Large-Amplitude, Short-Scale Stationary Rossby Waves in the Southern Hemisphere: Observations and Mechanistic Experiments to Determine their Origin

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ABSTRACT

Studies by van Loon and Jenne, van Loon et al., Trenberth and others indicate that stationary waves in the Southern Hemisphere are dominated by planetary scales. Kalnay and Halem reported the presence of large amplitude, short-scale stationary waves during the month of January 1979 in the lee of South America and their disappearance in February 1979. In this paper we present further observational evidence of the January waves.

We also perform two 15-day forecast experiments with the GLAS Fourth-Order General Circulation Model, and initial conditions corresponding to 5 January and 4 February 1979. These forecasts reproduce reasonably well the presence of the January waves and their absence in February. Several mechanistic experiments to determine the origin of the waves are then performed.

The principal conclusions are

a) Large amplitude stationary Rossby waves with zonal wavenumber ≈7 were present between 20° and 40°S both in the South Pacific and east of South America during January 1979. They appear in satellite observations as enhanced bands of high clouds associated with the South Pacific Convergence Zone (SPCZ) and the Amazon. Examination of satellite observations during 1974–79 indicates a correlation between the intensity of stationary cloud bands in the two regions.

b) The stationary waves in the lee of South America are not of orographic origin since they are associated with a ridge rather than a trough east of the Andes. A "no Andes" forecast experiment confirms this argument.

c) The waves could not be produced by a CISK mechanism suggested by Kalnay and Halem, because of their rather barotropic vertical structure. Sea surface temperature (SST) anomalies in the South Atlantic were of the same scale as the waves, but stronger at the end of January. This, and strong correlation between low level atmospheric cyclonic vorticity and cold SST anomalies indicate that the atmospheric stationary waves were the cause of the ocean temperature anomalies, which in turn provided a negative feedback to the atmosphere.

d) Several experiments modifying the coefficient of latent heat lead to the conclusion that tropical heating is important in the maintenance of the waves. Furthermore, the convection in the subtropical waves themselves is important in sustaining their amplitude and phase, and the Walker type of circulation associated with the SPCZ is also a contributor to the maintenance of the South American waves. These results confirm the existence of a relationship between the occurrence of a strong South Pacific Convergence Zone, somewhat eastward from its climatological position, and the strong "South Atlantic Convergence Zone" observed in outgoing longwave radiation maps.

1. Introduction

The First GARP Global Experiment (FGGE) resulted in the most extensive atmospheric data set ever compiled. Satellite temperature soundings, cloud-tracked winds and drifting buoys provided for the first time a basis for global observations. The FGGE special observing system was particularly important in the tropics and Southern Hemisphere, regions grossly underobserved by conventional systems.

Kalnay-Rivas et al. (1980) reported preliminary results of a FGGE global analysis carried out at the Laboratory for Atmospheres (formerly Goddard Laboratory for Atmospheric Sciences; GLAS). They pointed out the unexpected presence in 16-day averages of very large amplitude, short wavelength waves in the Southern Hemisphere, between 20° and 40°S, especially in the lee of South America. They suggested that these waves might be Rossby lee waves forced by the Andes. Kalnay and Halem (1981) showed that the presence of the very large amplitude, short stationary waves was apparent in a 30-day average from 5 January to 3 February 1979, corresponding to the first month of the FGGE Special Observing Period 1 (SOP-1). Even more surprisingly, the waves disappeared in the second month of SOP-1, from 4 February to 5 March 1979. Kalnay and Halem (1981) indicated that the short waves, with zonal wavenumber 7 or higher were probably not of orographic origin because of their orien-

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tation with respect to the Andes. They suggested that an instability mechanism such as CISK might be the cause of their presence in January and not in February.

The purpose of this paper is to present further observational evidence of the existence of large amplitude stationary waves in the Southern Hemisphere during January 1979, describe their characteristics, and perform experiments with a general circulation model (GCM).

In the first two experiments, we attempt to reproduce as closely as possible the observed January and February 1979 atmospheric circulation by performing 15-day forecasts from real initial conditions. Because of the well-known limited predictability of the atmosphere, we cannot expect a priori to simulate well the observed stationary circulation. However, since the GCM partially succeeds in reproducing the stationary waves in January and their absence in February, we have the possibility of modifying the model and performing other *mechanistic* experiments designed to determine the precise role of orography, tropical heating, etc.

Section 2 contains a brief review of previous studies of stationary waves in the Southern Hemisphere and the observations corresponding to January and February 1979. The possible forcing mechanisms for the stationary waves are discussed in section 3.

In section 4, we present two control experimental forecasts: 15-day integrations with the GLAS Fourth Order GCM, starting from 5 January and 4 February 1979. We compare them with the GLAS analyses for the same periods and discuss the extent to which the observed January waves are reproduced in the forecast. Section 5 is devoted to several mechanistic experiments in which we artificially modify the Andean orography, tropical heating, and regional heating and the initial westerly flow, and observe the effect of these changes on the stationary waves. Finally, section 6 contains a summary and conclusions.

2. Observational evidence of short stationary Rossby waves in the Southern Hemisphere

One can expect significant differences in the structure and distribution of stationary waves in the Northern and Southern hemispheres. In the Northern Hemisphere the geographical distribution of orographic and thermal forcing occurs on very large scales. Therefore it is not surprising that stationary waves have most of their energy in planetary wavenumbers 1, 2 and 3 (Charney and Eliassen, 1949; Smagorinsky, 1953). The Southern Hemisphere, on the other hand, is much more homogeneous, with smaller isolated regions of land and sea contrast (South America, Southern Africa and Australia), one major narrow orographic chain (the Andes) and smaller mountains in Africa and the Australian regions. No counterpart of the strong midlatitude heating regions associated with the Gulf and Kuroshio western currents (Geller and Avery, 1978) exists in the Southern Hemisphere.

Van Loon and Jenne (1972) and van Loon et al. (1973) studied the standing (stationary) waves in the Southern Hemisphere and compared them with those of the Northern Hemisphere. They found that at 50°S, planetary wavenumbers 1 and 3 contain 99% of the variance of the annual mean, and contrary to their Northern Hemisphere counterpart, are essentially barotropic. As in the Northern Hemisphere, they found no significant stationary waves with synoptic scales. These results were based on data from the period 1957–66 from an analysis made by Taljaard et al. (1969). Trenberth (1979) has studied planetary waves for the period 1972–78, with data from the Australian Bureau of Meteorology. He found somewhat larger amplitudes in wavenumbers 2 and 3 at 50°S, but still less than 2% variance in wavenumbers 4 or higher. Trenberth (1980) computed the interannual variability of the monthly means and found that high wavenumbers make an even smaller contribution to interannual variability than to the monthly means. However, his Table 1 indicates that in subtropical latitudes (35°S) wavenumbers 4–6 contribute 24% of the interannual variability, and about 5% must be explained by zonal wavenumbers higher than 6. Yasunari (1977) analyzed stationary waves in the Southern Hemisphere by means of the average satellite brightness charts for 1969. He found waves with a northwest–southeast tilt, with wavenumbers 1 and 3 dominating but some presence of waves 2 and 4 especially in the subtropics.

A rather different picture, with short stationary waves dominating the monthly average subtropical circulation emerges when one examines the FGGE data during SOP-1. The results to be presented here are primarily based on the GLA SOP-1 analysis (Halem et al., 1982). The analysis is obtained from a 6-hour assimilation cycle (Baker, 1983), using the GLA Fourth Order General Circulation Model (Kalnay-Rivas et al., 1977; Kalnay et al., 1983) to provide a first guess. No initialization procedure is applied, but the use of a Matsuno time step during the analysis cycle results in an effective damping of fast inertia–gravity waves. During the analysis all model-derived quantities such as vertical motion, surface fluxes, heating rates, clouds, etc. are also saved for diagnostic purposes.

The presence of stationary waves is most clearly depicted in time averaged fields of meridional velocity v, since in the absence of asymmetric orographic and thermal forcing the averaged v velocity would be very small. Figures 1a and b present the 200 mb meridional velocity averaged over two consecutive 30-day periods of SOP-1; 5 January–3 February and 4 February–5 March, respectively. For simplicity hereafter, these averages will be denoted as "January" and "February."

Figure 1a, corresponding to January, shows Northern Hemisphere stationary waves of planetary scale and

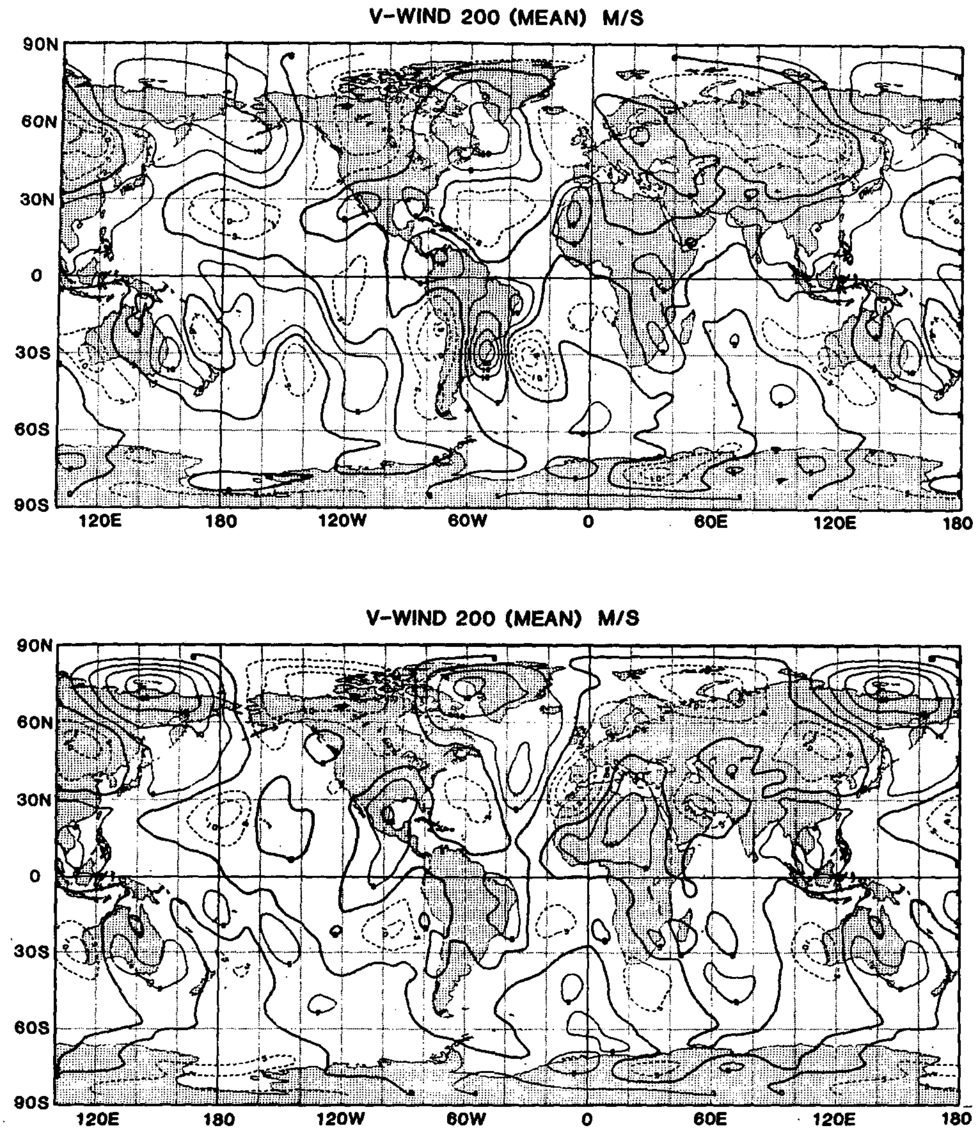


FIG. 1. Thirty-day averaged meridional velocity at 200 mb; contour interval 5 m sec^{-1}; (a) 5 Jan to 3 Feb 1979 ("January"), (b) 4 Feb to 5 Mar 1979 ("February").

