STATIONARY PLANETARY WAVES, BLOCKING, AND INTERANNUAL VARIABILITY

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1. INTRODUCTION

This paper is a somewhat didactic discussion of various current trends in the study of large-scale planetary waves and their anomalies. The intensity of current activity on this topic stems from the belief that the anomalies can be unusually long lived and may, therefore, represent particularly predictable features of weather. The word "blocking" is sometimes associated with these anomalies. Much of the present activity stems from the winter of 1976/1977, when the period December to mid-February was, on the average, unusually cold; this was associated with a stationary wave pattern that was significantly amplified over its climatological mean (Namias, 1978).

It seems to me that much of the current approach is unbalanced at best. Far more work is being devoted to accounting for anomalies than to accounting for the climatology itself. Moreover, the contention that the anomalies are persistent may itself be misleading. By persistence I suppose is meant slow time variation compared to the expected periods of oscillation of the atmosphere. Such persistence, I hope to show, accounts for a relatively small part of the planetary-wave anomalies.

I will begin, in Section 2, by examining some aspects of the observed time behavior of anomalies. It appears that there is some modest interannual variability of stationary wave patterns, but little evidence of unusual persistence in the larger anomalies. Indeed it appears that a significant part of interannual variability is simply a statistical residue of short-period anomalies.

Given the above conclusions, it is awkward to discuss the various explanations put forward to account for the allegedly persistent anomalies. However, the observational picture is not yet convincingly clear. There is some

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evidence, that on rare occasions, long-lived (> 1 month) significant anomalies do occur. The period 1962 – 1963 is sometimes cited in this regard (Tung and Lindzen, 1979). (Even in such events it seems possible that we are simply dealing with shorter events "running into each other.") Two approaches have been particularly popular: multiple equilibria, and teleconnections between the tropics and midlatitudes. The former, which is amply represented in this volume, considers the possibility that stationary wave patterns have several equilibrium configurations and that persistent anomalies arise when the atmosphere passes from one equilibrium state to another. If multiple-equilibria theories were correct, then the nonexistence of persistent anomalies would be a problem. As I will show in Section 3, the most common multiple-equilibria theories appear inappropriate to the atmosphere.

The role of teleconnections is more complicated. Horel and Wallace (1981) noted that patterns of geopotential heights involving both the tropics and midlatitudes accounted for significant (about 20%) portions of the winter variability of monthly means. Thus, it was conjectured that tropical occurrences like El Niño should have anticipatable midlatitude consequences. Given the modest role of this pattern it is difficult to believe that it can offer much improvement in long-term forecasts. Certainly, it does not appear to be a mechanism for the prominent short-period anomalies. In Section 4, I will simply note the poor correlation between El Niño years and North American winter climate. I will show some recent data analyses by Plumb (1985) which appear to suggest a very small role for the tropics in forcing the climatological stationary waves of northern midlatitudes. The clear conclusion that one is forced to is that the tropics are certainly not the major factor in determining midlatitude stationary waves, though they may be one contributor among others to interannual variability. This is consistent with the recent work of Lau and Phillips (1984) and Dole (1985), who found that composites of planetary-wave anomalies in midlatitudes showed no evidence of a tropical precursor. On the contrary, there was a suggestion of tropical response (i.e., time lag). Nevertheless, a large number of theoretical papers have purported to find large midlatitude responses to tropical forcing — duplicating the Horel – Wallace teleconnection pattern.

We will discuss the theoretical papers in Section 5 where, however, I concentrate on recent results by Jacqmin and Lindzen (1984) on the climatological stationary wave pattern and its sensitivity to changes in both the zonally averaged flow and in the thermal forcing.

Finally, in Section 6, some recent work on the atmosphere's free transient Rossby waves is described. It has been found that these oscillations are planetary in scale, of significant amplitude, and characterized by periods of 10 – 20 days — periods not unlike those identified with unusual persistence.

2. How Persistent Are Anomalies?

Although it is commonly taken for granted that anomalies of unusually long persistence are an important feature of weather, I would like to suggest that this may, in fact, be untrue. Consider Fig. 1, taken from the *New York Times* of 9 January 1983, which summarizes New York City's weather in 1982 (there was no particular reason for choosing 1982 other than the convenient availability of this figure). As always, the temperature vacillates above and below the "normal" range. Of particular note is December 1982, an unusually warm month. Note that the warmness of the month as a whole was due to a sequence of warm episodes, none of which lasted longer than a week. Note also that this warm month also had episodes of below-normal temperature. The point is perhaps obvious: namely, a warm month does not represent an anomaly which persisted for a month.

This is consistent with Fig. 2 taken from Dole and Gordon (1983). This figure shows number of anomalies (for different anomaly thresholds) versus duration. We see that the expected duration of any anomaly, once observed, is less than 6 days.

To be sure, there are times when 6 days seems anomalously long. However, for persistence to have a physical meaning, "long" must be long compared to the normal time scales for transiency. The most obvious comparison, here, is with the time scales of the free *planetary-scale* Rossby waves. As we shall describe in Section 6, such waves are prominent in the data and commonly have periods of from 10 to 20 days, consistent with the theory of such waves. In comparison with these periods, the persistence time scales are certainly not long.

While the bulk of planetary-wave anomalies are not "persistent" in a physically meaningful way, there is in fact some significant interannual variability in "stationary" waves. Figure 3 from van Loon *et al.* (1973) shows

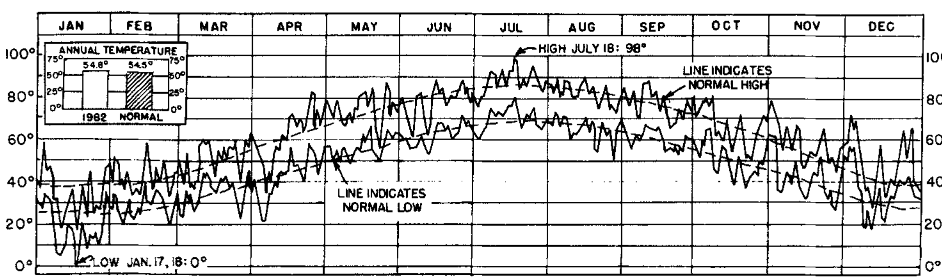

FIG. 1. Temperature in New York City as a function of time for 1982. (From *New York Times* of 9 January 1983.)

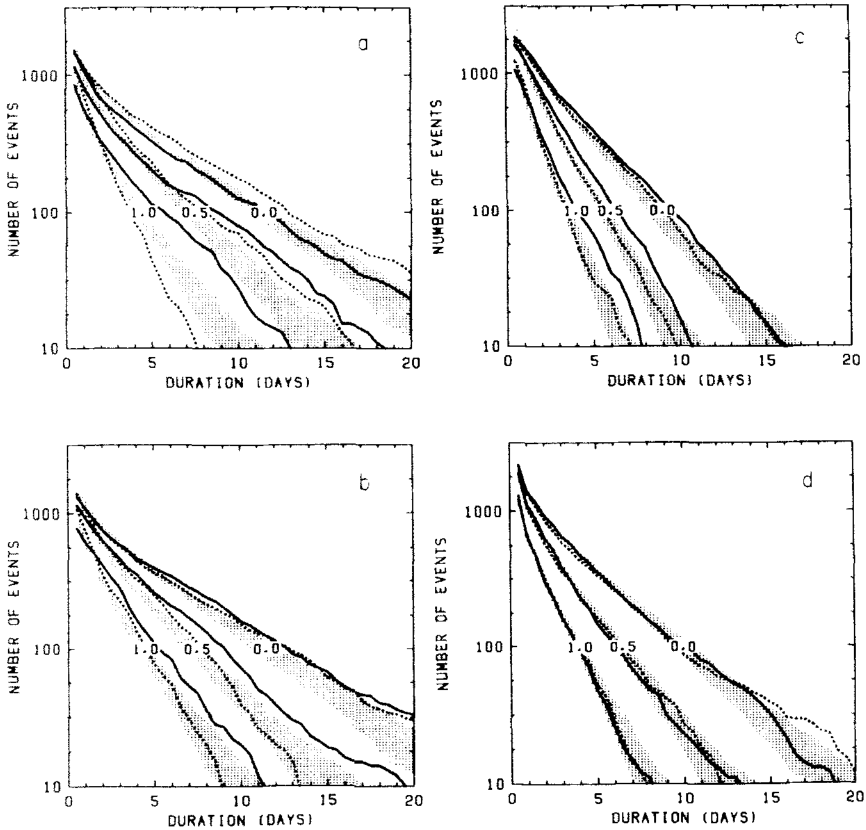

FIG. 2. Histograms of number of persistent anomalies versus duration, for different areas and for positive (solid lines) and negative (dotted lines) anomalies. (a) For area PAC; (b) for area AME; (c) for area ATL; (d) for area EAS. (After Dole and Gordon, 1983.)

