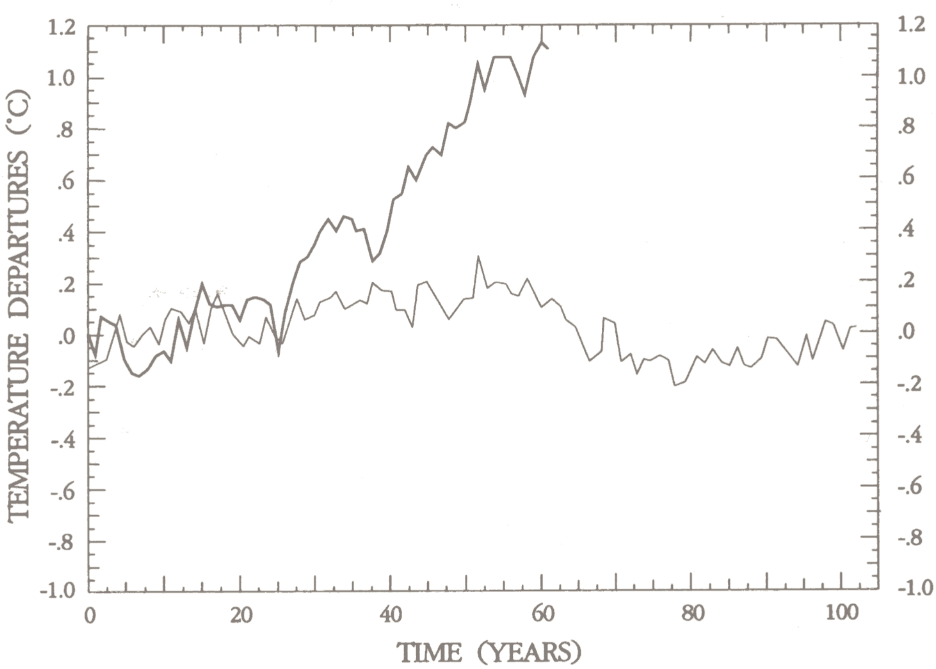

Fig. 1. The thick line shows global annual-mean surface-air-temperature trend in a 100-year control run, starting at an initial state described by average conditions in 1958. In this run the amount of trace gases estimated for 1958 remains the same throughout. The thin line shows the same run with the assumption that the amount of trace gases increases at a constant rate (from Hansen et al. *[1988]).*

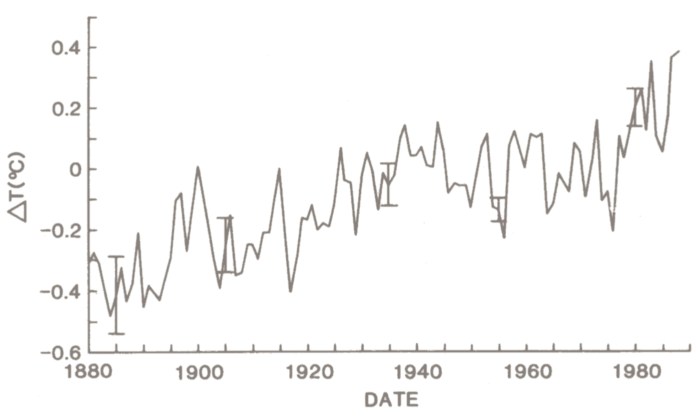

Fig. 2. Yearly global surface air-temperature departures for 1881–1988, from the reference period 1951–1970 (from Jones et al. *[1986a, 1986b, 1986c] and* Jones *[1988]). Selected uncertainty bars indicated 95% confidence limits for global values (from* Hansen and Lebedeff, *[1987]).*

University of Wisconsin-Milwaukee, Department of Geosciences, Milwaukee, WI 53201

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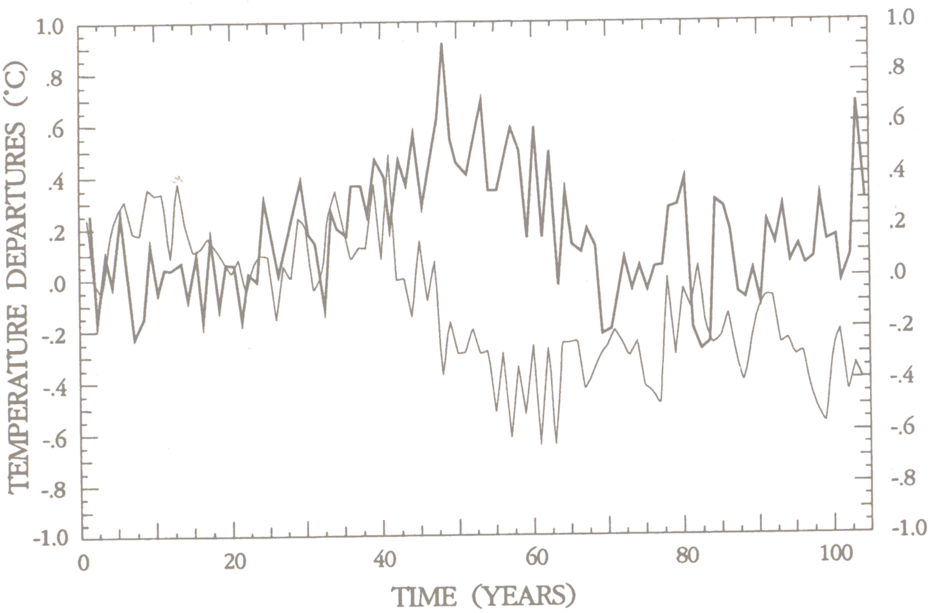

