Predictability in the Midst of Chaos: A Scientific Basis for Climate Forecasting

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The Earth's atmosphere is generally considered to be an example of a chaotic system that is sensitively dependent on initial conditions. It is shown here that certain regions of the atmosphere are an exception. Wind patterns and rainfall in certain regions of the tropics are so strongly determined by the temperature of the underlying sea surface that they do not show sensitive dependence on the initial conditions of the atmosphere. Therefore, it should be possible to predict the large-scale tropical circulation and rainfall for as long as the ocean temperature can be predicted. If changes in tropical Pacific sea-surface temperature are quite large, even the extratropical circulation over some regions, especially over the Pacific–North American sector, is predictable.

At the beginning of the 20th century it was hypothesized that it should be possible to predict weather by solving the mathematical equations that describe the physical laws that govern the motion of air. It took several decades to develop an appropriate set of mathematical equations and numerical techniques to solve these equations and to demonstrate that, given a powerful computer, the time-dependent mathematical equations can be numerically integrated forward in time to produce useful weather forecasts. This was a major breakthrough that laid the scientific foundation for routine weather prediction by using global observations, complex mathematical equations, and fast computers. The exuberance, however, was short-lived, because at about the same time it was discovered (*1*) that the mathematical equations for weather forecasting represent a forced dissipative nonlinear dynamic system, and even an infinitesimally small uncertainty in the initial conditions will grow exponentially to make the forecast useless after a finite amount of time. This discovery contributed to the birth of the study of "chaos," and this property of the finite limit of weather predictability is popularly referred to as the "butterfly effect" (*2*).

One of the simplest and perhaps the most elegant definition of a chaotic system was provided by Lorenz (*2*) as "one that is sensitively dependent on interior changes in initial conditions." The Earth's atmosphere is an example of a chaotic system; irreducible errors in and incompleteness of observations of the initial conditions as well as the imperfection of the models prohibit accurate forecasts of the day-to-day sequence of weather beyond a few days. However, it is shown here that aspects of the tropical atmosphere do not conform to the above definition of chaos. The tropical flow patterns and rainfall, especially over the open ocean, are so strongly determined by the underlying sea-surface temperature (SST) that they show little sensitivity to changes in the initial conditions of the atmosphere. Multiple integrations have been made with significantly different initial conditions of a dynamic model of the Earth's atmosphere, which is as realistic and complex as the models used for routine numerical weather prediction. It is found that even after very large changes in the atmospheric initial conditions are made (as large as the largest observed difference in the same season during the past 50 years), the resulting large-scale wind patterns and rainfall in certain tropical regions do not diverge, as would be the case for a chaotic system; instead they converge to nearly identical values determined by the ocean temperature. It appears to be a unique and fundamental property of the tropical atmosphere that its large-scale seasonal circulation and rainfall are almost completely determined by the boundary conditions of SST. This provides a scientific explanation for why, although it is not possible to make accurate forecasts of the day-to-day sequence of weather events beyond 1 or 2 weeks, it should be possible to predict the large-scale seasonal tropical circulation and rainfall for as long as the ocean temperature can be predicted. It is also found that, during the years of large El Niño events, the atmospheric circulation patterns over certain extratropical regions of the globe, most notably the winter season mean circulation over the Pacific–North American region, are also strongly influenced by the tropical SST and rainfall, and they are much less sensitively dependent on initial conditions than other extratropical patterns. This suggests that, for all future major El Niño events, it should be possible to predict large-scale changes in the winter season mean circulation over North America several months in advance, as indeed was the case for the 1997–1998 El Niño. However, the extent to which this apparent high potential predictability of the tropical and extratropical atmosphere can be realized in routine forecasting will depend on our ability to predict the SST itself.

The numerical model used in this research has been described (*3*). The dynamic equations and the numerical techniques used to integrate the model are the same as those used by the U.S. National Weather Service for routine weather prediction, and the accuracy of short-range weather forecasts made with this model is comparable to the state-of-the-art weather forecast models.