amplitudes of about 10 m sec^{-1}. In the Southern Hemisphere, on the other hand, the January mean is dominated by large amplitude (15 to 25 m s^{-1}) *synoptic scale* waves in the South American region, and similar 10 m s^{-1} waves in the South Pacific Convergence Zone and over Australia. Even though this is the summer of the oceanic hemisphere, the South American waves have the largest amplitude in the meridional velocity over the whole globe. A comparison with the same field in the December–February climatology (Newell et al., 1972, p. 116) shows the following differences: during January 1979 the stationary waves in the South American–South Atlantic region were much stronger (20–25 versus 7.5 m s^{-1}), further south (maximum amplitude at 30°S rather than 20°S) and of shorter wavelength (corresponding to zonal wavenumber ≈ 7 rather than the climatological wavenumber ≈ 4).

In the average February circulation (Fig. 1b) the short stationary waves have virtually disappeared in the Southern Hemisphere, and the circulation is therefore much more in agreement with the results of van Loon et al., (1973) and Trenberth (1980): weak stationary waves of planetary scale. The February average meridional velocity is also in rather good agreement with the climatological field of Newell et al. (1972).

Figure 2 presents the Hovmoller diagram (time–longitude) of the smoothed meridional velocity at 200 mb and 30°S for the complete SOP-1. It is clear that the large amplitude stationary waves apparent in Fig. 1a persisted for more than 30 days, dominating the

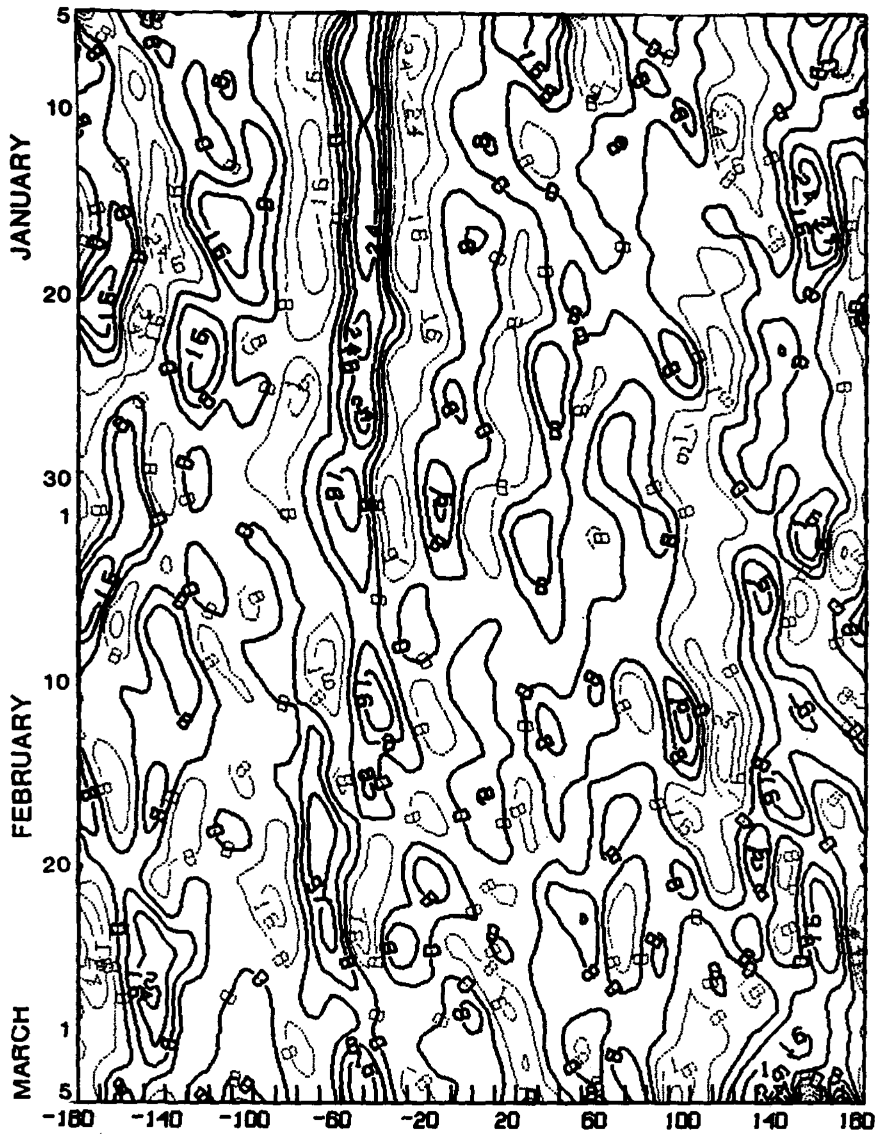


FIG. 2. Hovmoller diagram of meridional velocity at 200 mb at 30°S from 5 Jan to 5 Mar 1979; contour interval for 10 m s^{-1}.

circulation in the region around 30°S. The intensity of the cyclonic shear around 40°W is remarkable. This figure also shows some weaker stationary wave patterns at about 160°W during January and during one week of February at about 80°W.

Figures 3a and b present the corresponding January and February average maps of absolute vorticity. The regions with an average convective precipitation larger than 4 mm day^{-1} are also indicated with a thick line. Although the latter quantity is not directly measured but diagnosed by the model during the analysis cycle (Kalnay and Baker, 1984), it agrees well with observed high cloud-cover fields (Figs. 6a, b). We see that during January the strongest center of stationary cyclonic vorticity occur in the Southern Hemisphere, associated with the South American waves observed in Fig. 1a. The model's diagnosed precipitation shows distinct bands with a northwest–southeast tilt in the South Pacific and South Atlantic. The South Atlantic cyclone center, which has an almost barotropic vertical structure, is in a region of maximum advection of cyclonic vorticity of the stationary waves. In the February average (Fig. 3b), the Southern Hemisphere average absolute vorticity has a much more zonal character, with no closed centers, and there are no well-defined tilted bands of convective precipitation in the South Atlantic. In the South Pacific Convergence Zone (SPCZ), the average precipitation rate is about four times stronger in January than in February.

In Figs. 4a and b we can compare the averaged Jan-

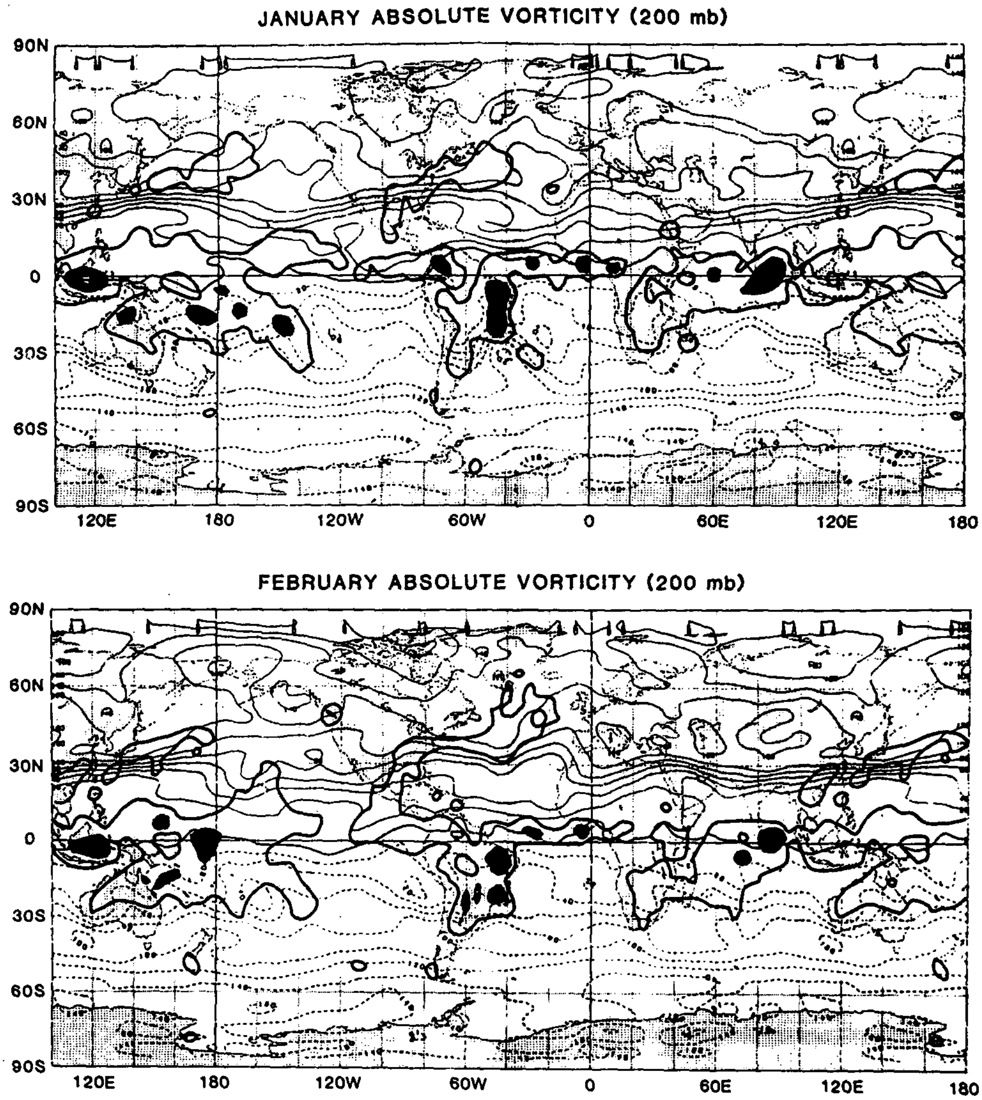


FIG. 3. Absolute vorticity at 200 mb for (a) "January," (b) "February" 1979. The regions with an average convective precipitation greater than 4 mm day^{-1} are indicated by a thick line.

uary and February 200 mb geopotential fields. Again, the presence of the short stationary January waves is strikingly apparent in the Southern Hemisphere 20° to 40°S latitude band. In February, by contrast, the flow over South America poleward of 30°S is much more zonal, whereas at lower latitudes it agrees well with the 200 mb climatology of Taljaard et al. (1972, p. 81), showing a broad anticyclone over the Amazonic region of South America at about 60°W. The presence of this upper level anticyclone was first pointed out by Gutman and Schwerdtfeger (1965), who also attributed it to convective heating during the Southern Hemisphere summer, and suggested that this effect was much stronger than the dynamical effect of the Andes.