January mean planetary-wave response for wavenumbers 1, 2, and 3 at fixed latitudes and for a range of years. There are variations but they are *not* 0(1) and judging from Fig. 1 they are significantly due to short-period episodes. This is supported by Table I, which shows the interannual variability of 3-month winter means of planetary-wave height fields at 50°N (where variability is usually largest). The variability is still smaller than found by van Loon for January means. Figure 4 shows the wavenumber 1 – 3 sums (based on Table I) for four of the most deviant years. There are indeed meteorologically significant differences but gross patterns and magnitudes remain similar.

Thus, we are left with a picture wherein strong planetary-wave anomalies are associated with short periods, while interannual variability, though real,

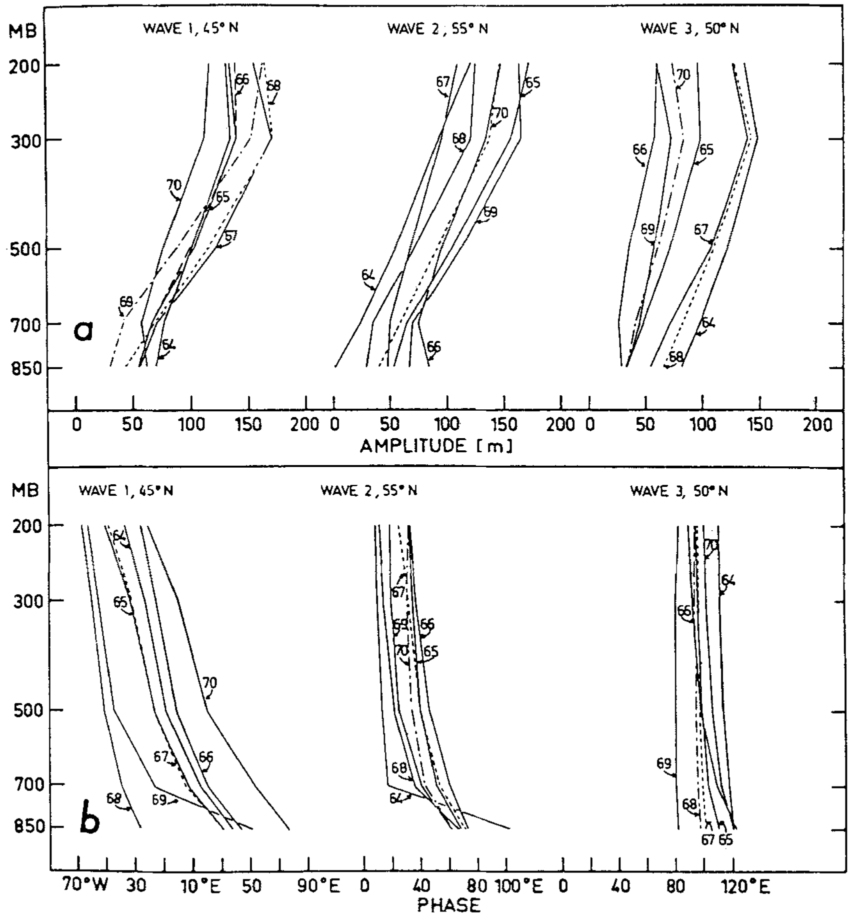

FIG. 3. Wavenumber decomposition of January mean height field for the years 1964–1970. (After van Loon *et al.*, 1973.)

is modest. It should be added that modest changes in stationary waves involving phase shifts of a few hundred kilometers and amplitude changes of 20% are still of major importance to the weather of specific regions.

3. Multiple Equilibria?

Under the impression that unusually persistent stationary anomalies existed (something we question in Section 2), models were developed suggesting that there existed a multiplicity of stationary wave states, each in equilib-

TABLE I. AMPLITUDE AND PHASE OF WAVENUMBERS 1, 2, AND 3[a]

	Wave 1		Wave 2		Wave 3	
Year	Amplitude (m)	Phase (ridge longitude)	Amplitude (m)	Phase (ridge longitude)	Amplitude (m)	Phase (ridge longitude)
1	105	2	85	91	115	−29
2	108	−6	81	73	96	−84
3	85	−5	131	97	40	−94
4	125	−9	87	91	95	−63
5	81	−18	64	78	100	−66
6	110	−26	81	65	49	−116
7	124	−5	90	110	84	−62
8	80	2	97	63	69	−56
9	72	6	116	57	71	−53
10	114	−6	92	73	75	−34
11	93	6	91	81	59	−49
12	117	1	92	79	88	−43
13	116	−9	66	70	116	−52
14	103	0	135	103	80	−41
Average	102 ± 17		93 ± 20		81 ± 22	
Phase	−4.8		80.8		−60.1	
Range	28° long.		27° long.		28° long.	
	± 14° long.		± 13.5° long.		± 14° long.	
	± 14° phase		± 27° phase		± 42° phase	

[a] Contributions to winter average height field at 500 mbar for 1964–1977.

rium with the topography and the forcing of the zonally averaged basic state. The pioneering effort along these lines was due to Charney and DeVore (1979). Among the successor efforts, several are discussed in these proceedings. All such models of multiple equilibria depend on the existence of stationary free waves (normal modes) which are resonantly forced by stationary forcing. Clearly, the existence of resonance is crucially dependent on the mean zonal wind. In addition, in each model, stresses due to the resonant stationary wave ("form–drag") play a major role in determining the mean flow. The interplay of these two dependences (the dependence of resonance and hence form–drag on the mean flow and the dependence of mean flow on form–drag) is at the heart of the existence of multiple equilibria. In most approaches, different equilibria are associated with different mean flows and different stationary wave amplitudes. However, recent work by Speranza (this volume) has considered nonlinear resonance curves where two different stationary amplitudes can be associated with almost identical mean flows.

The purpose of this section is to briefly note some objections to the existing theories of multiple equilibria. [Other objections are described in Tung and

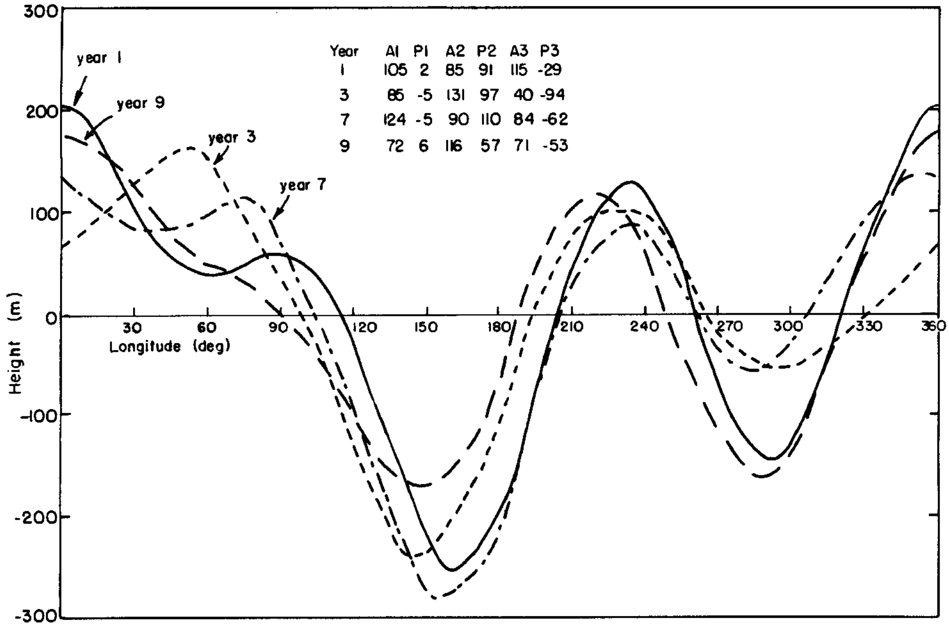

FIG. 4. Winter (Dec–Feb) average height fields versus longitude at 50°N for various years.