Two sets of simulations were carried out with the same prescribed SST but quite large differences in the initial conditions of the atmosphere. This simulation requires a selection of two very different initial conditions. Rather than choosing them arbitrarily, or constructing them artificially, atmospheric states observed during the past 50 years were chosen. The data show that the Southern Oscillation Index, which is defined as the difference of sea level pressure anomalies at two points in the eastern (Tahiti) and western (Darwin) southern tropical Pacific, had its highest and lowest seasonal mean values in the boreal winters of 1988–1989 and 1982–1983, respectively. Therefore, the atmospheric initial conditions in mid-December 1982 and 1988 were chosen to conduct this experiment, because they represent two very different states of the tropical atmosphere.

Two sets of five-member ensembles of model integrations were carried out for more than 100 days starting with the observed initial atmospheric conditions in mid-December 1982 and 1988 and the corresponding observed global SST. The five different initial conditions for each year correspond to five different sets of global observations, 12 hours apart, centered in mid-December. All model integrations were carried through the end of March and SST was updated daily by interpolating from the observed monthly mean global SST for each year. Two additional sets of five-member ensembles of model integrations were carried out in which the years of initial and boundary conditions were switched: the observed atmospheric initial conditions for December 1982 were used with observed SST for 1988–1989 as the boundary condition, and atmospheric initial conditions for December 1988 were used with SST for 1982–1983 as the boundary condition. The winter season mean circulation and rainfall for each year was calculated by averaging the values for January, February, and March (referred to as JFM) of the corresponding year for all members of the

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ensemble. The winter season mean anomaly for any variable for any year is calculated by subtracting the seasonal mean model climatology of that variable from the seasonal mean of that year. The model climatology for any variable is calculated by averaging the seasonal mean values for all members of the ensemble for 14 different years (1983–1996).

The space-time structure of many variables was analyzed from these model integrations; however, results for only three selected quantities—namely, rainfall and wind velocity in the tropics and geopotential height in the extratropics—are presented. Results for rainfall were deliberately chosen from present results for rainfall because it is one of the most highly variable quantities both in observations and in model simulations.

Figure 1 shows maps of the winter (JFM) mean rainfall anomalies for two sets of model integrations with identical SST (as observed in 1982–1983) that were started from the two very different initial conditions in mid-December 1988 (Fig. 1A) and 1982 (Fig. 1B). The two maps are remarkably similar. The simulated rainfall anomalies are also in reasonably good agreement with the observed rainfall anomalies (*4*) for JFM 1983 (Fig. 1C). Figure 1 demonstrates that the model simulation of tropical rainfall is insensitive to the differences in the initial conditions, and, even if there are large changes in the initial conditions of the atmosphere, the model simulations converge to a solution uniquely determined by the boundary condition of SST. The similarity between the observed and the model simulated rainfall anomalies suggests that the seasonal mean rainfall anomalies are largely determined by the boundary conditions of SST. It is also clear that this model has some deficiencies and needs further improvements.