The fact that the short-scale stationary waves were anomalously large during January 1979 in the subtropics is also apparent in a Fourier wave decomposition. Table 1 presents the amplitude and percentage contribution to the variance of stationary waves at 200 mb based on the analysis of the Australian Bureau of Meteorology for the period 1972–81. In the subtropical band 30°–40°S, the Australian climatology indicates that wavenumbers 1–4 contribute during the southern summer between 60 to 90% of the total variance. In contrast, in January 1979, the long waves 1–4 contributed only 56% at 30°S and 45% at 38°S. Zonal wavenumber 7, which normally contributes to about 2% of the variance, contributed 9% during January 1979 at 38°S, and was back to a value close to climatology in February 1979. The January GLAS analysis is similar, except that waves 5–7 are somewhat larger at 30°S, in agreement with the ECMWF analysis. Both the National Meteorological Center (NMC) and the European Centre for Medium-range Weather Forecasts

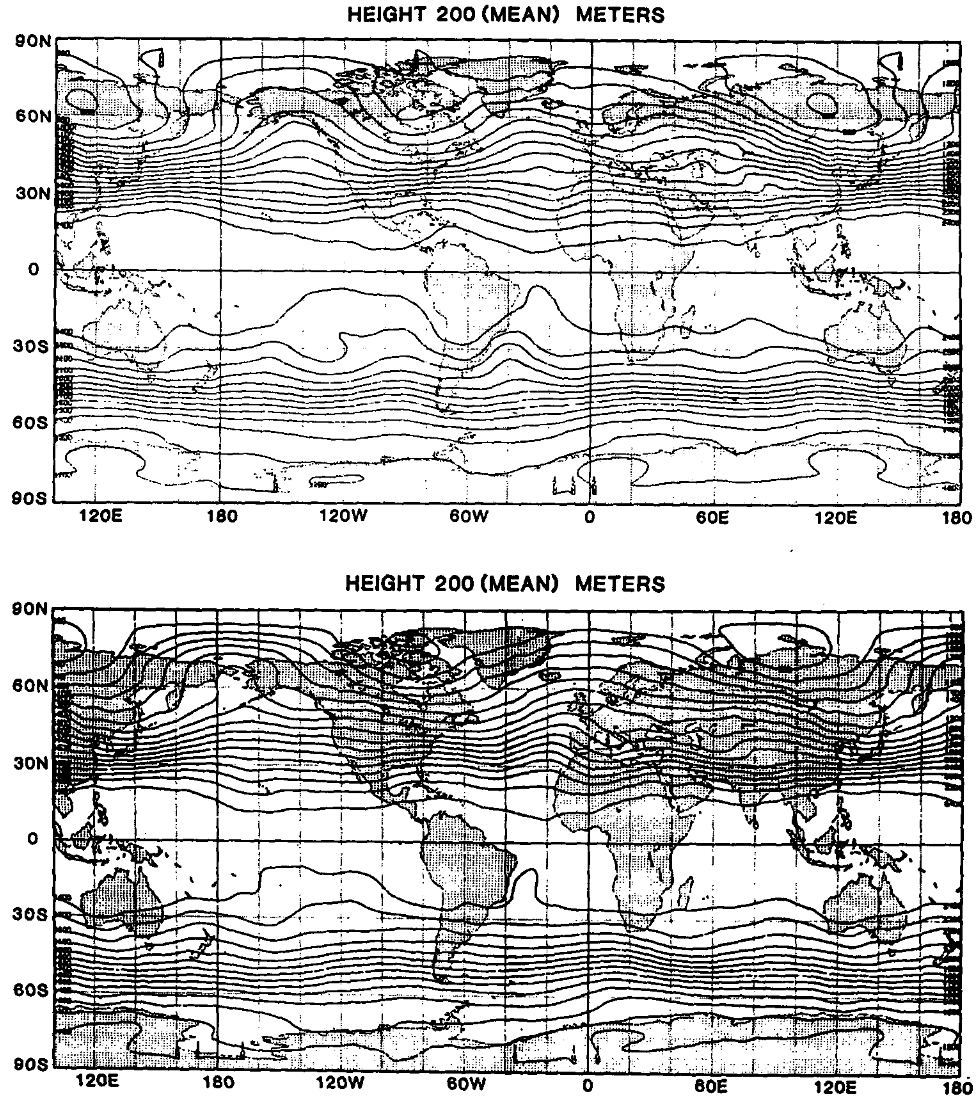


FIG. 4. 200-mb geopotential height fields for (a) "January," (b) "February"; contour interval 100 m.

(ECMWF) analyses for January 1979 agree well with ours. However, in order to ensure that the short wave January waves were real and not an artifact of the analysis schemes, we need to consider independent observations.

Figures 5a and b present maps of average outgoing longwave radiation prepared from NOAA/NESS data for the same January and February 30-day periods. Cold regions, with outgoing longwave radiation (OLR) less than 250 W m^{-2} are shaded. At high latitudes, cold surface and cloud top temperatures cannot be distinguished in these maps. At low latitudes, however, the shaded cold regions correspond to the presence of active convection. We can again observe a dramatic difference between January and February. Strong cloud bands appear in the January average as "connections" between the Indonesian and Amazonian convective regions and cold high latitudes. These connections have almost completely disappeared from the February average map. For comparison, Fig. 5c presents the December to February average outgoing longwave radiation for the years 1975 to 1983. It indicates that, on the average, the South Pacific Convergence Zone (SPCZ) is stronger than it was in February 1979 but weaker than in January 1979. The South Atlantic Convergence Zone (SACZ) is on the average much weaker than in January 1979. A comparison with high cloud-cover maps (tops at 300 mb or higher), generated using the GLAS Temperature Retrieval System (Susskind et al., 1984) also indicates that the January waves were indeed present in the atmosphere and were not a result of the analysis scheme (Figs. 6a and b).

In order to determine whether the January 1979 stationary waves were a unique phenomenon or occurred with relative frequency, we examined the NMC Southern Hemisphere summer analysis for the period 1978–

TABLE 1. Amplitude and percentage contribution of the first seven zonal wavenumbers to the total variance of stationary waves of the 200-mb geopotential heights. Both the climatological values (averaged over the 1972–81 period) and the 1979 values are based on the Australian Bureau of Meteorology analysis.

	January climatology				January 1979			
	Amplitude (m)		Percentage (%)		Amplitude (m)		Percentage (%)	
Zonal wavenumber	30°S	38°S	30°S	38°S	30°S	38°S	30°S	38°S
1	25	21	34	41	35	34	25	25
2	6	6	2	3	11	11	2	3
3	10	11	6	12	24	24	11	13
4	21	7	24	5	30	14	18	4
5	17	15	16	20	37	40	29	36
6	6	8	<1	6	13	17	3	7
7	3	5	<1	6	13	19	4	9
	February climatology				February 1979			
1	22	19	30	41	16	14	10	8
2	13	11	10	14	15	19	10	14
3	7	11	3	13	7	3	2	1
4	24	9	34	9	35	33	53	44
5	10	10	6	10	11	20	5	16
6	2	4	<1	2	8	12	3	6
7	4	3	1	1	5	9	1	3

81. No other episode of stationary subtropical waves as strong and persistent as the January 1979 waves over South America was found. However, several cases of stationary waves lasting about 10 days were found over South America: 1–11 January 1978, 18–28 February 1978, 14–23 December 1978, 15–27 February 1979, 15–26 December 1979, and 27 January–4 February 1980. Other episodes with similar duration were found in the central Pacific.

3. Possible forcing mechanisms for the January waves

a. Orographic forcing

A first look at Fig. 1a, with the striking short waves in the South American region suggests the possibility of waves forced by the Andes. The importance of Rossby lee waves generated by isolated forcing has been the subject of several recent papers (Grose and Hoskins, 1979; Opsteegh and van den Dool, 1980; Kalnay-Rivas and Merkine, 1981; Hoskins and Karoly, 1981). An isolated region of forcing such as a warm island, embedded in a westerly mean flow, will produce a train of stationary Rossby waves. These waves appear in the lee side of the region of forcing because the group velocity for waves with zero phase speed is always positive. For a barotropic flow, the zonal wavenumber k of the train of waves is given approximately by $(\beta/U - l^2)^{1/2}$ from the frequency dispersion relationship of stationary Rossby waves, where U is the mean flow and l the meridional wavenumber.[1] Grose and Hoskins (1979) pointed out the importance of meridional propagation and spherical geometry, and obtained quite realistic stationary waves by forcing a barotropic model with 300 mb mean flow and real orography. Hoskins and Karoly (1981) provided an analysis of the propagation of the influence of isolated thermal or orographic forcing in a three-dimensional atmosphere. Kalnay-Rivas and Merkine (1981) showed that the presence of two regions of isolated forcing with the right phase relationship can easily produce blocking through local resonant enhancement.

