# Weather Regimes: The Challenge in Extended-Range Forecasting

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**A hypothesis to explain the low-frequency (10- to 90-day) variance of the mid-latitude atmosphere is presented. In this hypothesis it is proposed that the planetary-scale waves forced by topography or other zonal inhomogeneities and the day-to-day weather disturbances (synoptic scales) influence each other to generate weather regimes. These quasi-stable flow configurations are responsible for short-range climate anomalies such as droughts, heat waves, deep freezes, and excessive precipitation, as the weather-producing disturbances are organized into storm tracks. Onset and disruption of the weather regimes may be induced by the anomalous development of perhaps a single cyclonic disturbance, which can throw the quasi equilibrium out of balance. Thus, rapid changes in flow regimes can occur almost at random. The development and transition of weather regimes may then be purely internal (that is, depending only upon the properties of the fluid motions themselves) to the atmospheric dynamics. This internal quality suggests that the chaotic, abrupt short-range climatic behavior of the mid-latitudes is a natural behavior of the system that requires no assistance from the outside. The weather regime concept presents a different view of the extended-range atmospheric behavior than the stimulus-response model, such as the atmospheric response to the El Niño.**

METEOROLOGISTS HAVE LONG SOUGHT TO BE ABLE TO forecast the weather for periods of time longer than the typical influence time (2 to 6 days) associated with mobile storm systems, which meteorologists often refer to as the "synoptic scale." The benefits of such extended forecasts are clear, for at these time scales (10 to 90 days) the atmosphere has the greatest nonseasonal variance (*1, 2*) that gives rise to economically catastrophic droughts, precipitation, heat waves, deep freezes, and otherwise regionally anomalous weather events. Although the understanding and prediction of the short-range evolution of the mobile synoptic-scale disturbances have steadily developed over the decades, those features that appear to control the large-scale organization and tracking of the mobile disturbances continue to be highly elusive. Extended-range forecasts of even mean or average quantities tend to be no better than forecasts based on climatological mean values. Correctly predicted departures from normal at one time are often offset by the occurrence of departures from normal opposite to those predicted at other times (*3*).

Several complicating factors contribute to the difficulty of generating extended-range forecasts. Perhaps the central issue is the inability of meteorologists to ascertain unambiguously the dynamic mechanisms that control the evolution of the slowly varying meteorological phenomena that appear to organize and steer the mobile disturbances. Without this knowledge, no scientific grounds exist on which to base an extended-range forecast or to judge whether the mathematical formulations of numerical models are complete enough to represent accurately the low-frequency behavior.

Recently, there has been much excitement about the possible extended-range meteorological influences of the so-called El Niño event, a very slow anomalous warming of the tropical Pacific sea-surface temperatures (*4*). Since this phenomenon takes about 2 years to complete its cycle, it is highly predictable relative to the seemingly capricious variability of the atmosphere. If the atmospheric response to this event, and to the similar events in mid-latitude oceans, could be adequately understood (even in some time-averaged sense), meteorologists would have a powerful tool for the generation of extended-range forecasts. However, this concept of stimulus-response, though aesthetically enticing, may not be an appropriate one for the mid-latitudes.

Correlations between sea-surface temperature anomalies and mid-latitude circulation anomalies tend to be weak (*5*). Furthermore, numerical studies with highly sophisticated general circulation models both with and without changing external boundary forcings tend to show the same dominance in the 10- to 90-day fluctuations as the atmosphere (*6*). But perhaps the greatest inconsistency with the varying external forcing and response model is the nature of the low-frequency atmospheric variance itself.

In a study of 500-mbar data for 14 winters in the Northern Hemisphere (*1, 7, 8*), it was noted that geopotential height anomalies persisting longer than 10 days with amplitudes greater than ±100 m tend to be on the planetary scale, occur in three geographically favored regions (the central-eastern Pacific, eastern Atlantic, and northern Soviet Union), and tend to recur with qualitatively similar regional structures. Since the positive- and negative-persistent anomaly centers occur in each of the regions with about equal frequency, these events were called "Pacific positive" and "Pacific negative." (The Pacific case is illustrated in Fig. 1.) The patterns are often reminiscent of what meteorologists call "blocking" (*8a*), particularly the "positive" events. Their time-dependent behavior, however, is highly erratic. The anomalies frequently develop and dissipate rapidly, regardless of how long they last. No dynamically preferred time scale seems evident, in the sense that once an anomaly is established, the probability of its surviving another day is roughly constant. The sequence of the anomalies appears equally chaotic; a positive-persistent anomaly in a given region can be followed either by a negative- or by a positive-persistent anomaly separated by an arbitrarily long period of no persistent anomaly. The presence of one type of persistent anomaly in one of the favored regions tends to be uncorrelated with the persistent anomalies in any of the remaining regions.