Rosenthal (1984).] The objections fall into two broad categories. The first deals with the existence of suitable resonances, the second with the effect of stationary waves on the mean flow.

As concerns the existence of resonance, several difficulties exist. The only well-documented planetary-scale free oscillations of the atmosphere are the external modes associated with global scales (zonal wavenumbers 1–3 with comparably small meridional wavenumbers) and very large westward phase speeds [0(70 m $\sec^{-1}$)]. The most recent description of these waves is in Lindzen *et al.* (1984). These waves are only mildly altered by realizable changes in the mean flow; there are *no* observed mean flows which reduce their phase speed to zero. Thus they cannot be resonantly forced by stationary forcing. The only free waves with suitably low phase speeds would be internal modes. Since the atmosphere does not have a lid, the only internal modes arise from internal reflections from surfaces in the atmosphere where its index of refraction changes sign (Tung and Lindzen, 1978; Held, 1984). Resonances arise from the repeated reflection of waves from such surfaces where incident and reflected waves are in phase so that amplification may take place. In idealized models the reflecting surface is perfectly horizontal and the necessary constructive interference is readily achieved. Unfortunately, in reality this surface (when it exists at all) is quite bent and distorted

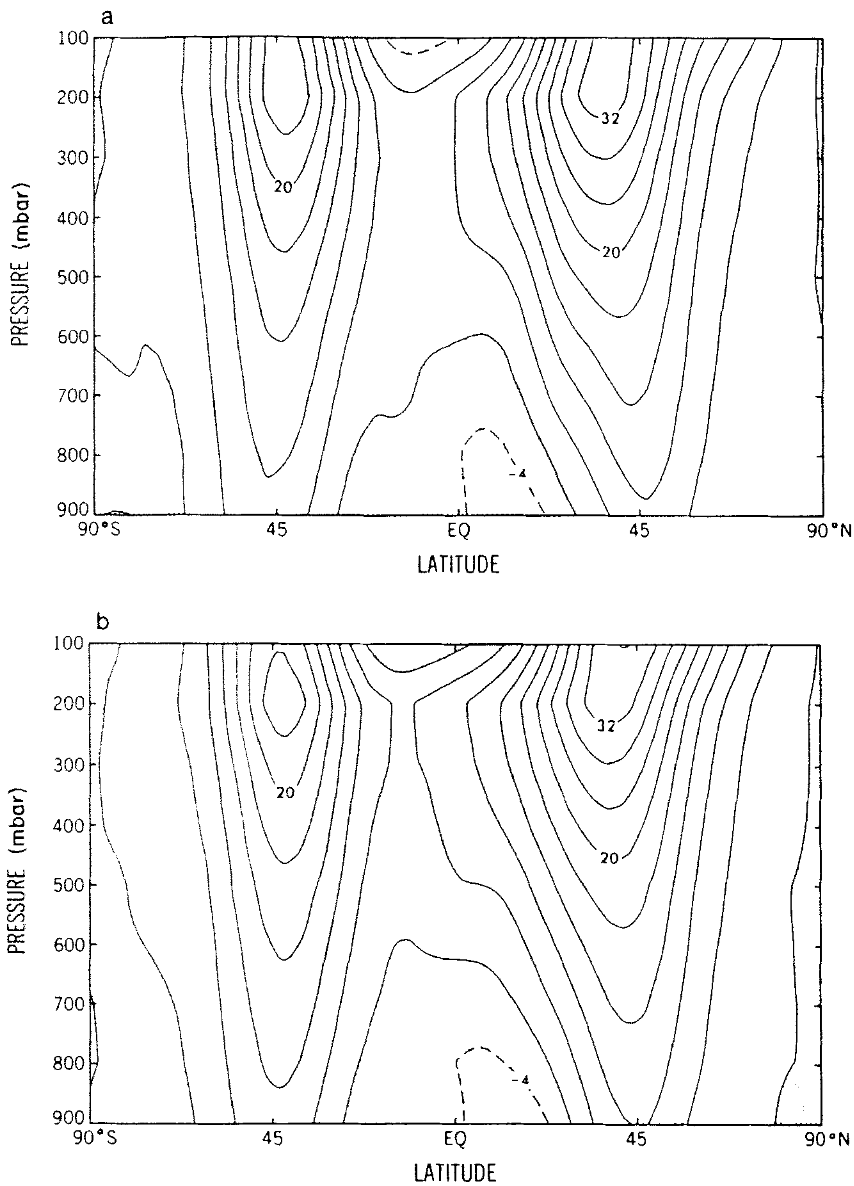

FIG. 5. Zonally averaged mean zonal wind in GCMs without (a) and with (b) mountains. (After Nigam, 1983.)

and reflected waves do not coincide with incident waves; resonant amplification, therefore, is profoundly limited. A clear example of this effect is given by Lindzen and Hong (1974). The situation is rendered even more negative by the fact that stationary resonant modes would also encounter zero wind surfaces. Although it has been argued that nonlinearity can lead to reflection at such surfaces (Tung, 1979), it is also true that in the neighborhood of such surfaces damping becomes very important and is inimical to resonance. Even normal damping will severely restrict resonance. It has recently been suggested by McIntyre and Palmer (1984) that wave steepening near such surfaces leads to irreversible mixing so that the damping limit may, in fact, be intrinsic. [However, P. Killworth and M. E. McIntyre (private communication) recently noted that this may not be uniquely associated with wave absorption.]

For all the above reasons one may reasonably conclude that the resonance called for in multiple-equilibria theories is unlikely under realistic circumstances. This view is supported by the recent work of Jacqmin and Lindzen (1984) wherein stratospheric wind configurations suggested by Tung and Lindzen (1979) as favorable for resonance were used, and no anomalous tropospheric response was obtained.

We turn, finally, to the influence of stationary waves on the mean flow— an influence essential to most multiple-equilibria theories. Nigam (1983) recently ran a general circulation model (GCM) at Geophysical Fluid Dynamics Laboratory (GFDL), where zonal wind distributions were calculated in models with and without mountains (the major forcers of stationary waves at midlatitudes). His results are shown in Fig. 5. Clearly the zonal winds (except at the surface) are almost identical.

Thus on both essential grounds, there seems to be little theoretical support for the possibility of proposed multiple equilibria.

4. Teleconnections—The Tropical Connection?

In the search for a means to anticipate years with anomalous stationary wave patterns, teleconnections have played a prominent role. The term was introduced by J. Namias to describe the apparent correlation of weather at remote points. In recent years the idea has been closely associated with the notion that tropical heating plays a major role in forcing high-latitude stationary waves (Wallace and Gutzler, 1981; Horel and Wallace, 1981). Figure 6 shows the Pacific–North American (PNA) pattern from Wallace and Gutzler (1981) which is found to account for about 18% of the planetary-wave variance. Clearly, this is not a dominant factor. Moreover, the omission of the tropical part of the PNA pattern would not greatly reduce the variance it accounts for. Despite this, great emphasis has been placed on this

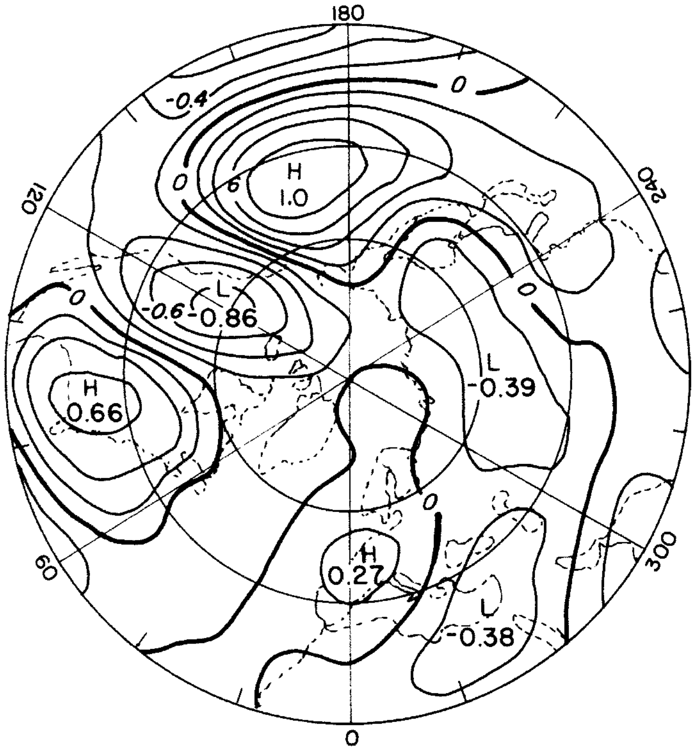

FIG. 6. Coherence map for PNA pattern. (After Wallace and Gutzler, 1981.)

pattern—with the promise that the sea surface temperature anomalies (and the resulting anomalies in cumulus convection distribution and latent heating) associated with El Niño might have predictable consequences for North American weather.