An important characteristic of orographic forcing in an equivalent barotropic model is that the atmospheric response is associated with a trough in the lee of the mountain. This condition, equivalent to having *equatorward* geostrophic flow on the average over the mountains, corresponds to positive form-drag (Charney and DeVore, 1979): the atmosphere accelerates the solid earth through an east–west pressure gradient across the mountain and, in turn, the mountain slows down the atmospheric mean flow. Alternatively, as shown in Kalnay-Rivas and Merkine (1981), equatorward flow over orography is necessary in order to have *a positive transfer of energy from the mean flow to the Rossby waves.* Without this positive generation of perturbation energy, orographic waves cannot be maintained.

Figure 1a, on the other hand, shows that at 300 mb the January meridional velocity over the Andes is mostly negative, i.e., polewards. Similarly, Fig. 4a shows the geopotential field for the January flow indicating that there is a ridge rather than a trough in the lee of the Andes. During February, when the waves disappear, the flow is much closer to climatology (Newell et al., 1972): there is weak equatorward flow over the Andes south of 30°S and weak poleward flow

[1] An interesting example of a train of stationary Rossby waves with both zonal and meridional propagation can be observed over Africa and Eurasia in Fig. 1b, corresponding to February 1979.

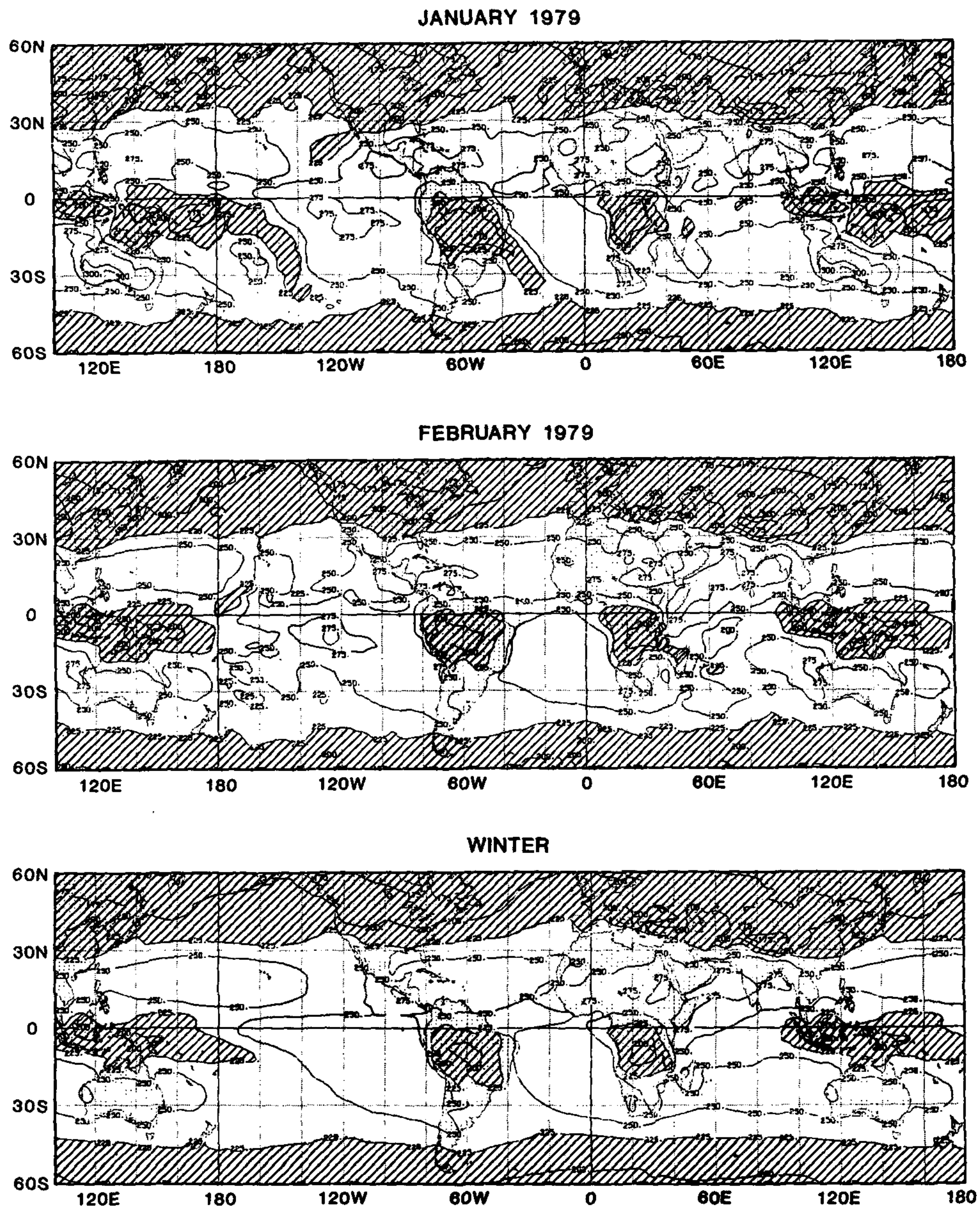


FIG. 5. Averaged outgoing longwave radiation for (a) "January," (b) "February" 1979, (c) climatology; contour interval 25 w m^{-2}.

in the northern Andes (Figs. 1b and 4b). At 700 mb the average meridional flow over the Andes (not shown) is weak and very similar during both January and February, with no clear predominance of either poleward or equatorward flow except south of 40°S. To the extent that the atmospheric response to a narrow mountain is equivalent barotropic, we can conclude that *the January waves have such a phase relationship to the Andes that they cannot be of orographic origin.*

b. Air–sea interaction during January 1979

The disappearance in February of the strong January waves suggests that they may have originated because of an atmospheric instability. Kalnay and Halem (1981) indicated the possibility that a CISK mechanism might have generated the waves, with convergence over regions of warm sea surface temperature (SST) anomalies increasing latent heat release and in turn the vertical motion of the waves strengthening the surface convergence.

In order to consider this possibility, we examine the sea surface temperature (SST) anomaly field determined by the GLAS Temperature Retrieval System (Susskind et al., 1984). Figure 7a shows that during January 1979 there were indeed SST anomalies in the tropical and subtropical South Atlantic ocean with

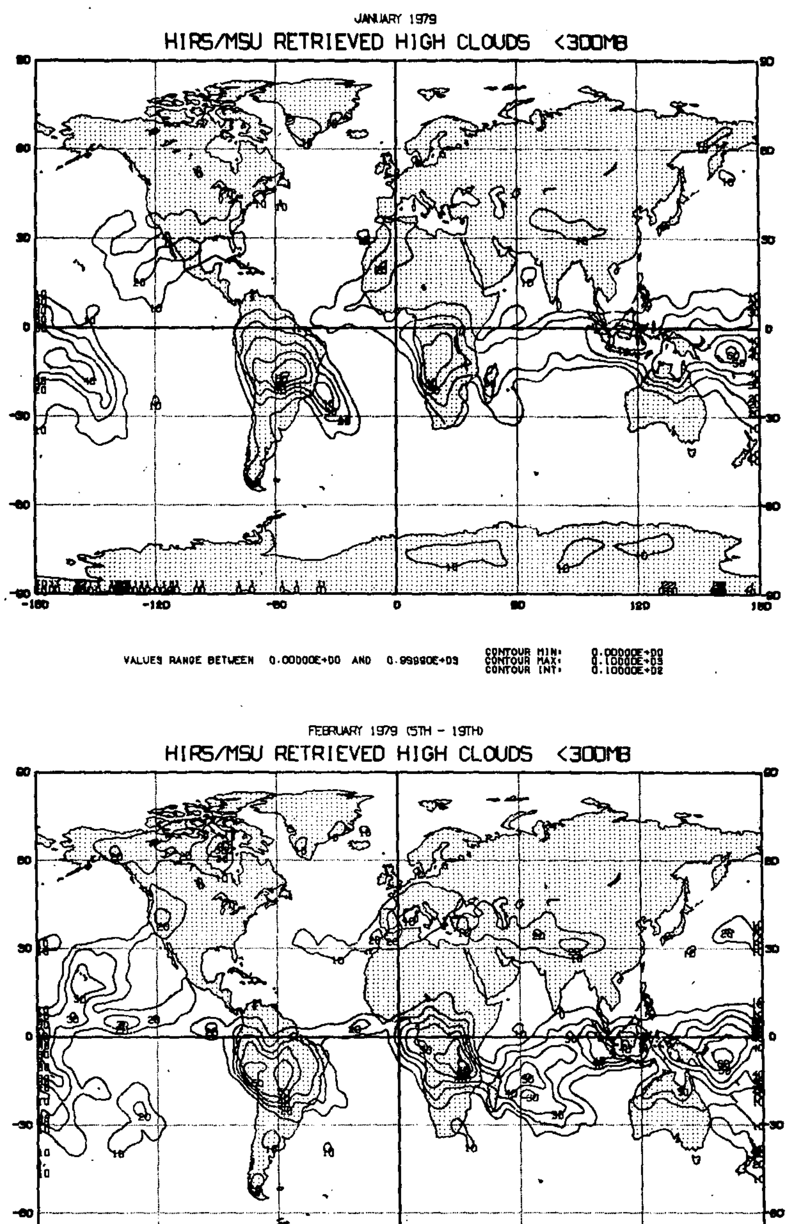


FIG. 6. High cloud cover map (cloud top at 300 mb or higher) generated using the GLAS temperáture retrieval system for (a) "January," (b) 5–19 "February" 1979.

small horizontal scales similar to the observed atmospheric waves. However, by comparing the SST anomalies with the low-level average January relative vorticity (Fig. 7b), it is possible to answer the question of whether the SST anomalies were the *cause* or the *result* of the presence of strong stationary atmospheric waves.