An example of this chaotic behavior is the breakdown of the now

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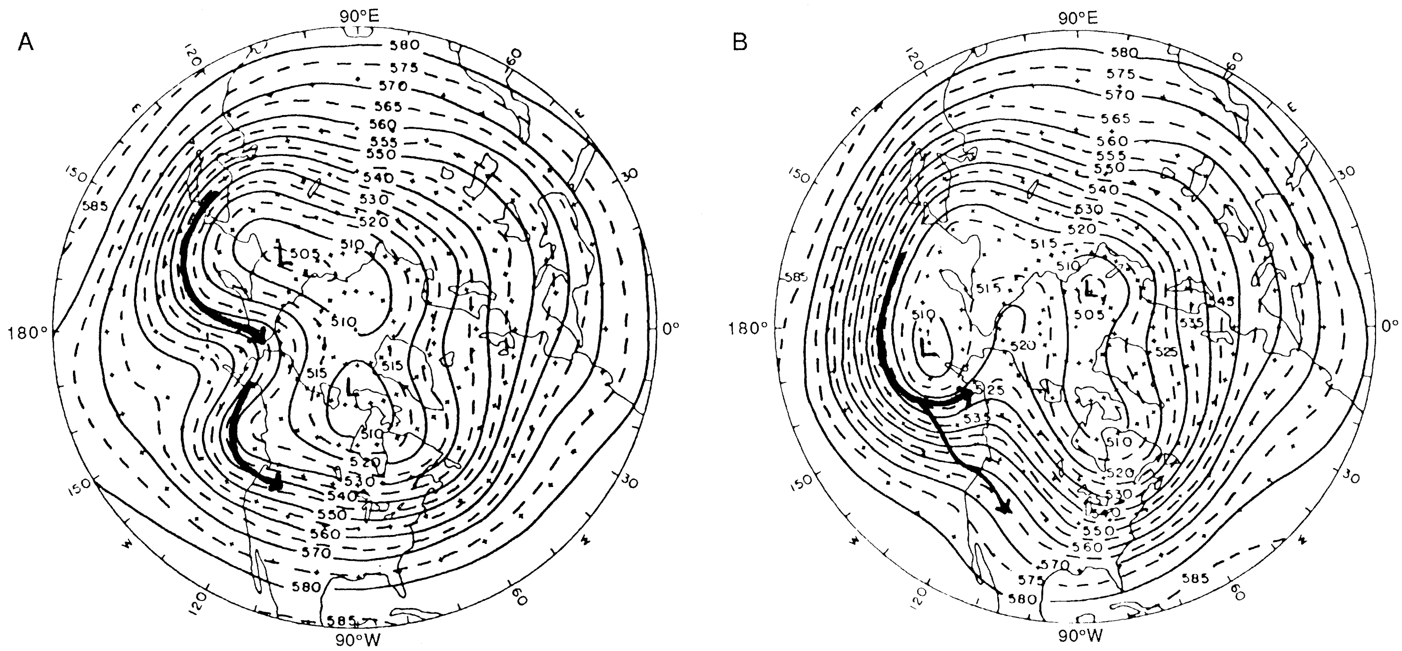


**Fig. 1.** Polar stereographic projection of the composite 500-mbar flow patterns for the (**A**) positive- and (**B**) negative-persistent anomaly states for the Pacific region. The arrows on each figure represent the principal storm tracks associated with each pattern, ascertained by calculating the regions of maximum activity on the 2- to 6-day time scale. These figures show the different, systematic persistent structures present in the atmosphere. [From (*7*)]

famous regime of the winter of 1976–77, as shown in Fig. 2, A and B. The collapse of this extraordinarily persistent Pacific negative anomaly pattern (which consisted of a strong Pacific zonal flow followed by an amplified ridge over western North America) occurred in a day or two around 21 February 1977, after having persisted since mid-autumn 1976.