Figure 7 shows the distribution of winter temperature in the continental United States for 8 El Niño years. There is little more similarity in these patterns than may be found among arbitrarily chosen years. The figure shows regions of normal, above-normal, and below-normal temperature for the various winters. These designations are such that one-third of all winters fall into each of the categories. The category limits for selected cities are given in Table II.

It should be realized that anomalous heating associated with El Niño is primarily a redistribution of heating which occurs normally, rather than some source of additional heating. Thus, if El Niño were a profound influence on midlatitude stationary waves, one would also expect that the tropics would be a major source for climatological stationary waves. Plumb (1985)

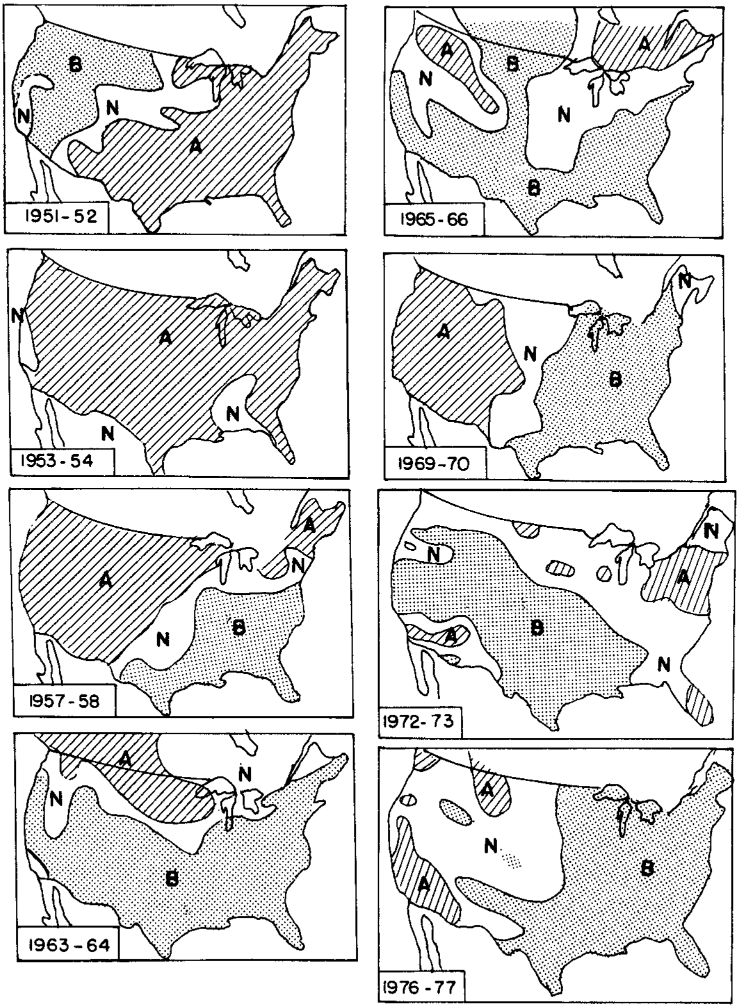

FIG. 7. Winter temperature pattern over North America for 8 El Niño years. (From NWS climate alert.)

TABLE II. WEATHER SERVICE CLASS LIMITS FOR 90-DAY WINTER MEANS

Boston	30.9° ± 1.3°F
New York City	33.6° ± 1.3°F
Miami	67.8° ± 1.2°F
New Orleans	54.4° ± 1.9°F
Des Moines	22.8° ± 1.6°F
Denver	31.7° ± 1.5°F
Los Angeles	55.3° ± 1.2°F
San Francisco–Oakland	49.7° ± 1.0°F
Seattle	40.2° ± 1.2°F
Great Falls	21.1° ± 2.9°F

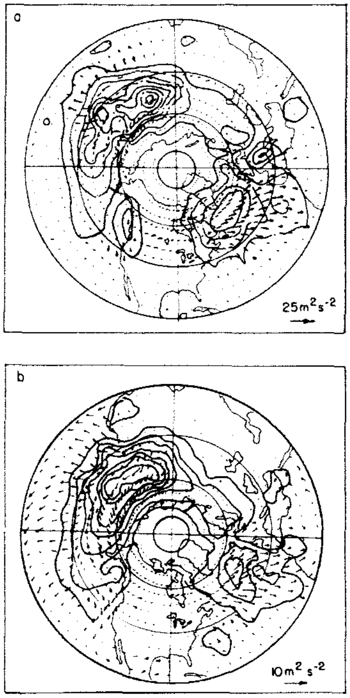

FIG. 8. Total stationary-wave flux at (a) 500 and at (b) 150 mbar. (After Plumb, 1985.)

has recently developed a three-dimensional variant of the E–P (Eliassen–Palm) flux in order to ascertain the geographic origin of climatological stationary waves. His approach is not without ambiguities. However, his results, shown in Fig. 8, are certainly suggestive. Not only do they fail to show the tropics as a source of stationary wave flux, they even suggest that the tropics are a modest sink of such fluxes.

Finally, Dole (1985) has recently performed a composite analysis of persistent anomalies in the North Pacific. This study suggests that the tropical part of the PNA pattern actually lags behind the more prominent northern part. This result was also obtained by Lau and Phillips (1984) in a study of satellite cloud data.

The above results are compatible with Jacqmin and Lindzen's (1985) recent stationary-wave calculations, which will be discussed next.

5. Linearized Response to Stationary Forcing

The most common approach to studying stationary waves has been to calculate them as forced linearizable perturbations on a zonally symmetric basic state. There are a number of worrisome questions about such an approach. Although the most obvious question concerns the validity of linear theory itself, there are still many uncertainties remaining even if linearity itself were acceptable. At the most basic level is the question of the forcing. Although orographic forcing is well known, thermal forcing is more ambiguous. The question of thermal forcing is discussed in some detail in Jacqmin and Lindzen (1985); the contribution of latent heating is to some extent documented in atlases of rainfall (viz., Schutz and Gates, 1972; Dorman and Burke, 1979); the contribution of sensible heat flux, while likely to be smaller (Charney, 1973), is not at all well known. There is also the possibility that transient disturbances traveling along geographically preferred storm paths might contribute to the modification of stationary waves (Youngblut and Sasamori, 1980; Niehaus, 1980; Frederiksen, 1979). An interesting test of this situation was made in the previously mentioned work of Nigam (1983). Nigam, working with his advisor, I. M. Held, developed a simplified, but physically complete, general circulation model. The model was run long enough for time averages to delineate the model's stationary waves. The same model was then linearized and its response to the stationary components of the forcing was calculated. The differences in the results are presumably due to the above factors (transients, nonlinearity, etc.).

Some results are shown in Fig. 9. This figure shows the January mean of the 500-mbar height taken from a 20-year run of the GCM (Fig. 9a), the same mean obtained from observations (Fig. 9b), the linearized response to topography and the GCM's January diabatic heating using the GCM's January zonally averaged zonal wind (Fig. 9c), the response to topography alone (Fig. 9d), the response to diabatic heating alone (Fig. 9e), and the stationary waves forced by the GCM's transient disturbances (Fig. 9f). The most important point is that the GCM and linearized results, while not identical, are both quantitatively and qualitatively close. It is also clear that a significant part of the small difference is due to the forcing of stationary waves by the GCM's transients. Finally, we see that the GCM and linearized results are equally close matches to the data.