The fact that there is a clear correlation between low-level cyclonic vorticity and negative SST anomalies (both shaded), indicates that *the atmospheric anomalies are causing the SST anomalies,* which in turn provide *a negative feedback* to the atmosphere. This is because in a region with cyclonic vorticity, the atmosphere, which rotates faster than the ocean, will tend to produce upwelling and cooling of the ocean surface. This cooling will be enhanced by the stronger low-level winds that tend to occur with cyclonic systems. At the same time, the cloudiness associated with the region of low pressure reduces the summer insolation which can

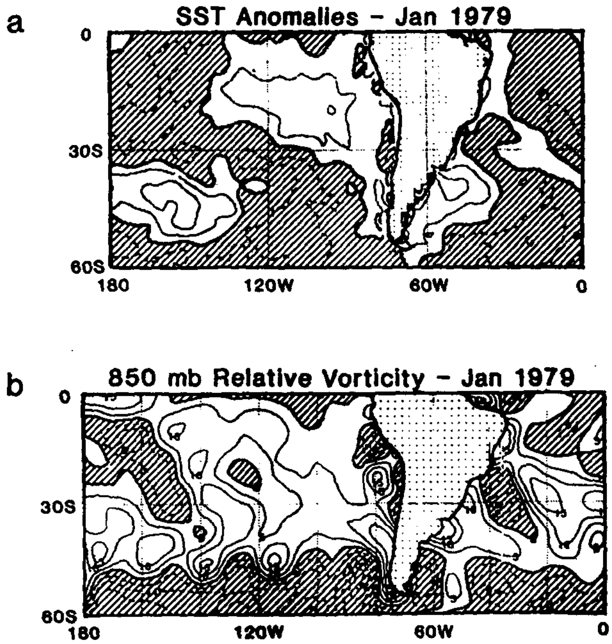


FIG. 7. (a) SST anomalies for January 1979 from the GLAS temperature retrieval system, (b) 850-mb relative vorticity for January 1979.

reach the surface, also contributing to the cooling of the SST. Conversely, the presence of clear regions of anticyclonic circulation and the associated weak downwelling will tend to warm the resulting stable mixed layer. On the other hand, if the ocean temperature anomalies were driving the atmospheric stationary circulation, the correlation between vorticity and SST anomalies would be opposite to that observed in Fig. 7, with warm SSTs associated with upward atmospheric motion and low-level cyclonic circulation.

We can conclude from this discussion that the atmospheric stationary waves in the South Atlantic were *not* produced by SST anomalies. This is further confirmed by the following consideration: If the atmospheric waves were maintained by local release of heat such as in a CISK circulation triggered by SST anomalies, they would have a strongly baroclinic (monsoonal) structure. Regions with strong heating are characterized by upward motion, low-level cyclonic circulation, and reversal of the circulation at the upper levels. This strong monsoonal structure is generally observed at low latitudes, especially in regions of maximum heating. However, Fig. 8, which presents a cross section of the distribution of mean meridional wind at 30°S during January, shows that the South Atlantic waves have only a very small tilt in the vertical.

On the basis of these observations we can conclude that the atmospheric waves observed in the South America and South Atlantic regions during January 1979 were probably not driven by local release of latent heat or by SST anomalies.

c. Tropical heating

We next consider the possibility that the wave may have been forced by changes in the tropical heating associated with convective precipitation. Although we do not have direct measurements of tropical precipitation, there is strong indirect evidence of significant differences between the January and February convective precipitation rates. Both the outgoing longwave radiation (OLR) maps (Figs. 5a, b) and the model derived precipitation (Figs. 3a, b) show considerably stronger convection during January east of Indonesia

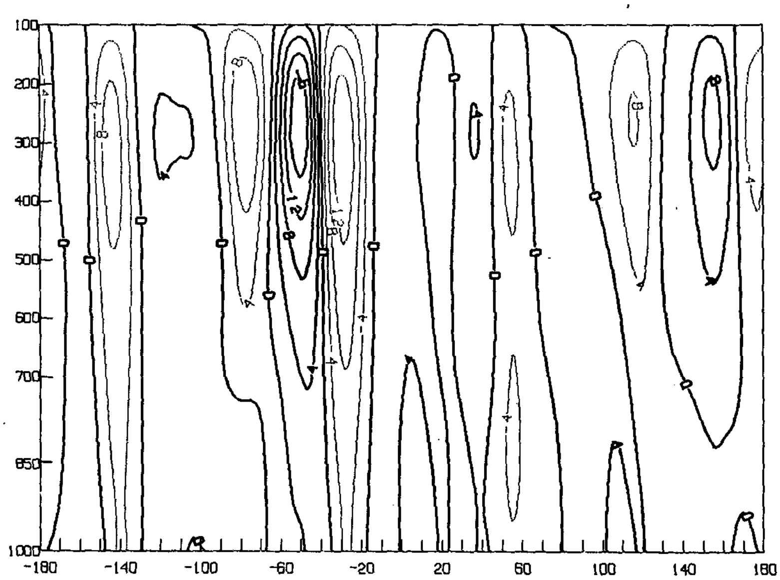


FIG. 8. Vertical cross secton of the distribution of the meridional wind at 30°S for January; contour interval 4 m s^{-1}.

and in the central Pacific. The SPCZ is stronger and further east during January than in February (Figs. 3, 5 and 6), in a configuration that resembles an El Niño year episode, although of much shorter duration. Over South America, convection seems somewhat stronger over central and eastern Brazil during January and the "South Atlantic Convergence Zone" is also considerably more pronounced. On the other hand, convection over southern Africa is stronger during February, when there is also the appearance of a weaker "southern Indian Ocean Convergence Zone" emanating from the African continent.

Another indirect evidence of these changes in tropical convection is provided by the observed changes in the monthly averaged zonal velocity. If we compare the zonal velocity at 200 mb for January and February (Fig. 9), we observe locally stronger easterlies over Indonesia and the Amazons in January, and over southern Africa in February. Correspondingly, the subtropical jets off the east coast of North America and Asia are considerably stronger in January, whereas in February there is a third strong jet maximum over the Middle East. The changes of the polar jets in the Southern Hemisphere are similar but weaker. At low levels (not shown), the changes are of opposite sign.

The net result of these changes is a weakening of the zonally averaged upper-level tropical easterly flow during January, which as pointed out by Paegle and Baker (1983), became westerly at the equator. We may assume that the weakening of the easterly flow will also decrease the barrier effect that the critical line separating easterlies and westerlies has on the propagation of tropical energy from fixed sources into the extratropics (e.g., Eliassen and Palm, 1961; Charney and Drazin,

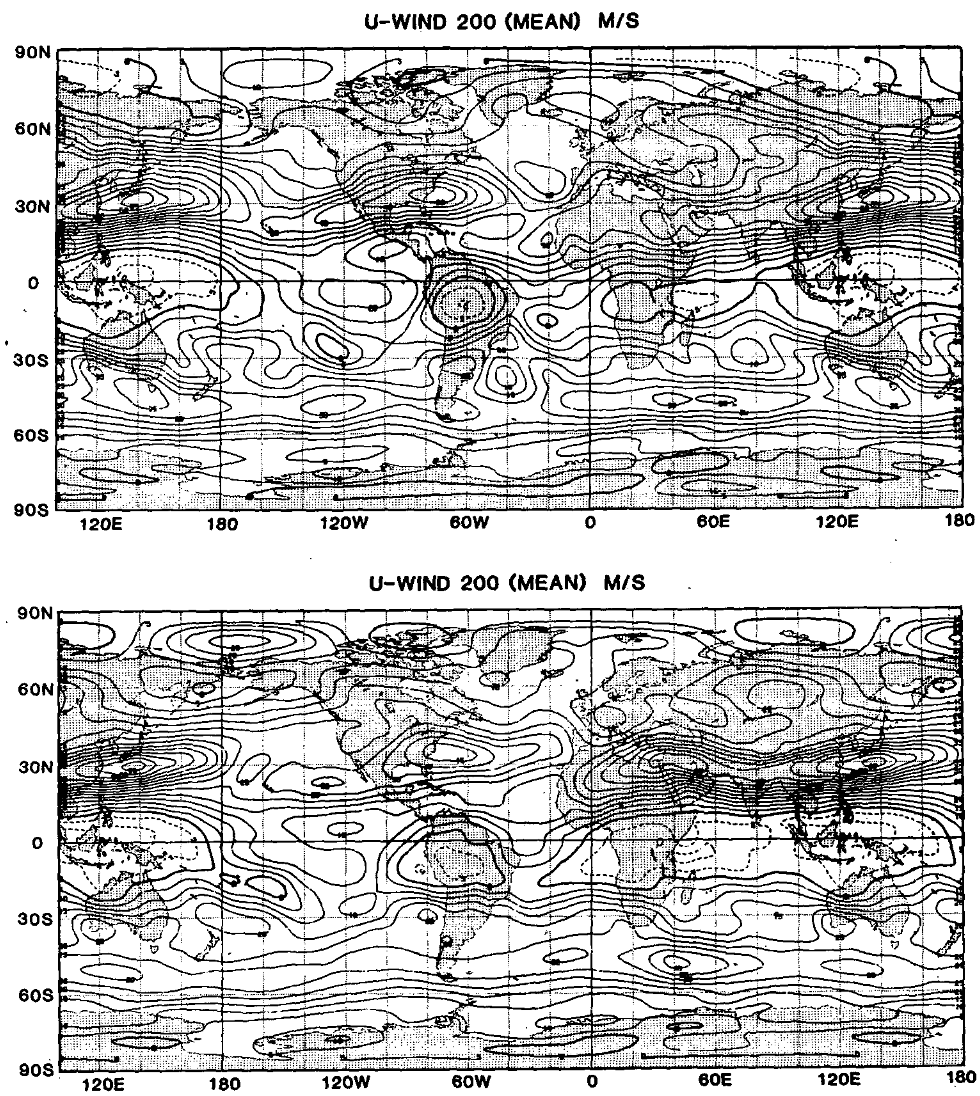


FIG. 9. Thirty-day averaged zonal velocity at 200 mb; contour interval 5 m s^{-1}.
(a) "January"; (b) "February."

1961; Hoskins and Karoly, 1981). If this is true, the effect of enhanced tropical heating may be double: weakening of the easterlies and the barrier effect of the critical line, and stronger propagation of energy from the stationary forcing into the extratropics, especially through zonal breaks in the critical line (Webster and Holton, 1982). The convergence zones in the South Pacific and South Atlantic in January, and in the southern Indian Ocean in February may be a symptom of this effect.

We should note that there is also a strong suggestion of a teleconnection between the SPCZ and the SACZ. An inspection of the OLR maps produced by NOAA/NESS (Winston et al., 1980) suggests that in the Southern Hemisphere summer the SACZ tends to occur when the SPCZ is strong and displaced to the east, as in January 1979. This observation is in agreement with the results of Lau and Chan (1983) who computed the correlation of OLR anomalies and the OLR at the equatorial dateline. Such a teleconnection between the SPCZ and the SACZ presumably takes place through corresponding changes in the Walker circulation, which during negative values of the Southern Oscillation index (i.e., months that resemble El Niño circulation) may favor the formation of stationary waves in the lee of South America.