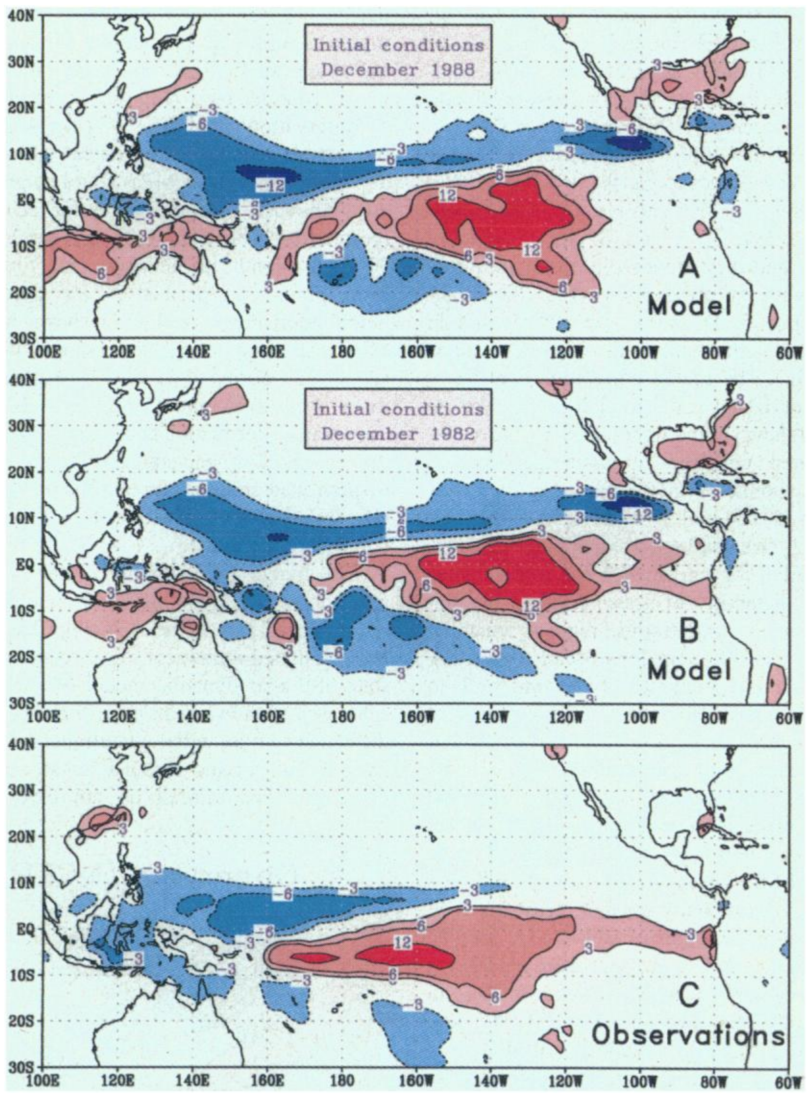

Fig. 1. Average rainfall anomaly (mm day^{-1}) for JFM for two sets of five-model integrations with observed SST in 1982–1983 starting from atmospheric initial conditions in mid-December 1988 (**A**) and 1982 (**B**) and observed (**C**).