The above leaves us with some confidence that linearized results are meaningful. This is of considerable importance since neither of Nigam's models is entirely adequate from the point of view of resolution. While the costs of suitable resolution in a GCM might prove prohibitive, they are easily acceptable in a linearized model. Such a high-resolution linearized model was developed by Jacqmin and Lindzen (1984). In this model [characterized by vertical resolution 0 (1 km) and meridional resolution 0 (1°)], the response of an atmosphere with realistic distributions of zonal wind and zonally averaged temperature to realistic orography and to heating derived from rainfall atlases (latent heating is likely to be the dominant thermal forcing) is calculated. There is no point in giving a detailed discussion of the model here, but in general the response was in tolerably good agreement with the

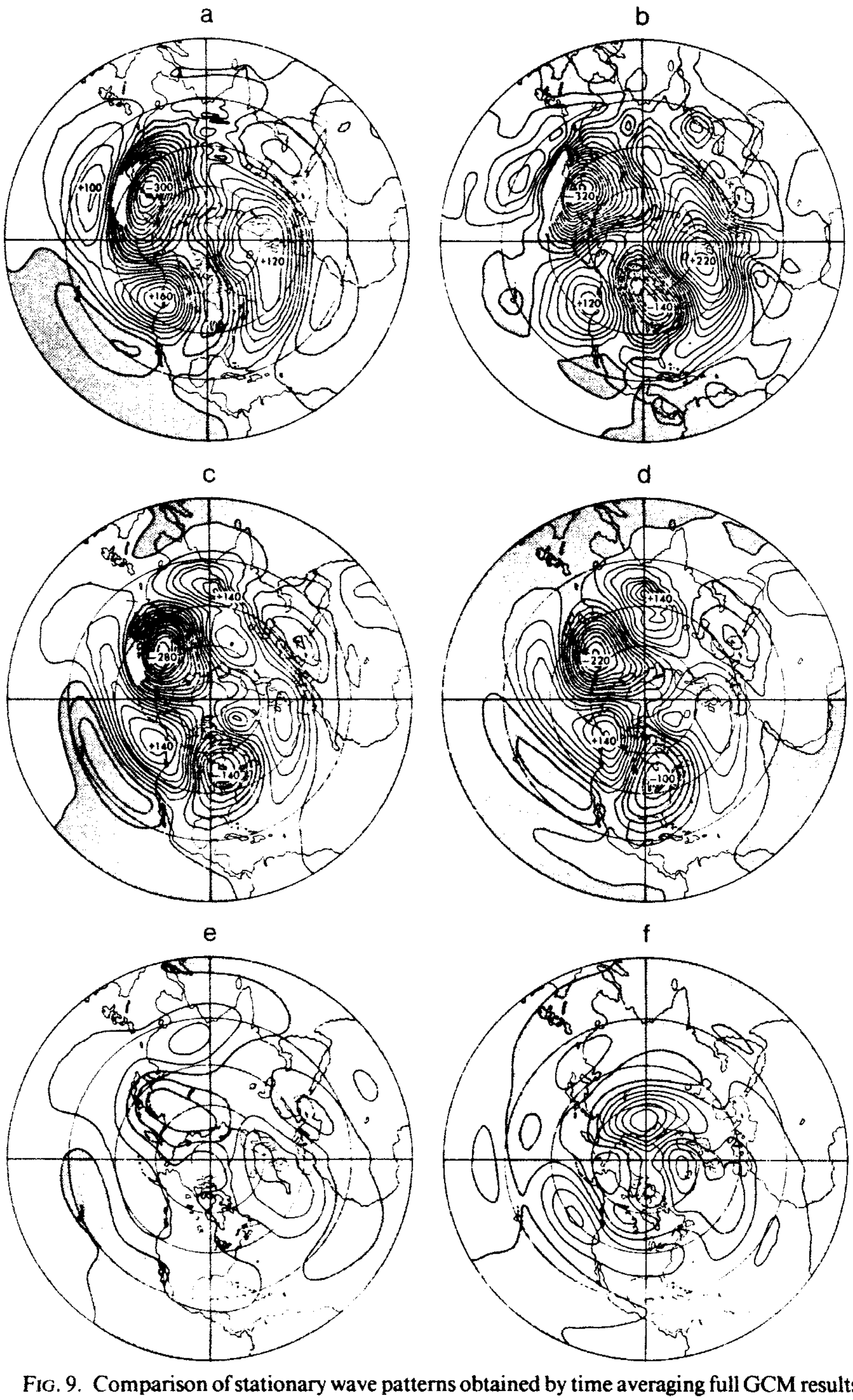

FIG. 9. Comparison of stationary wave patterns obtained by time averaging full GCM results and data and results from a linearized version of the GCM. (a) GCM; (b) atmosphere; (c) total; (d) topography; (e) heating; (f) transients. See text for details. (From Nigam, 1983.)

stationary-wave climatology of van Loon *et al.* (1973). One might, therefore, hope that the model might in fact tell us something about how stationary waves in the atmosphere work. Figure 10 shows the calculated stationary-wave height contours at various levels. Figure 11 shows the contours due to topographic forcing alone, while Fig. 12 shows the contours due to thermal forcing alone. Clearly Figs. 10 and 11 are almost identical; the contribution from thermal forcing is relatively small. It should be noted, moreover, that

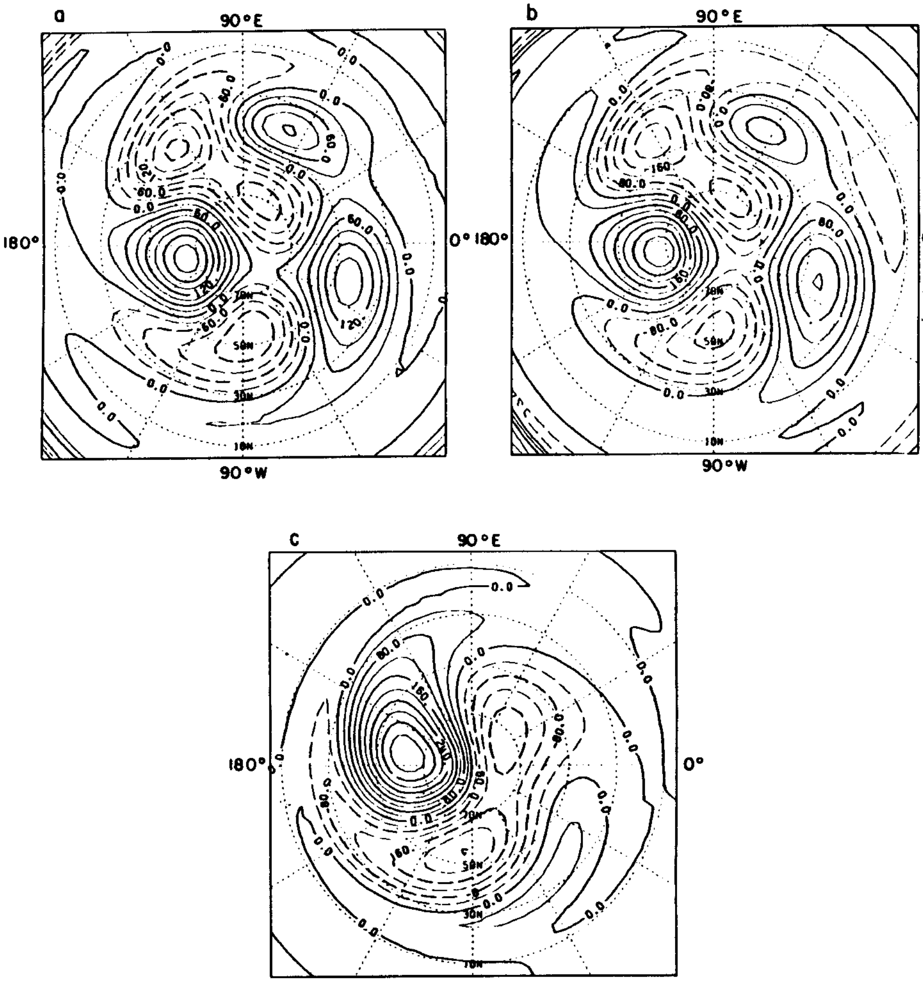

FIG. 10. Stationary-wave height field at various levels calculated from a high-resolution linear model with mountain and thermal forcing. (a) 6 km; (b) 10 km; (c) 30 km. (From Jacqmin and Lindzen, 1985.)