Following a reviewer's suggestion, we examined the possibility that the waves over South America might be the local response to deep convective heating through a simple Sverdrup balance: $\beta v \approx -f\nabla\cdot\mathbf{v}$. Figures 10a and b present the 200 mb divergence field for the January and February analyses, respectively. There is very little indication of a Sverdrup balance; on the contrary, the vorticity balance is much closer between the $\bar{u}\partial\zeta/\partial x$ and βv terms (cf. Fig. 3a), suggesting that these are indeed a train of stationary Rossby waves. Although the analysis of the field of divergence may not be very reliable because of observational difficulties, a similar approximate linear Rossby balance is observed in the general circulation model forecasts. Moreover, the divergence fields in January and February show more similarities than differences, with maximum outflow over the Amazon basin, and a band of convergence at about 30°S, suggesting again that the January waves are not purely a response to local forcing.

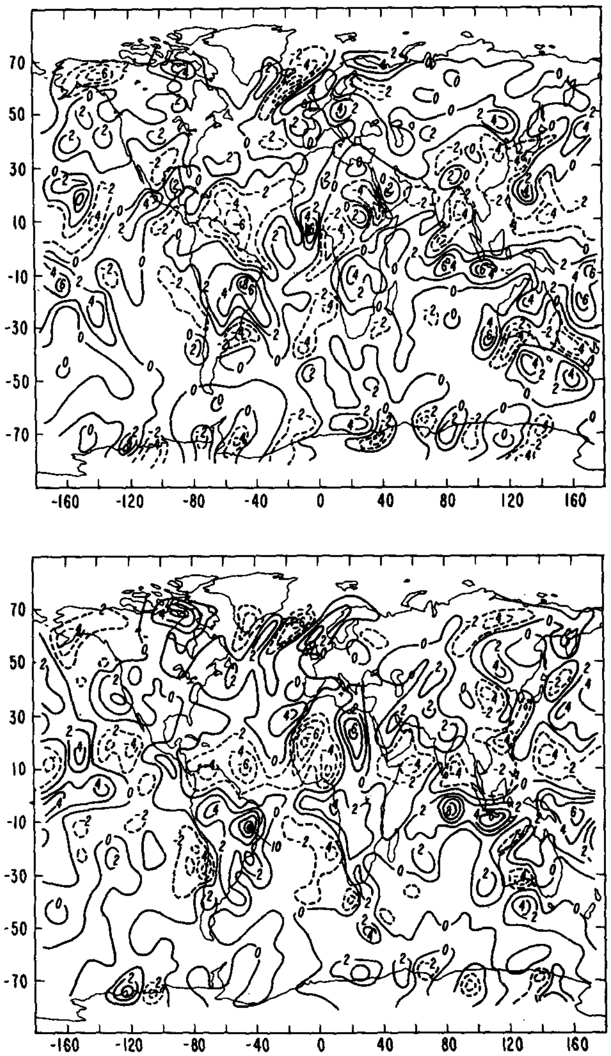


FIG. 10. (a) 200 mb divergence field averaged for the month of January 1979. The contour interval is 10^{-6} s^{-1}. (b) As in Fig. 10a but for the month of February 1979.

4. Control forecasts

In this section we compare the time averages of 15-day control forecasts started from 5 January 1979 and from 4 February 1979 with analyses averaged over the same period. We will redefine "January" and "February" as these 15-day averages. Since operational forecasts retain useful skill for only about one week (e.g., Bengtsson, 1984) and we are trying to reproduce the persistent anomalous waves observed in January 1979, it does not seem warranted to make forecasts longer than two weeks.

The forecasts are performed with the GLA Fourth Order GCM as documented in Kalnay et al. (1983), which has a resolution of 4° latitude, 5° longitude and nine vertical levels. The rather coarse resolution is partially compensated for by the use of fourth-order horizontal differences, so that the model has a short range forecast skill comparable to that of models of finer resolution (e.g., Atlas, 1984; Halem et al., 1982; Baker et al., 1984). The model has a complete parameterization of subgrid scale physical processes, and when used in a simulation mode, reproduces rather well the summer and winter atmospheric circulation (Kalnay et al., 1983). For verification, we use the GLA Analysis.

Figures 11a and b present the observed (15-day averaged) January and February mean meridional velocity at 200 mb. A comparison with Fig. 1a and b maps shows the same characteristics almost everywhere

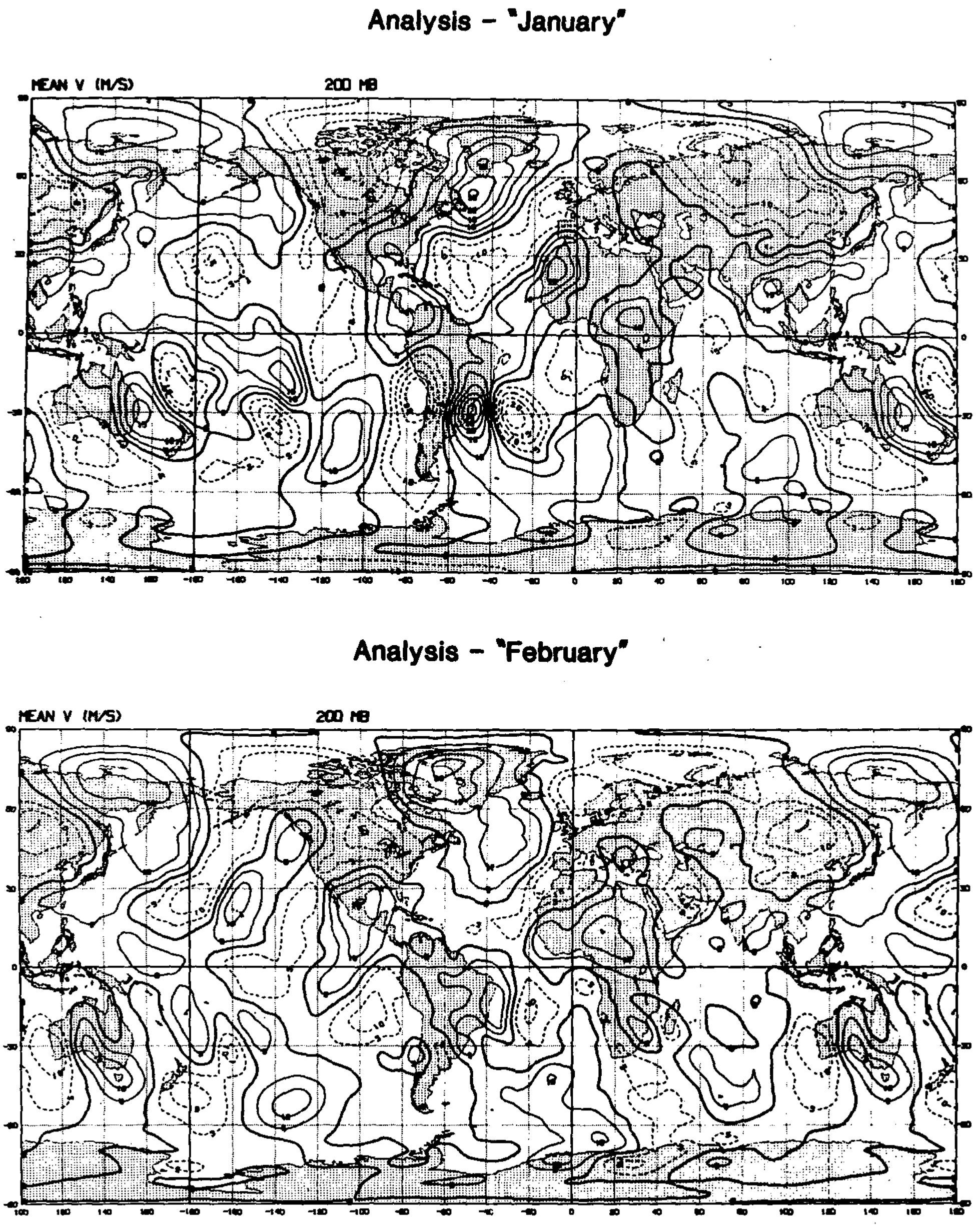


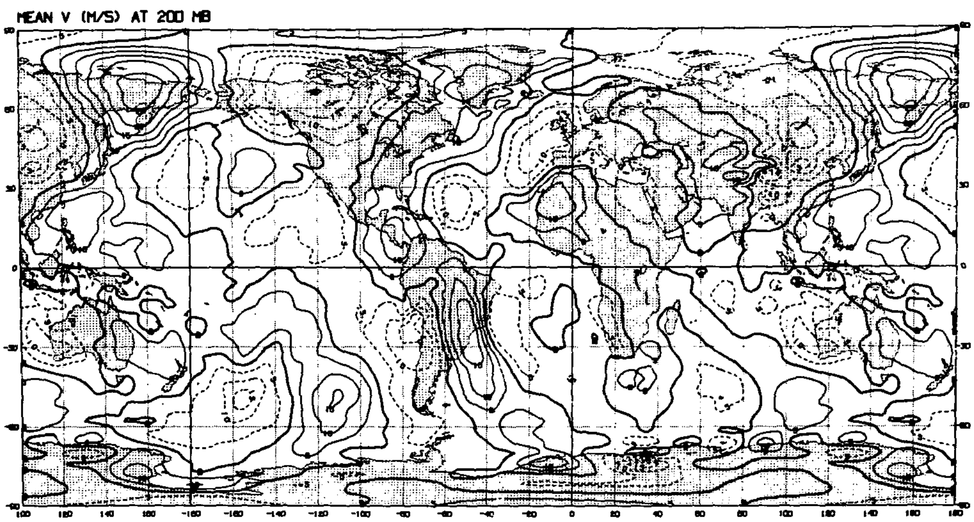
FIG. 11. Fifteen-day averaged meridional velocity at 200 mb from the GLAS analysis. Contour interval 5 m s^{-1}; (a) from 5 Jan to 20 Jan; (b) from 4 Feb to 20 Feb.

except that the stationary waves appear somewhat stronger in the 15-day average than in the 30-day average.

Next we present the 15-day average control forecasts for January and February (Figs. 12a and b). With a few exceptions (e.g., northwest Africa in February), the model succeeds in predicting the average direction of the meridional flow, and its changes between January and February. In our region of interest, South America, we observe that during January there are short stationary waves elongated in the north–south direction which are similar but weaker than the January waves of the analysis. These results have little dependence on the particular initial condition used: a 14-day forecast begun one day later, on 6 January 1979, resulted in a very similar but slightly better forecast of the stationary waves. In the February forecast (Fig. 12b) the stationary waves over South America are weaker than in January, and, in agreement with the analysis, are tilted in the northwest–southeast direction. The forecast has also succeeded in placing the cyclone center in the correct position, 20°S and 30°W.