Rapid transition is also demonstrated in Fig. 3, which gives the average change of anomaly height at the fixed point where the Pacific negative and Pacific positive events are most frequent. Day zero represents the day of onset of the individual events for each type, which are then averaged to form a 14-year composite. This figure demonstrates that even the average transition occurs on a short time scale compared to the length of time during which the anomaly is sustained.

The chaotic time-dependent behavior and systematic recurrence of these anomalies are difficult to account for by using a stimulus-response model, especially in a situation where all the stimuli tend to vary smoothly on time scales of several months to a few years. Although features such as El Niño influence the mid-latitude circulation, the processes leading to the catastrophic, erratic fluctuations between the observed anomalies that account for the dominating 10- to 90-day variance signal do not seem consistent with a stimulus-response model. Even if one could determine that the presence of an El Niño event leads to, for example, a bias in the frequency of occurrence of negative anomalies, the transition to and from the positive anomalies or erratic periods remains as the dominant contribution to the variance. It is precisely these fluctuations, which represent the initiations and terminations of extended periods of anomalous weather events, that provide the ultimate challenge of extended-range forecasting.

## Weather Regimes

What then could account for the aforementioned erratic character of low-frequency behavior that dominates the nonseasonal mid-latitude atmospheric variance? And why do there appear to be two very different yet systematically recurrent time-averaged states? One clue can be obtained by investigating the behavior of the day-to-day weather systems during these persistent, time-averaged anomaly states. Such analyses have been done (*7, 8*), and, as expected, the motions of the mobile storm systems during each of these events tend to follow the large-scale flow, with maximum activity extending from the long-wave trough to the downstream ridge, as shown by the arrows in Fig. 1. The existence of multiplicity in time-averaged states is highly controversial, but investigators have demonstrated that multiple, purely stationary equilibria are present in many highly simplified flow models. The process requires nonlinear interactions between waves induced by a fixed source of external forcing (such as topography) and the zonal flows (*9*). The structures of some of these solutions often appear to be qualitatively representative of the observed persistent anomaly states. However, since all of these idealized solutions are unstable to the synoptic-scale weather systems, they can never be realized in realistic flow configurations. On the other hand, these studies have not considered the dynamic interactions of the purely stationary equilibria with the mobile weather-producing systems. These interactions dramatically alter the idealized solutions, leading to a few select quasi-steady planetary-scale states with an associated set of storm tracks instead of the numerous purely stationary equilibria (*10, 11*).

The hypothesis presented here is that the low-frequency variance of the atmosphere is a consequence of transitions between the configurations in which the large-scale flow and the mobile weather systems have established a quasi equilibrium. It has often been assumed in meteorology that the large scale organizes the synoptic scale into these so-called storm tracks. However, an important element of this hypothesis is that the organized storm tracks are equally important in determining the structure of the large-scale flow and also in providing the necessary mechanism for stabilizing some of the idealized purely stationary equilibria.

These events are referred to as "weather regimes," primarily because of the systematic organization of the weather-producing mobile systems and the consequent influence they exert on the day-to-day weather of a given region.

## Dynamics of the Weather Regime

The process through which the synoptic scales and planetary scales establish a weather regime illustrates the potentially influential mechanism of nonlinearity in atmospheric behavior. A description of the weather regime equilibration process is presented below.

In a simplified context, the atmospheric motions can be thought of as instabilities that develop upon the otherwise symmetric hemispheric westerlies generated by the differential solar heating between the equator and the pole. The primary instability mechanism through which this temperature gradient is reduced is baroclinic instability, a process that is highly scale selective in both time and space and is primarily responsible for the familiar characteristics of the day-to-day mobile synoptic-scale disturbances or highs and lows (*12*). However, the presence of large-scale mountain ranges and ocean-continent contrasts forces phase-fixed planetary-scale undulations in the otherwise uniform westerlies (*13, 14*). (Some type of external forcing mechanism is necessary in the weather regime process to perturb the uniform westerlies, although it need not be time varying.) Since the scale of these forced waves tends to be much larger than that characteristic of synoptic-scale disturbances, the baroclinic instability mechanism tends to be rather weak, and the equator-to-pole temperature differences are initially reduced through the synoptic scales instead. However, the presence of the large-scale undulations subtly modifies the classic baroclinic instability mechanism on the synoptic scales. Instead of developing uniformly with random phase as they would on the zonally symmetric westerlies, certain regions within the large-scale undulations provide environments that enhance the instability mechanism relative to other regions, as well as influence the steering of the mobile centers, resulting in storm tracks (*15*). But the nonlinear coupling mechanism that allows for the establishment of weather regimes is the feedback forcing upon the large-scale waves by the synoptic disturbances that have been organized into storm tracks.