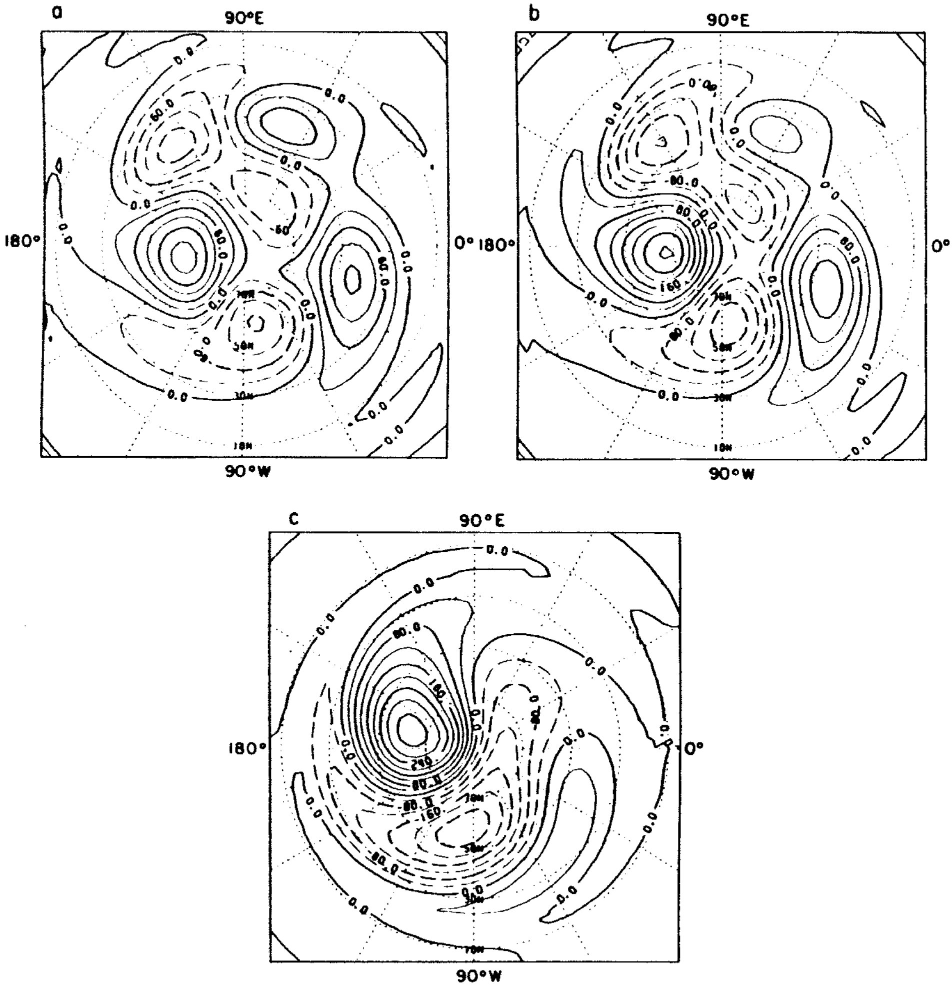

FIG. 11. Same as Fig. 10, but with mountain forcing only.

Fig. 12 includes thermal forcing from all latitudes. The contribution from tropical forcing alone is responsible for only about half of the midlatitude response shown in Fig. 12. These results are completely consistent with the observationally based analysis of Plumb (1985) cited earlier in this article. They are also compatible with results obtained by Nigam and shown in Fig. 9.

The question finally arises as to how to reconcile these results with the multitudinous results showing the important influence of tropical heating on Northern Hemisphere stationary waves (Hoskins, 1978; Hoskins and

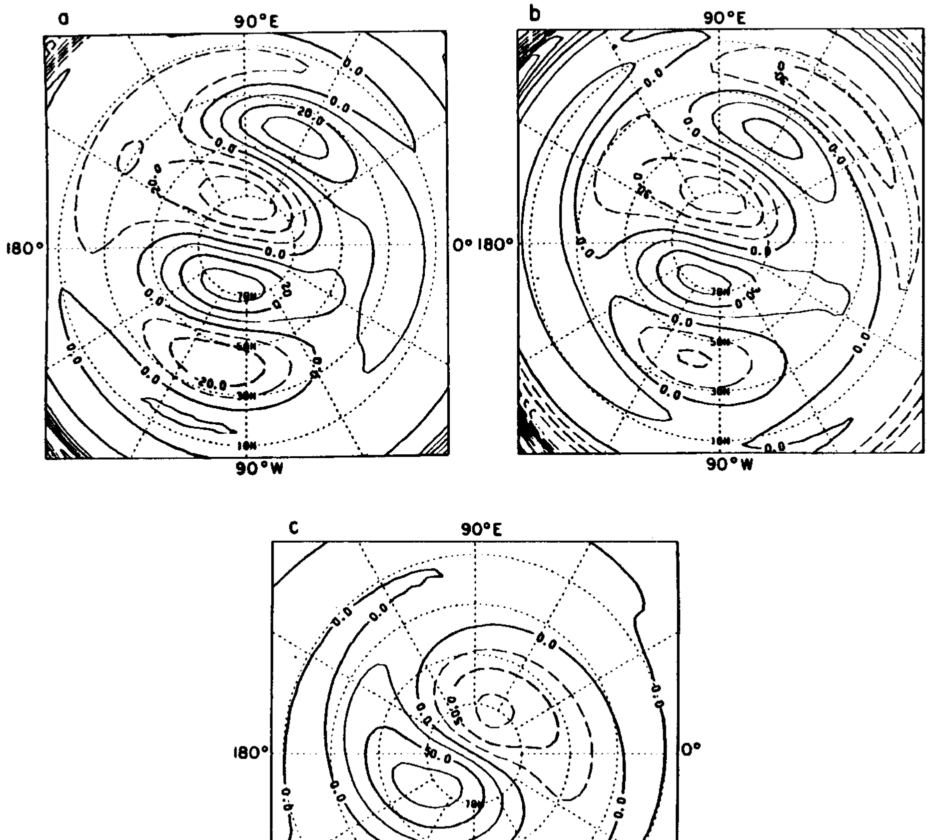

FIG. 12. Same as Fig. 10, but with thermal forcing only.

Karoly, 1981; Karoly and Hoskins, 1983; Egger, 1976; Opsteegh and van den Dool, 1980; Webster, 1981; Simmons, 1982; and many others). Most of these calculations, in fact, used oversimplified models (one- or two-level models) whose shortcomings are obvious. However, Simmons (1982), with a nine-level model in a spherical geometry, did not, in large measure, suffer from these shortcomings. His global response to tropical forcing is shown in Fig. 13. The midlatitude response at 500 mbar is somewhat large but certainly smaller than the climatological stationary-wave amplitudes (essentially those shown in Fig. 10). If Simmons had used more plausible damping,

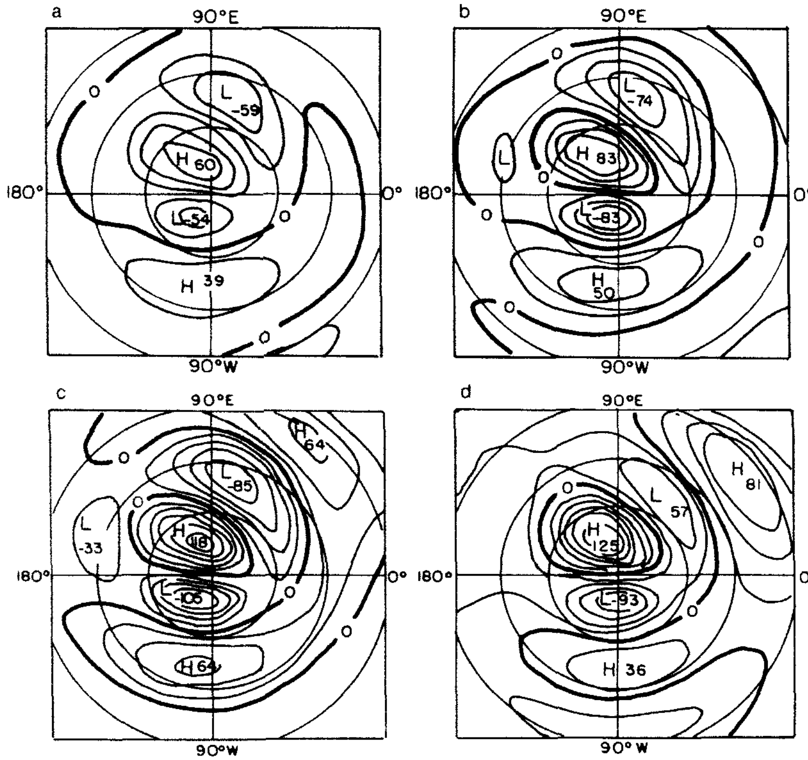

FIG. 13. Polar plots of the response to tropical forcing. (a) 700 mbar; (b) 500 mbar; (c) 300 mbar; (d) 100 mbar. (After Simmons, 1982.)

it is likely that the modest reduction in response would bring it into consistency with observed interannual variability.