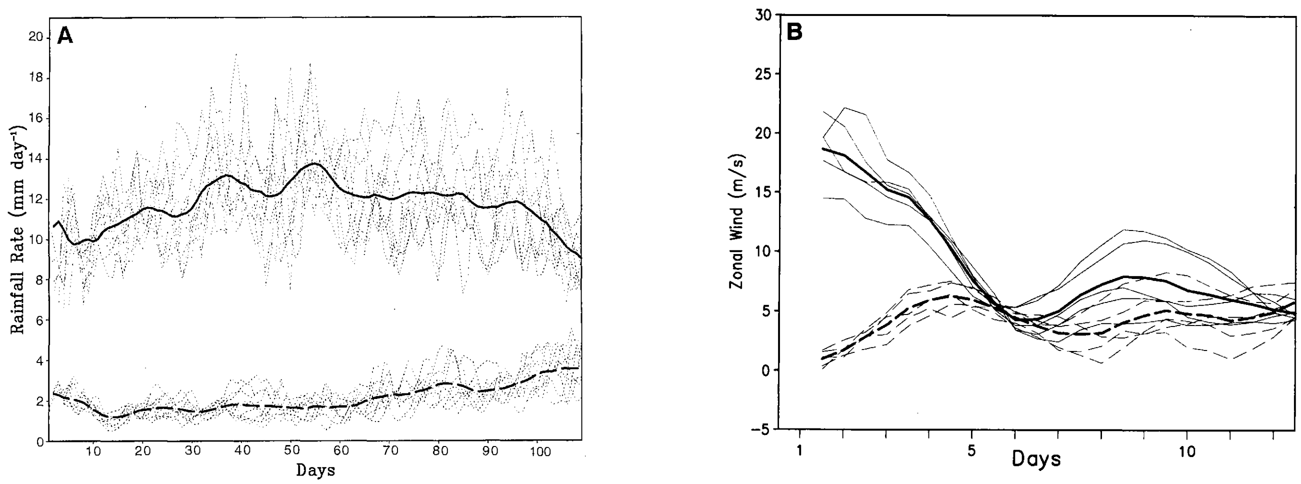

Fig. 2. (**A**) Daily values of area averaged (10°S to 10°N, 120°W to 160°W) rainfall (mm day^{-1}) using observed SST for 1982–1983 (thick solid curve) and 1988–1989 (thick dashed curve). Thick lines represent average of nine members (thin lines) of each ensemble. (**B**) Daily values of area averaged (10°S to 10°N, 120°W to 160°W) zonal wind (m sec^{-1}) at 200 millibars (0.02 MPa) for model integrations with observed SST in 1982–1983 starting from atmospheric initial conditions in mid-December 1988 (solid curves) and 1982 (dashed curves). Thick lines represent average of five members (thin lines) of each ensemble.

In Fig. 2A, daily time series of area averaged (10°S to 10°N, 120°W to 160°W) rainfall for two sets of integrations using the observed SST for 1982–1983 and 1988–1989 and observed initial conditions in mid-December of corresponding years are shown. The integrations were repeated nine times with nine different initial conditions in mid-December. This particular area has been chosen to maximize the difference in zonal wind and rainfall between the 2 years. However, the conclusions do not change even if the area is enlarged to include the entire eastern tropical Pacific Ocean. The small uncertainty within each set of nine initial conditions amplifies rapidly in the beginning but reaches its saturation within a few days. The most remarkable aspect of this figure is that, even after 100 days, the spread among the nine different initial conditions for each year remains smaller compared with the difference between the 2 years corresponding to two different SST fields. The day-to-day evolution of the area averaged zonal wind at 200 millibars (0.02 MPa) (Fig. 2B) over the same area (10°S to 10°N, 120°W to 160°W) shows that time series of zonal wind for the two sets of integrations converged in about 5 to 7 days. The simulated rainfall converged even faster, in 1 to 3 days. The convergence of two solutions suggests that the parameterizations of boundary layer dynamics and moist convection in this model are such that it takes only 5 to 7 days for convection and the associated flow patterns to reach equilibrium with a given SST distribution.

In Fig. 3, the JFM mean geopotential height anomalies at 500 millibars (0.05 MPa) are presented for four model runs: model run I (Fig. 3A), observed SST for 1982–1983 and atmospheric initial condition (IC) for December 1982; model run II (Fig. 3B), SST for 1982–1983 and IC for December 1988; model run III (Fig. 3D), SST for 1988–1989 and IC for December 1982; model run IV (Fig. 3E), SST for 1988–1989, IC for December 1988, and observations for 1983 (Fig. 3C) and 1989 (Fig. 3F). This is a significant result because Fig. 3, A and B, are remarkably similar and they are also in excellent agreement with the observations (Fig. 3C). Likewise, Fig. 3, D and E, are similar and in excellent agreement with the observations (Fig. 3F). The spatial correlation coefficient and root mean square (rms) difference for the region shown in the figure between the model simulated and the observed geopotential height anomalies are 0.91 and 25 m for JFM 1983 and 0.84 and 29 m for JFM 1989. This suggests that the high predictability of tropical rainfall for a given SST can also enhance the predictability of seasonal mean circulation in certain extratropical regions, which, in the absence of anomalous ocean conditions, would have no predictability beyond the 1- to 2-week period. However, in the extratropics such high predictability is limited to the Pacific–North American region.

The high predictability of the seasonal mean circulation over the Pacific–North American region in the presence of large tropical SST anomalies is further confirmed by the exceptionally good forecast for JFM 1998 made 6 months in advance. A coupled tropical Pacific Ocean atmosphere model was first used in the northern summer of 1997 to predict the SST anomalies for JFM 1998, and the predicted SST anomalies for JFM 1998 in the tropical Pacific were used to calculate the global SST anomalies and the contemporaneous geopotential height anomalies (*5*). The 6 months lead model predictions of geopotential height anomalies from initial conditions during summer 1997 (Fig. 4B) were verified by observations for JFM 1998 (Fig. 4A). It is remarkable that the extratropical circulation at 500 millibars (0.05 MPa) could be predicted with such a high degree of accuracy (correlation coefficient, 0.81; rms difference, 37 m) 6 months in advance. Had the SST been predicted "perfectly," the predicted height anomalies would be as shown in Fig. 4C, which is a model simulation with observed SST during JFM 1998. The verisimilitude between A and C of Fig. 4 is quite remarkable (correlation coefficient, 0.93; rms difference, 22 m) and suggests the possibility of improved seasonal forecasts over the Pacific–North American sector if SST forecasts could be improved.