The asymmetry of the baroclinic storm development gives rise to favored regions within the large-scale pattern where the time-averaged vorticity, momentum, and poleward heat transports are of greater amplitude than in other regions, and they act as a forcing upon the large-scale circulation. The large-scale pattern must then be altered in response to this forcing, just as it is changed by the presence of land-sea contrasts and topography (*14*). A new planetary-scale flow results, which then changes the organization characteristics of the mobile waves, which in turn alters the feedbacks. A weather regime is established when the organization of the instabilities by the planetary-scale flow and the consequent feedbacks due to the organized storm tracks reach one of perhaps several quasi equilibria. Once in a weather regime state, the flow can be highly persistent, as perturbations in the large-scale flow induce changes in the storm tracks whose feedbacks act against the sense of the large-scale perturbation, forcing the flow back to its original state (*10*).

The weather regime equilibration process is unusual in that it is the net effects of the storm tracks that lead to quasi equilibrium. On an instantaneous basis, the behavior is quite different. The growth and decay of individual cyclones within the storm track generate instantaneous feedbacks whose structures deviate from the time-averaged feedbacks that are essential in the regime balance. Consequently, a completely steady planetary-scale component is difficult to establish. But of greater significance is the consequence of individual cyclone development of substantially different character than cyclones that typically occur during the given regime event. The instantaneous forcings from the growth and decay of individual cyclones could then attain sufficient amplitude, or be directed, so that the necessary balances maintaining the quasi equilibrium could be disrupted, leading to weather regime collapse. This type of process drives the state of the atmosphere between its spectrum of possible weather regimes, be it the sudden abrupt intensification of an individual cyclone or even the lack of a synoptic development in the required chain of events in the storm track. The disruption of regime events after the occurrence of explosive cyclogenesis has long been recognized by experienced forecasters and synoptic meteorologists (*16*).