Fig. 3. Simulated global mean temperature records for 108 years, using a fourth-order autoregressive model. The model is an optimum one derived from the observed global mean temperature record shown in Figure 2. The two records indicated by thin and thick lines are initiated from very close initial conditions (1% difference). Note that after about 40 years the two records lose any resemblance.

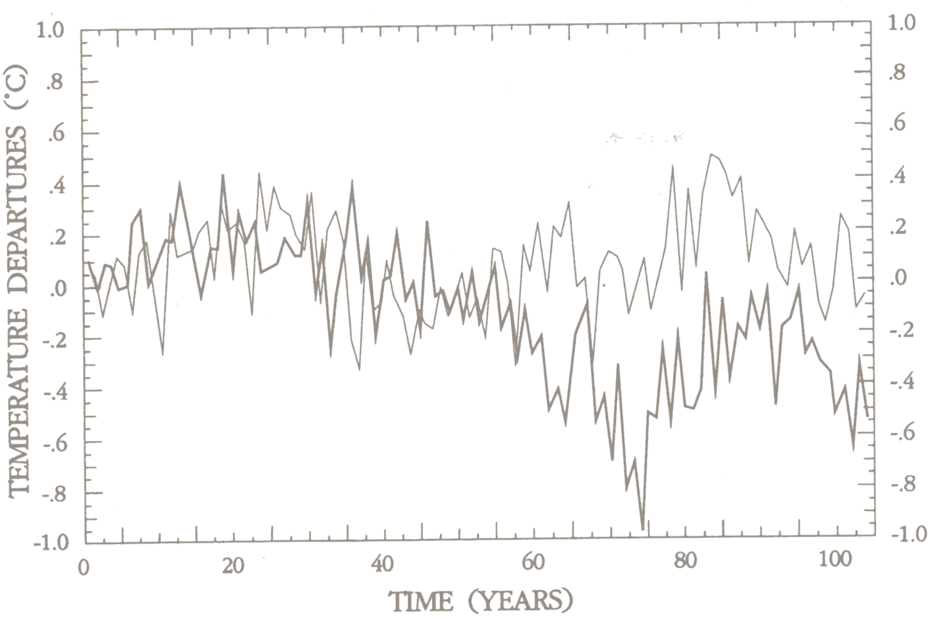

Fig. 4. Same as Figure 3 but for different initial conditions. Here the two records lose any resemblance after about 55 years.

distribution—an assumption that has been widely used for global temperature data. The optimum autoregressive model for the data set was found to be of the fourth-order. The model seems to reproduce the qualitative and quantitative properties of the global temperature record very well (for more details, see *Tsonis and Elsner* [1989]).

Once we have such a model, we can easily generate samples of any size, starting from any initial condition. Figures 3 and 4 show two examples. Each simulation depicts two evolutions from very close initial conditions (1% difference). As the figures show, the records diverge significantly after some time. Thus, in Figure 3, the two records seem to stay similar up to 40 years into the future; in Figure 4, they are similar up to about 55 years. By performing 1000 such simulations we find that, on the average, two runs starting very near each other will lose any resemblance after about 50 years. This result might explain the previously cited results of *Hansen et al.* [1990].

Fifty years is longer, but not significantly so, than 30 years, which apparently is the time after which the broken line loses any resemblance to the solid line in Figure 1. The earlier loss in resemblance may be due to the increasing concentration of greenhouse gases, representing a change in the forcing of the system rather than the sensitivity of the system to initial conditions. However, this interpretation is not very conclusive, because it is based on only one such model simulation.

Similar results are obtained when the global temperature record of *Hansen and Lebedeff* [1987, 1988] is used, which one would expect, given the very good agreement between the two data sets. The results, however, are based on the modeling of particular data sets—data that some may view as not very representative of the actual dynamics of the climate system over the last 110 years. Obviously, constructing a representative global temperature record presents many difficulties. The oceans are not adequately presented, the quality of the measurements and the density of the reporting stations have not remained the same throughout the record period, urbanization effects are not included, among other problems. Nevertheless, one must currently rely on such data sets to address certain global climate issues, such as the one discussed here.

It is clearly important to address climate predictions' sensitivity to initial conditions. Predictions must be evaluated according to the system's degree of dependence on initial conditions. Following the statistical analysis presented here, such predictions extended to more than 50 years or so might not have any merit. This must be confirmed using GCMs, however, and preliminary work in this area using simplified GCMs is in progress.

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