The higher predictability of the tropical atmosphere was hypothesized previously (*6, 7*); however, this is the first time that carefully designed numerical experiments with a state-of-the-art dynamic model of the atmosphere have shown that, even for very large differences in the initial conditions, the model solutions for the seasonal mean tropical circulation and rainfall do not diverge as

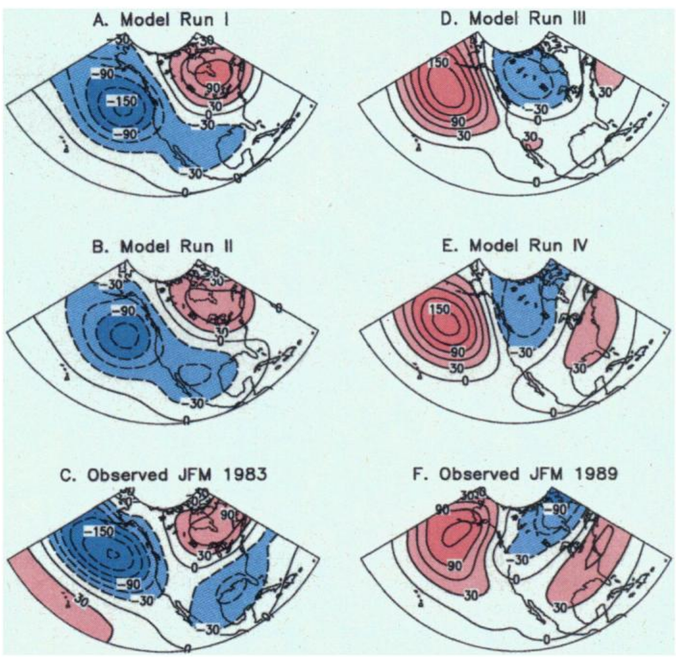

Fig. 3. Average 500-millibar (0.05 MPa) height anomaly (meters) for JFM for integrations with observed SST in 1982–1983 starting from atmospheric initial conditions in mid-December 1982 (**A**) and 1988 (**B**) and observed (**C**), and with observed SST in 1988–1989 from initial conditions in mid-December 1982 (**D**) and 1988 (**E**) and observed (**F**).

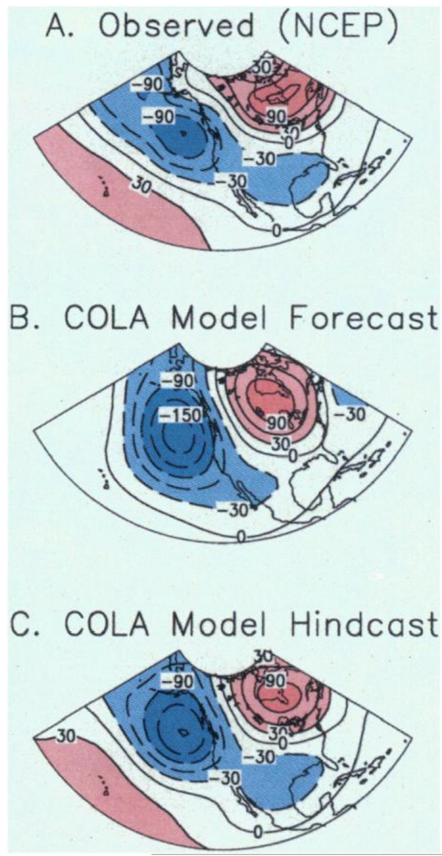

Fig. 4. Average 500-millibar (0.05 MPa) height anomaly (meters) for JFM 1998 as observed (**A**), 6-month lead forecast (**B**), and simulation with observed SST (hindcast) (**C**).

would be expected in a chaotic system but instead converge to nearly identical values. There are several models (*8, 9*) that have successfully simulated the observed seasonal mean tropical rainfall with prescribed SST. This apparent lack of sensitive dependence on the initial conditions provides a scientific basis for long-range forecasting of tropical climate variations. As shown by several modeling and theoretical studies (*10–13*), reliable probabilistic estimates of extratropical predictability are also realizable but only in the case of large tropical SST anomalies.