Figure 13a presents the Hovmoller diagram for 200 mb for the January forecast. It is apparent that during

"Control" January forecast



"Control" February forecast

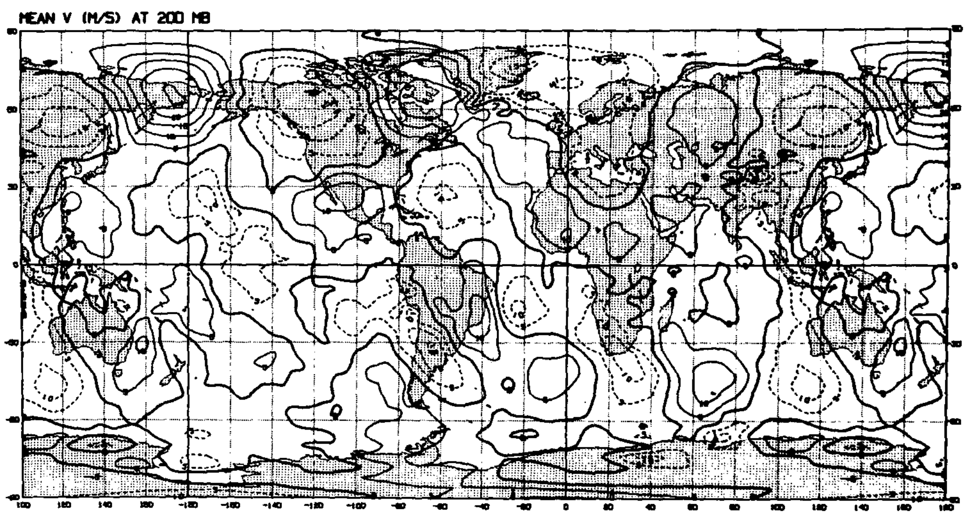


FIG. 12. Fifteen-day averaged meridional velocity at 200 mb from forecasts using the GLAS Fourth Order Model. Contour interval is 5 m s^{-1}; (a) January control forecast (b) February control forecast.

the first eight days, the model is able to predict and even amplify the stationary waves over South America: on 10–12 January, the waves reach an amplitude of 40 m s^{-1} in the meridional wind, about 10 m s^{-1} stronger than in the analysis. After that, however, there is a sudden breakdown of the stationary waves, with a partial regeneration at about 16 January. In order to test the possibility that the sudden breakdown of the forecasted stationary waves may be due to barotropic instability, we computed the barotropic stability parameter $\beta - (\partial^2 u/\partial y^2)$. A Hovmoller diagram of this parameter computed at the same latitude of 30°S confirms this hypothesis (Fig. 13b). The stationary waves are associated with a strong minimum in the zonal velocity, which results in negative values of $\beta - (\partial^2 u/\partial y^2)$ at about 10–12 January, indicating barotropic instability. A similar computation for the analysis (not shown) indicates that in the real atmosphere the observed stationary waves were barotropically stable.

For reference in the following section, we also present the 200 and 700 mb time-averaged forecasts of the zonal wind (Figs. 14a and b). In the upper levels, the January forecast has stronger tropical westerlies than the February forecast (not shown). At 700 mb, both forecasts have somewhat similar strength in the tropical flow.

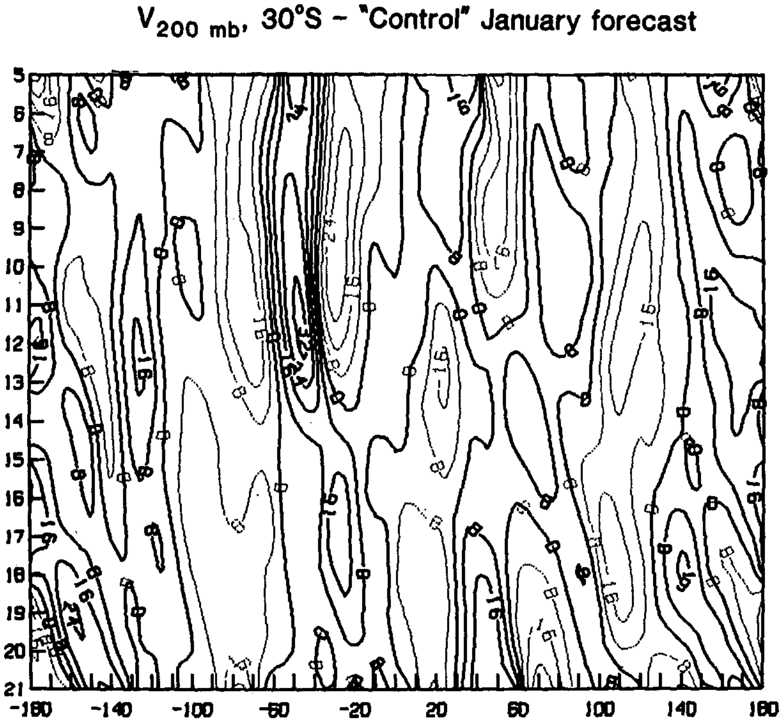


FIG. 13a. Hovmoller diagram of the meridional velocity at 200 mb and 30°S for the January control forecast; contour interval is 8 m s^{-1}.

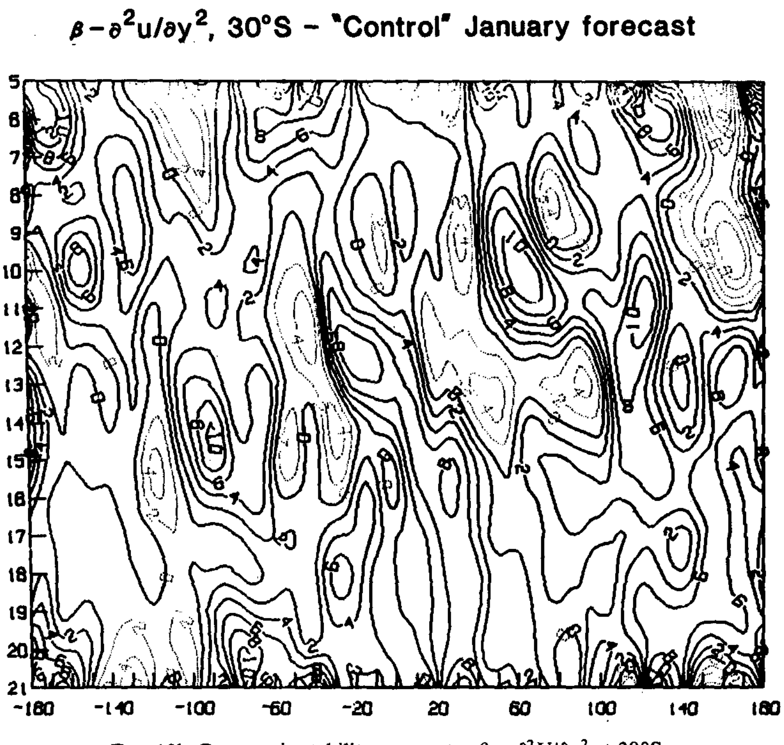


FIG. 13b. Barotropic stability parameter $\beta - \partial^2 U/\partial y^2$ at 30°S for the January control forecast.

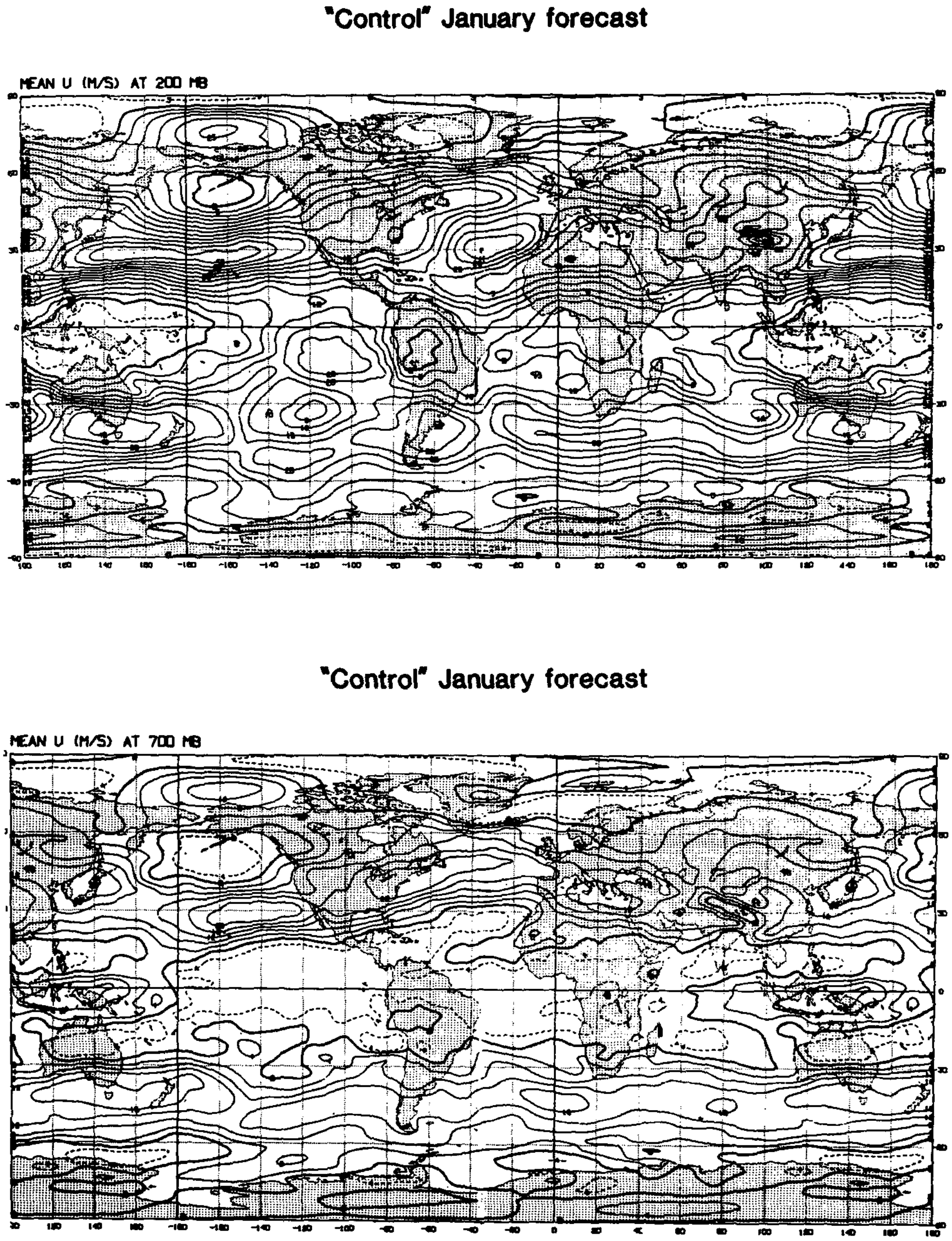


FIG. 14. Fifteen-day averaged zonal velocity at (a) 200 mb level, (b) 700 mb level, for the January control forecast. Contour interval is 5 m s^{-1} for (a) and 4 m s^{-1} for (b).