This weather theory has been studied in a highly simplified

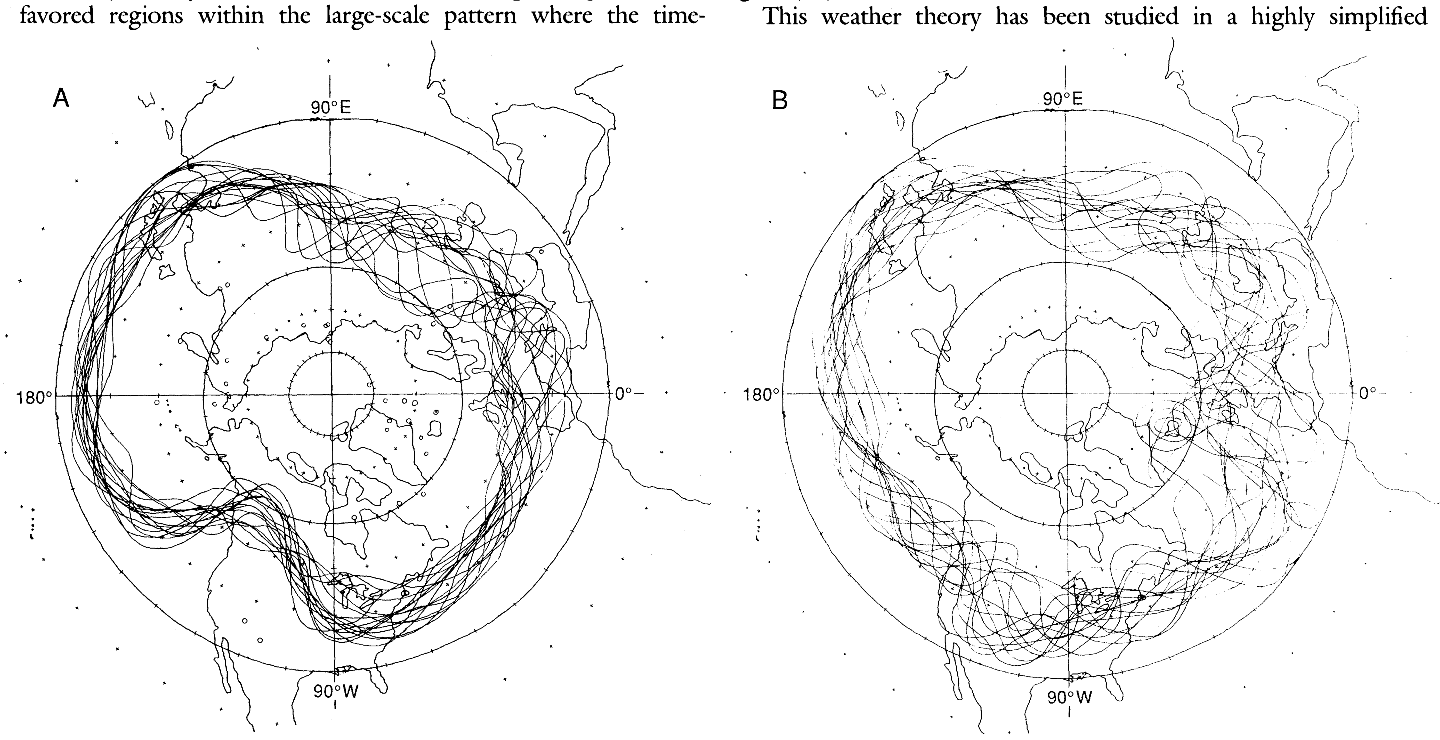


**Fig. 2.** Limited contour analyses of the breakdown of the persistent Pacific negative anomaly event during the winter of 1976–77. The plots are drawn by superposing the 00:00 Greenwich Mean Time, 552-dm, and 500-mbar height contours for a period of several days, which gives a qualitative outline of the planetary-scale undulations. (**A**) The 16-day period before 21 February 1977; (**B**) the 16-day period after 21 February. These plots demonstrate the rapid collapse of the regime pattern that had persisted since the mid-fall season. The outer circles in (A) and (B) represent 30°S latitude.

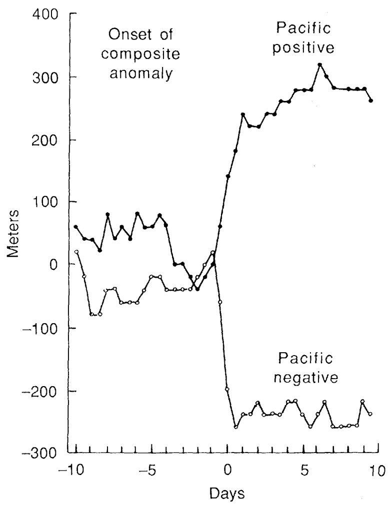


**Fig. 3.** Time series of the heights for the composite Pacific positive and negative events taken near the anomaly antinodes. Day zero is the day of onset (the day the absolute values of the height anomaly first exceeded the 100-m level). This figure shows the potentially rapid rates of transition of the persistent anomalies.

mathematical channel model with idealized sinusoidal large-scale topography. The model consists of two layers (allowing for baroclinic instability) and retains the minimum number of wave modes necessary to describe all types of nonlinear interactions: the direct interaction between waves of different scale (so-called wave-wave interaction) and the interaction between waves and the zonal flows, although in an approximated form. All external parameters, such as the driving, dissipation, and boundary conditions, are time invariant. Thus all temporal behaviors of the model are due entirely to internal dynamic processes.

Extensive numerical integrations demonstrate that the model possesses at least two weather regime states for a large range of the external parameters. A modified version of the model, which is explicitly designed to show how the synoptic-scale systems interact with the stationary equilibria, further demonstrates that the dynamic processes responsible for the regime-equilibration mechanism are those outlined above. The statistics from the numerical experiments reveal that the individual model weather regimes are systematically recurrent, are arbitrarily persistent, and have no dynamically favored time scale, analogous to the aforementioned persistent anomalies. These regimes will persist indefinitely until something disrupts the equilibration (occasionally catastrophically). Although the detailed mechanisms of transition are not understood, the synoptic-scale events play a significant role in this process (*10*).

However, a model is not the atmosphere, and one cannot be too hesitant about drawing conclusions. Nevertheless, comparisons of the model weather regimes and their statistics with the observed persistent anomalies strongly suggest that persistent weather regimes do occur in the atmosphere (*10*). An example of the qualitative relation between the model regimes and atmospheric anomalies can be obtained by comparing Fig. 4 with Fig. 1. Although the model regime structures of Fig. 4 consist only of a single periodic wave, the replication of two different time-averaged flow states (as well as the structure of the model "block") is good.