This, however, is only part of the story. Jacqmin and Lindzen (1984) found that for their reference basic state, the response to an isolated tropical heat source was similar in magnitude to that obtained by Simmons, but the shape of the response was very different. However, for a moderately different (but still reasonable) distribution of zonal wind, they could, in fact, closely duplicate Simmons' result. This sensitivity to zonal wind suggests that it will be difficult to use tropical sea surface temperature as a long-term predictor of midlatitude stationary waves, simply because the zonal winds themselves are variable over relatively short periods.

Where does the above leave us? If Jacqmin and Lindzen (1984) are correct in identifying flow over topography (primarily the Himalayas and secondarily the Rockies) as the dominant forcing for Northern Hemisphere midlatitude stationary waves, then flow over these mountains should at least provide a short-term precursor for downstream stationary-wave anomalies.

Dole (in this volume) has recently found some weak evidence in support of this. As far as tropical anomalies go, they may not be of practical importance in midlatitude forecasting, but they are certain to be a prominent factor in determining stationary waves (i.e., the Walker circulation) in the tropics.

6. Free Rossby Waves and the Meaning of Persistence

In discussing unusual persistence, it is, of course, essential to know what one means by persistence. As we have already noted, persistence ought to mean *long lasting* compared to the time scales expected for transients of the same geographical scale. Historically, Rex (1950) noted that blocking tended to persist longer than the much smaller scaled synoptic disturbances whose period was as short as 2 days. Clearly, in view of the dissimilar scales, this comparison is not particularly relevant. The relevant transients are the planetary-scale free Rossby waves.

The periods of these waves have been calculated many times. Table III shows results calculated by Kasahara (1976) for basic states both at rest and with a barotropic mean flow corresponding to observed 500-mbar zonal flows in various seasons. We see that for zonal wavenumbers 1 – 3, the main symmetric meridional mode has a period 0 (5 days), the next antisymmetric mode a period 0 (10 days) and the next symmetric mode a period 0 (16 days). It has further been noted by Lindzen *et al.* (1984) that oscillations associated with the longer periods are dominant in the data. Using data from the First GARP Global Experiment (FGGE) year, Lindzen *et al.* (1984) found that 500-mbar data projected on individual Hough functions (the eigenfunctions appropriate to free Rossby waves) displayed almost precisely the predicted phase speeds. However, amplitudes varied significantly, with large amplitudes occurring episodically and with episodes seldom lasting longer than 2

Table III. Rossby Wave Periods[a]

Mode	Winter	Spring	Summer	Autumn
(1,2)	4.85	4.87	4.85	4.85
(1,3)	9.91	9.99	9.49	9.52
(1,4)	18.39	17.22	16.68	17.40
(2,3)	3.84	3.84	3.79	3.84
(2,4)	7.27	7.55	6.93	7.07
(2,5)	14.23	13.54	12.71	13.22
(3,4)	4.28	4.22	4.10	4.22
(3,5)	7.40	7.60	6.73	7.06
(3,6)	13.65	13.89	11.78	12.76

[a] Days, as calculated by Kasahara (1980) for climatological mean 500-mbar winds.

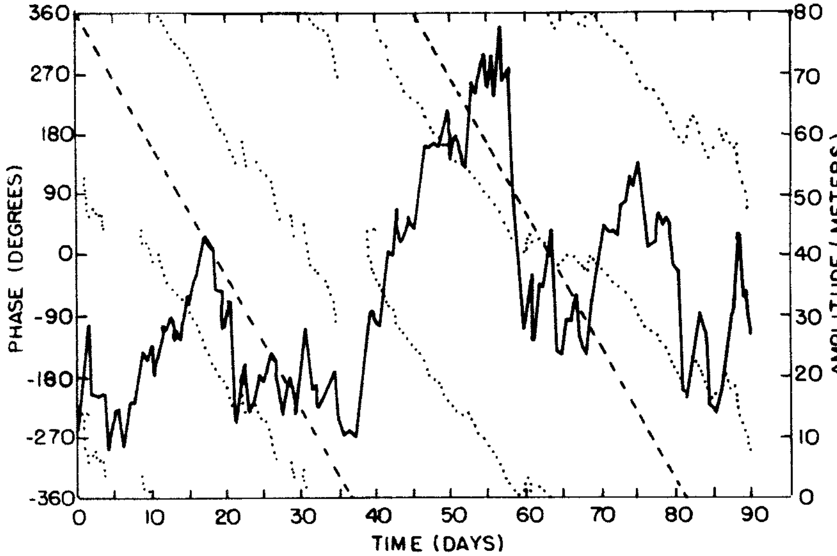

FIG. 14. Amplitude (solid lines) and phase (dotted lines) of the (1,4) Hough mode for December 1978–February 1979 from FGGE data. (From Lindzen *et al.*, 1984.)

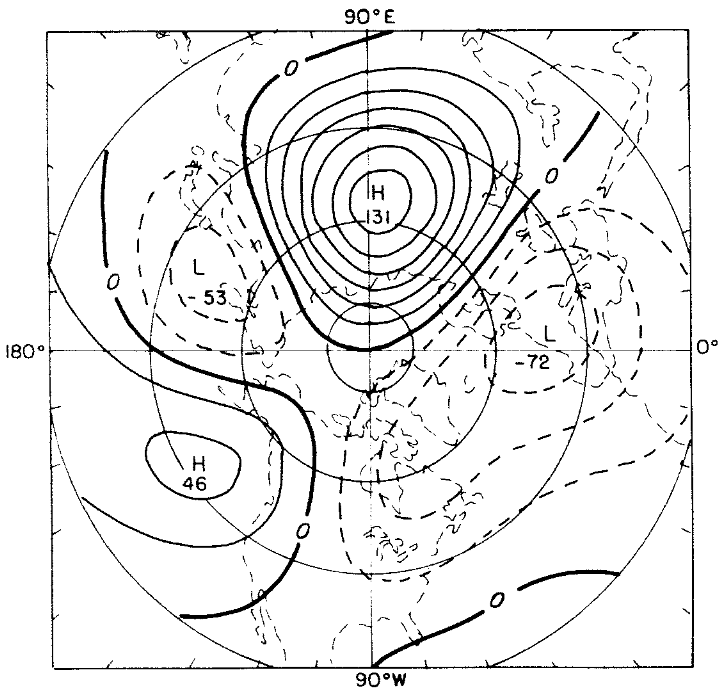

FIG. 15. Geopotential height field at 500 mbar due to nine main Hough modes, for 1200 GMT 12 January 1979. Contour interval is 20 m. (From Lindzen *et al.*, 1984.)