There is not yet a rigorous explanation for why the tropical atmosphere has such a unique property. However, it is reasonable to conjecture that the latitudinal dependence of the rotational force and solar heating produce the unique structure of the large-scale tropical motion field that, for a given boundary condition of SST, is stable with respect to the internal changes.

In spite of the apparent high predictability of the tropical atmosphere, accurate or useful forecasts for tropical circulation and rainfall can be made only if the tropical SST itself is accurately predicted. The tropical Pacific Ocean also has the unique property that changes in the tropical ocean circulation and SST are not sensitively dependent on the initial conditions of the ocean and are determined by the overlying atmospheric conditions (*14*). Lack of sensitive dependence on initial conditions for the tropical atmosphere and tropical oceans separately does not necessarily imply that the coupled tropical ocean–atmosphere system is also predictable. However, climate research in the past two decades has shown that the coupled tropical ocean–atmosphere system is indeed predictable for several seasons (*9, 15, 16*). This suggests that, at least for certain regions of the tropics, the potential exists for making dynamic forecasts of climate anomalies several seasons in advance.

Several news stories have reported that the 1997–1998 El Niño and its global effects were successfully predicted several months in advance. This paper suggests that the successful prediction of 1997–1998 climate anomalies did not occur by chance, and large-scale global climate anomalies associated with all future large El Niño events should be predictable several months in advance. This will be possible because, even if the initiation of an El Niño event could not be predicted several months in advance—and there is no evidence yet that it could be—once an El Niño event has begun, its growth and maturation for the following 6 to 9 months appear to be predictable. The reason successful long-range predictions of global climate anomalies could not be made in the past was because there were neither accurate models of the ocean and atmosphere to predict the SST and to calculate the associated changes in global circulation and rainfall nor sufficient observations for the tropical Pacific Ocean. The 1997–1998 El Niño event happened to occur just as the subsurface ocean observing system in the tropical Pacific was in place, and better models of the climate system had been developed. It is now clear that certain aspects of the climate system have far more predictability than was previously recognized. It also should be recognized that some aspects of the climate system will always be difficult to predict. For example, there has been no success in predicting subseasonal variations and, to the extent that they will influence the life cycle of El Niño events, our ability to predict the correct amplitude of El Niño events will also be limited. However, with further improved models and more accurate and extensive global observations, especially in and over the oceans, it should be possible to provide useful forecasts for seasonal mean climate.

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Climate and Groundwater Recharge During the Last Glaciation in an Ice-Covered Region

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A multitracer study of a small aquifer in northern Switzerland indicates that the atmosphere in central Europe cooled by at least 5°C during the last glacial period. The relation between oxygen isotope ratios ($\delta^{18}O$) and recharge temperatures reconstructed for this period is similar to the present-day one if a shift in the $\delta^{18}O$ value of the oceans during the ice age is taken into account. This similarity suggests that the present-day $\delta^{18}O$-temperature relation can be used to reconstruct paleoclimate conditions in northern Switzerland. A gap in calculated groundwater age between about 17,000 and 25,000 years before the present indicates that during the last glacial maximum, local groundwater recharge was prevented by overlying glaciers.

Continental climate records from mid-latitude regions that experienced ice cover during the last glacial period are scarce. Groundwaters have been used as paleoclimate archives in permanently ice-free regions (*1–4*). Here we present groundwater data from the Glatt Valley, Switzerland, which was ice-covered after a glacial advance during the last glacial maximum (*5*). The impact of glaciation on groundwater recharge and dynamics is not well known, but numerical models have shown that glaciers can dramatically change groundwater flow (*6*). In groundwater, past values of climate variables can be derived from the stable isotope composition of water molecules (*7*) and the concentrations of dissolved atmospheric noble gases (*8*).

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