What types of behavior does this weather regime theory imply for the atmosphere? The first and foremost is perhaps the notion of the existence of short-range climatic states. As long as a given weather regime is established, certain regions will experience persistent temperature or precipitation anomalies depending on the region's relative position with respect to the associated principal storm tracks. Certain areas outside of the storm tracks will have day after day of heat or cold, while others within it will experience wave after wave of cyclones following very similar paths. In the latter case the weather pattern may seem far from persistent because of the large day-to-day changes from the passing of the mobile systems, yet the repetitive nature of the weather signifies a uniformity of its own type. Forecasting during these time periods is often quite simple, as the rule of thumb degenerates to "persistence," that is, simply to continue to predict the weather that is currently occurring.

The second important behavior inferred from the model weather regime dynamics is regime transition. The rate of the transition can be very rapid, as the details of the synoptic-scale motions ultimately determine the time evolution of the weather regimes. This feature sets up an opportunity for the forecaster to make a two-point error, that is, predicting above normal temperatures and getting below normal. Furthermore, the nature or speed of transition is entirely independent of the previous persistence of the regime. Consequently, a weather regime that had maintained itself for several months can be obliterated in a day or two. The erratic behavior of the regimes also poses problems for the prediction of time-averaged states over specified time intervals such as a month or a season. An example of this difficulty is the near normal average temperatures on the East Coast during the 1980–81 winter, when in fact the temperatures were much below normal during December and most of January, but so much above normal during February that the net temperatures were about average. The average temperature was almost never experienced during the entire period.

Perhaps the most important implication of this theory is that the

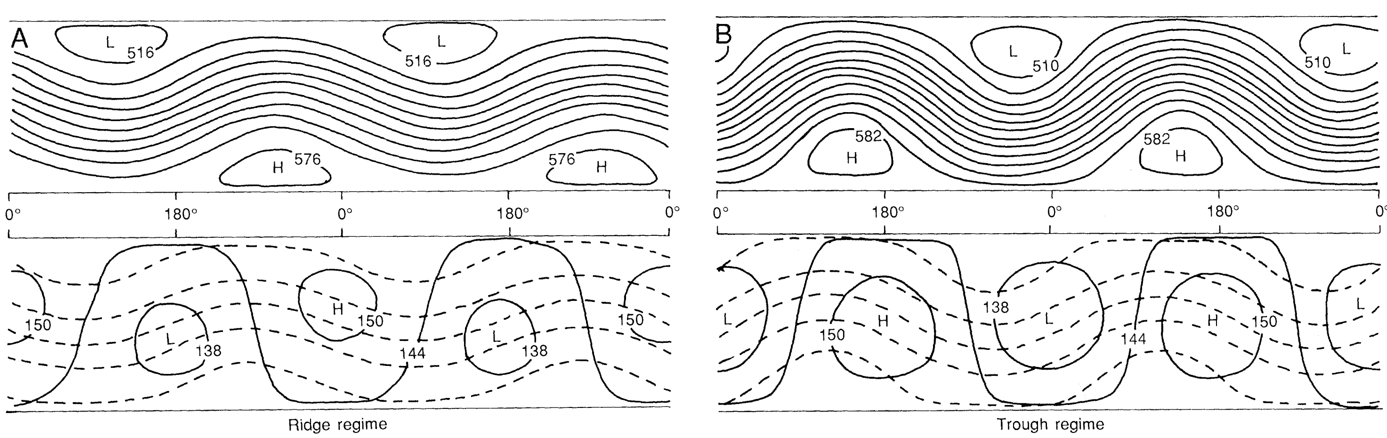


**Fig. 4.** Time-averaged weather maps of the two regime states from the model experiments. In each case the upper map is the 500-mbar flow, and the lower map is the 800-mbar flow. The solid lines are height contours in decameters, and the dashed lines are 800- to 500-mbar thickness lines, which are proportional to the temperature. The ticks marked 0° and 180° are the locations of the sinusoidal mountain ridge and valley, respectively. (**A**) The ridge regime (so-named because the large-scale high-pressure center, or ridge, is upstream of the mountain ridge); (**B**) the trough regime (so-named because the large-scale low-pressure center, or trough, lies just upstream of the mountain ridge). These diagrams demonstrate the success of the model in developing the regimes and show the different internally generated states that are possible through the weather regime process.

short-range, within-season climatic anomalies and variations are primarily internal phenomena, depending only upon the atmospheric dynamics. No assistance from outside sources is required to establish these frequently costly events.