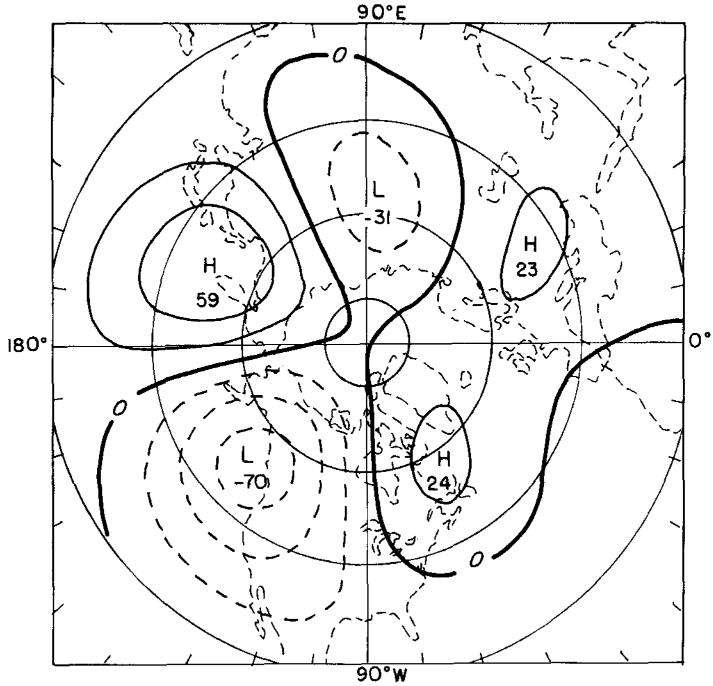

FIG. 16. Same as Fig. 15, but for 22 October 1979.

weeks. As an example, Fig. 14 shows the time series for the amplitude and phase of the 1,4 mode over a 3-month period. The particular choice of mode and period was completely arbitrary. Although individual modes rarely were found to exceed amplitudes of 60 – 80 m, the sum of the nine modes analyzed could contribute significantly more to the height field. Figure 15 shows this sum for a single day when at least one mode was particularly strong. We see anomalies amounting to as much as 137 m. Although anomalies in excess of 100 m due to these waves did not last in excess of 3 days, this is enough to contribute substantially to the overall picture. (Note from Fig. 2 that two-thirds of the anomalies do *not* last longer than 3 days.) Even on days when no modes were especially strong, the sum remains significant; this is seen in Fig. 16.

7. CONCLUDING REMARKS

The point of the present paper has been to suggest that anomalies of planetary waves are not, for the most part, unusually persistent, though some interannual variability exists. We argue that there is neither observational call nor physical basis for current models of multiple equilibria. We also show that realistic anomalies in tropical heating produce only modest anomalies [0 (50 m) at 500 mbar] in midlatitude stationary waves and that the distribution of even these anomalies depends strongly on the zonal wind distribution. This is not inconsistent with the modest amplitude of actual interannual variability, which is readily accounted for by some combination of anomalous tropical heating and variations of zonal flow over the Himalayas and Rockies. Finally we note that observed free Rossby waves contribute significantly to the large, transient planetary-wave anomalies, but by no means totally account for them.

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REFERENCES

Charney, J. G. (1973). Planetary fluid dynamics. *In* "Dynamic Meteorology" (P. Morel, ed.), pp. 97-352. Reidel, Dordrecht.

Charney, J. G., and De Vore, J. G. (1979). Multiple flow equilibria in the atmosphere and blocking. *J. Atmos. Sci.* **36,** 1205-1216.

Dole, R. M. (1985). Life cycles of persistent anomalies. *In* "Proceedings of the 1984 Stanstead Seminar, July 9-13, 1984" (J. Derome, ed.). McGill University, Montreal.

Dole, R. S. and Gordon, M. D. (1983). Persistent anomalies of the extratropical Northern Hemisphere wintertime circulation: Geographical distribution and regional persistence characteristics. *Mon. Weather Rev.* **111,** 1567-1586.

Dorman, C. E., and Bourke, R. H. (1979). Precipitation over the Pacific Ocean 30°S to 60°N. *Mon. Weather Rev.* **107,** 751-774.

Egger, J. (1976). On the theory of steady perturbations in the troposphere. *Tellus* **28,** 381-389.

Frederiksen, J. S. (1979). The effects of long planetary waves on the regions of cyclogenesis: Linear theory. *J. Atmos. Sci.* **36,** 195-206.

Held, I. M. (1983). Stationary and quasi-stationary eddies in the extratropical troposphere: Theory. *In* "Large-scale Dynamical Processes in the Atmosphere" (B. J. Hoskins and R. P. Pearce, eds.), pp. 127-168. Academic Press, New York.

Horel, J. D., and Wallace, J. M. (1981). Planetary scale atmospheric phenomenon associated with the Southern Oscillation. *Mon. Weather Rev.* **109,** 813-829.

Hoskins, B. J. (1978). Horizontal wave propagation on the sphere. *In* "The General Circulation" (M. L. Blackmon, ed.), pp. 144-153. Summer Colloquium Notes, N.C.A.R.

Hoskins, B. J., and Karoly, D. J. (1981). The steady linear response of a spherical atmosphere to thermal and orographic forcing. *J. Atmos. Sci.* **38,** 1175-1196.

Jacqmin, D., and Lindzen, R. S. (1985). The causation and sensitivity of the northern winter planetary waves, *J. Atmos. Sci.*, **42,** 724-745.

Karoly, D. J., and Hoskins, B. J. (1982). Three dimensional propagation of planetary waves. *J. Meteorol. Soc. Jpn.* **60**, 109–123.
Kasahara, A. (1976). Normal modes of ultralong waves in the atmosphere. *Mon. Weather Rev.* **104**, 669–690.
Lau, K. M., and Phillips, T. J. (1986). Extratropical geopotential height fluctuation associated with tropical convection. *J. Atmos. Sci.*, in press.
Lindzen, R. S., and Hong, S. S. (1974). Effects of mean winds and horizontal temperature gradients on solar and lunar semidiurnal tides in the atmosphere. *J. Atmos. Sci.* **31**, 1421–1446.
Lindzen, R. S., Straus, D. M., and Katz, B. (1984). An observational study of large-scale atmospheric Rossby waves during FGGE. *J. Atmos. Sci.* **41**, 1320–1335.
McIntyre, M. E., and Palmer, T. N. (1984). The 'surf zone' in the stratosphere. *J. Atmos. Terr. Phys.* **46**, 825–849.
Namias, J. (1978). Multiple causes of the North American abnormal winter 1976–1977. *Mon. Weather Rev.* **106**, 279–295.
Niehaus, M. C. W. (1980). Instabilities of non-zonal baroclinic flows. *J. Atmos. Sci.* **37**, 1447–1460.
Nigam, S. (1983). On the structure and forcing of tropospheric stationary waves. Ph. D. thesis, Princeton University.
Opsteegh, J. D., and van den Dool, H. M. (1980). Seasonal differences in the stationary response of a linearized primitive equation model: Prospects for long range weather forecasting? *J. Atmos. Sci.* **37**, 2169–2185.
Plumb, R. A. (1985). On the three-dimensional propagation of stationary waves. *J. Atmos. Sci.* **42**, 217–229.
Rex, D. F. (1950). Blocking action in the middle troposphere and its effects on regional climate. II. The climatology of blocking action. *Tellus* **2**, 275–301.
Schutz, C., and Gates, N. L. (1972). Supplemental global climatic data, January. Rand Corp. Rep.
Simmons, A. J. (1982). The forcing of stationary wave motion by tropical diabatic heating. *Q. J. R. Meteorol. Soc.* **108**, 503–534.
Tung, K.-K. (1979). A theory of stationary long waves. III. Quasi-normal modes in a singular waveguide. *Mon. Weather Rev.* **107**, 751–774.
Tung, K.-K., and Lindzen, R. S. (1979). A theory of stationary long waves. I. A simple theory of blocking. *Mon. Weather Rev.* **107**, 714–734.
Tung, K.-K., and Rosenthal, A. J. (1985). The nonexistence of multiple equilibria in the atmosphere: Theoretical and observational considerations. *J. Atmos. Sci.* **42**, 2804–2819.
Van Loon, H., Jenne, R. L., and Labitzke, K. (1973). Zonal harmonic standing waves. *J. Geophys. Res.* **78**, 4463–4471.
Wallace, J. M., and Gutzler, D. S. (1981). Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Weather Rev.* **109**, 784–812.
Webster, P. J. (1981). Mechanisms determining the atmospheric response to sea surface temperature anomalies. *J. Atmos. Sci.* **38**, 554–571.
Youngblut, C., and Sasamori, T. (1980). The nonlinear effects of transient and stationary eddies on the winter mean circulation. I. Diagnostic analysis. *J. Atmos. Sci.* **37**, 1944–1957.