## Discussion

If the weather regime hypothesis is correct for the atmosphere, does this imply that the role of time-varying external forcings such as an El Niño is irrelevant and that extended-range forecasting in itself is for all practical purposes hopeless? Not completely. In midlatitudes, the main effect of anomalous external forcings would be to introduce the weather regime phenomenon into a slightly different environment. Perhaps this action would bias the preference of one regime over the others, either through the influence of the anomalous forcings on the phase-fixing property of the time-invariant large-scale external forcing or through the local enhancement of cyclogenesis or some other similar effect. The major low-frequency variance, on the other hand, would continue to be a result of internally induced transitions by the mobile weather systems, and it is perhaps one explanation for the continued poor performance of extended-range forecasts that use stimulus-response models.

Extended-range forecasting is much more difficult than implied by any stimulus-response concept, though the picture may not be as bleak as it first appears. The best hope for making progress may be to direct research efforts toward identifying and understanding the interactions between the planetary and synoptic scales. What type of storm paths does a given large-scale pattern attempt to induce and why? Given a certain storm track pattern, what are the feedbacks upon the large scale, and how are these feedbacks altered as the storm track deviates from its idealized equilibrated structure? The answers to these questions would provide forecasters with some dynamic and scientific means of anticipating events that could potentially lead to transitions between flow regimes.


REFERENCES AND NOTES

1. R. M. Dole and N. D. Gordon, *Mon. Weather Rev.* **111**, 1567 (1983).
2. M. L. Blackmon, J. M. Wallace, N.-C. Lau, S. L. Mullen, *J. Atmos. Sci.* **34**, 1040 (1977).
3. M. L. Branick and L. Bosart, *Mon. Weather Rev.* **107**, 1245 (1979).
4. J. Shukla and J. M. Wallace, *J. Atmos. Sci.* **40**, 1613 (1983); E. Rasmusson and T. Carpenter, *Mon. Weather Rev.* **110**, 354 (1982).
5. J. D. Horel and J. M. Wallace, *Mon. Weather Rev.* **109**, 813 (1981); R. A. Madden, *J. Geophys. Res.* **86**, 9817 (1981).
6. N.-C. Lau, *Mon. Weather Rev.* **109**, 2287 (1981).
7. R. M. Dole, thesis, Massachusetts Institute of Technology (1982).
8. ——, *Mon. Weather Rev.* **114**, 178 (1986).

8a. "Blocking" is a flow situation in which a large amplitude, large-scale quasi-stationary center blocks the normal west-to-east progression of the mobile systems.

9. J. G. Charney and J. G. DeVore, *J. Atmos. Sci.* **36**, 1205 (1979); J. G. Charney and D. M. Straus, *ibid.* **37**, 1157 (1980); E. Källén, *ibid.* **38**, 969 (1981); R. T. Pierrehumbert and P. Malguzzi, *ibid.* **41**, 246 (1984); J. O. Roads, *ibid.* **37**, 1958 (1980); *ibid.*, p. 2381; A. Trevisan and A. Buzzi, *ibid.*, p. 947; J. Pedlosky, *ibid.* **38**, 2626 (1981).
10. B. B. Reinhold and R. T. Pierrehumbert, *Mon. Weather Rev.* **110**, 1105 (1982).
11. B. Legras and M. Ghil, *J. Atmos. Sci.* **42**, 434 (1985).
12. J. G. Charney, *J. Meteorol.* **4**, 135 (1947); F. Sanders, *Mon. Weather Rev.* **99**, 393 (1971).
13. J. G. Charney and A. Eliassen, *Tellus* **1**, 38 (1949).
14. K. E. Trenberth, *J. Atmos. Sci.* **40**, 1126 (1983).
15. J. S. Frederiksen, *ibid.* **36**, 195 (1979); M. C. W. Niehaus, *ibid.* **37**, 1447 (1980).
16. F. Sanders and J. R. Gykum, *Mon. Weather Rev.* **108**, 1589 (1980); S. J. Colucci, *J. Atmos. Sci.* **42**, 2701 (1985).


"I'LL SAY THIS FOR THE INVERTEBRATES—THEY PROBABLY NEVER GET BACKACHES."