Since the model succeeded in predicting the presence of stationary waves over South America in January and their absence in February, it has become a powerful tool to perform experiments designed to test the hypotheses formulated in section 3 about the possible origin of these waves. In section 5 we discuss such experiments which, because of the realism of the model, provide a more quantitative answer than would simple models or theoretical arguments.

5. Mechanistic experiments

a. *"No Andes" experiment*

In section 3 we argued that the January waves over South America cannot be due to the Andes because they correspond to a lee ridge rather than a lee trough. However, this argument is only valid to the extent that the atmospheric response to narrow orographic forcing is equivalent barotropic, and it is not possible to dem-

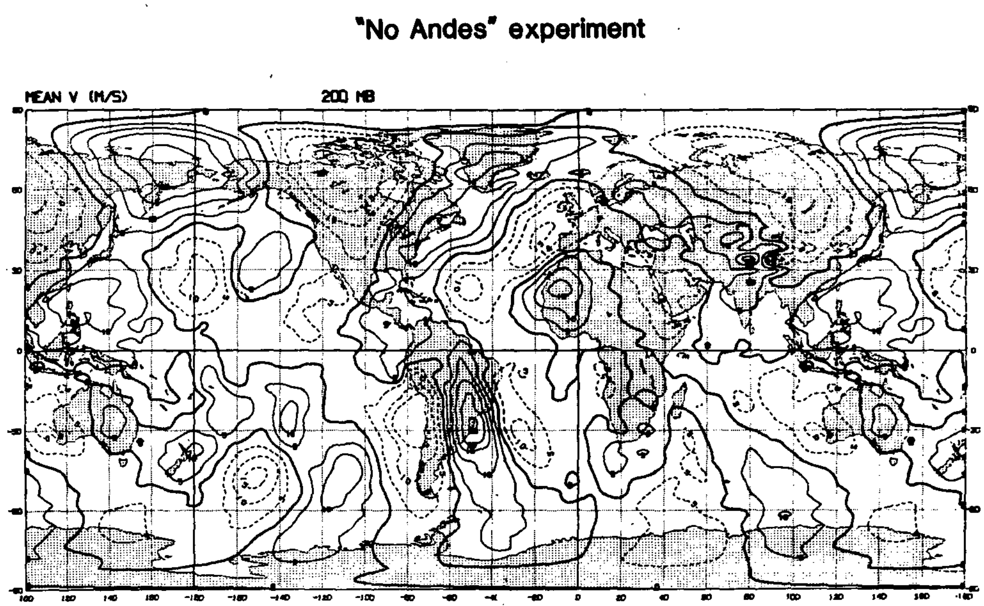


FIG. 15a. Fifteen-day averaged meridional velocity at 200 mb, for the "No Andes" experiment; contour interval is 5 m s^{-1}.

onstrate whether this is strictly true in the presence of vertical and horizontal shear.

In order to test this argument, we performed a forecast from the same initial conditions as the January control forecast but eliminating orography over the Andean region. The 15-day averaged meridional velocity field for the "No Andes" experiment is shown in Fig. 15a, and the corresponding Hovmoller diagram at 30°S in Fig. 15b. The results conclusively confirm the validity of the argument that the South American

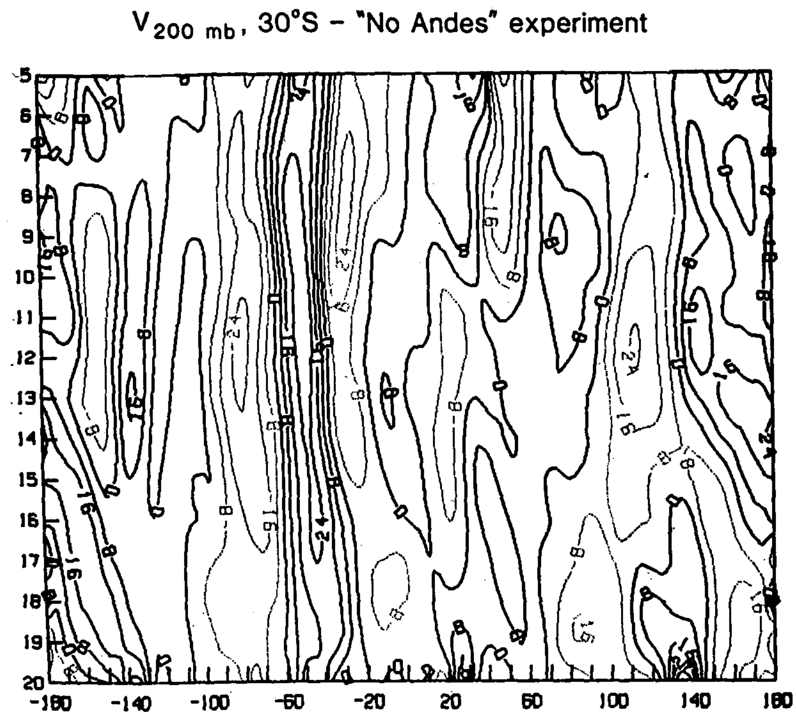


FIG. 15b. Hovmoller diagram of the meridional velocity at 200 mb and 30°S for "No Andes" experiment; contour interval is 8 m s^{-1}.

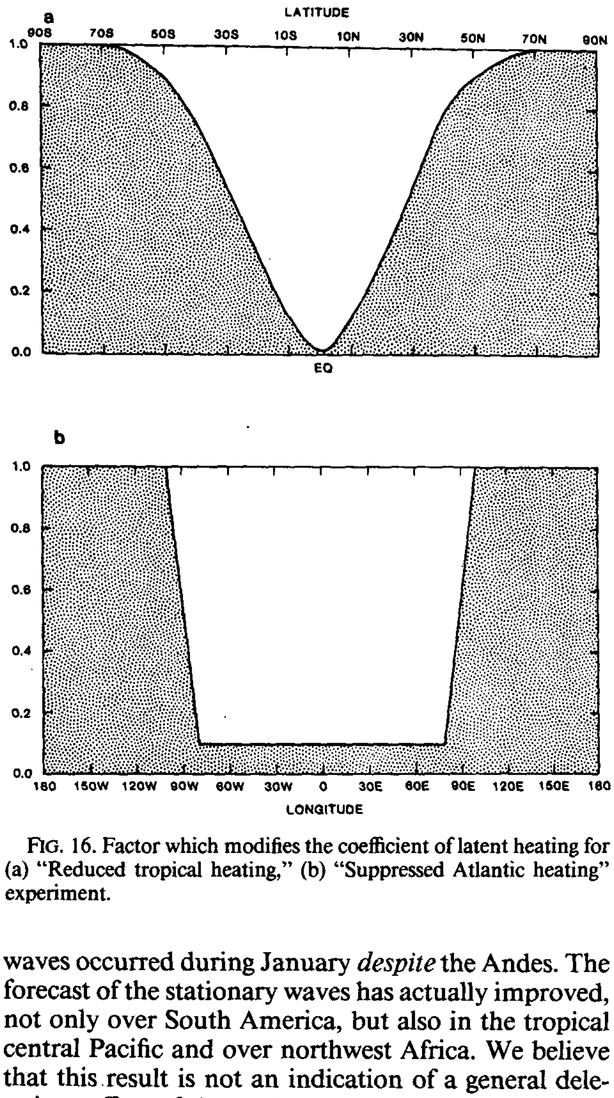


FIG. 16. Factor which modifies the coefficient of latent heating for (a) "Reduced tropical heating," (b) "Suppressed Atlantic heating" experiment.

waves occurred during January *despite* the Andes. The forecast of the stationary waves has actually improved, not only over South America, but also in the tropical central Pacific and over northwest Africa. We believe that this result is not an indication of a general deleterious effect of the Andes upon the model forecasts. The absence of the Andes has resulted in a better forecast of the stationary waves structure over South America, which remains accurate during all of the 15 days of integration. As a result, the associated convection is better represented and therefore tropical forcing is closer to the real atmospheric forcing.

b. "Reduced tropical heating" experiment

In this section, we try to assess the role of tropical heating in the maintenance of the Southern Hemisphere stationary waves by reducing tropical heating. Following an idea developed by Paegle and Baker (1983), we simply modify the value of the coefficient of latent heating by multiplying it by a factor which is latitudinally dependent and smaller than 0.5 between 30°S and 30°N for all longitudes (Fig. 16).

The 15-day averaged forecast of $\bar{v}_{200\ \mathrm{mb}}$ with the "reduced tropical heating" model, and the corresponding Hovmoller plot at 30°S are presented in Figs. 17a and b. It is apparent that all stationary waves have been strongly reduced in the Southern Hemisphere, even in the extratropical regions. In the extratropical Northern Hemisphere the relative change in the stationary waves is much smaller, indicating that in that region tropical heating is less important than orographic forcing. Although there is a remnant of a stationary wave over South America, the Hovmoller plot indicates that it is essentially a residual from the initial conditions.

Figures 18a and b show the difference in the mean zonal velocity at 200 and 700 mb, respectively, between the "reduced tropical heating" forecast and the control forecast at 200 and 700 mb, respectively. The result is very similar to the forced tropical circulation discussed by Gill (1980), Matsuno (1966), and Webster (1972), but with negative sources of heat in the regions where convection has been strongly suppressed: the Amazon, equatorial Africa, and most especially, Indonesia. Over and slightly westward of these regions, the anomaly corresponding to the reduced convection results in low-level easterlies and upper-level westerlies, exactly in opposition to the zonal flow in the control experiment. In the rest of the equatorial belt, there are stronger westerlies at low levels and easterlies at upper levels, presumably because forced Kelvin waves have propagated in these regions (Gill, 1980). Again, as described by Gill, there is a reduction in the subtropical westerly jets directly north and south of the suppressed convection regions. The reduction in the subtropical jet is about three times *stronger* than the increase in westerly flow over the convective regions. This is in contrast with Gill's solution, where the subtropical response was about three times *weaker* than the equatorial change. The change in the subtropical jets is rather symmetric over Indonesia and equatorial Africa, and agrees well with the intuitive notion of a "local Hadley cell."

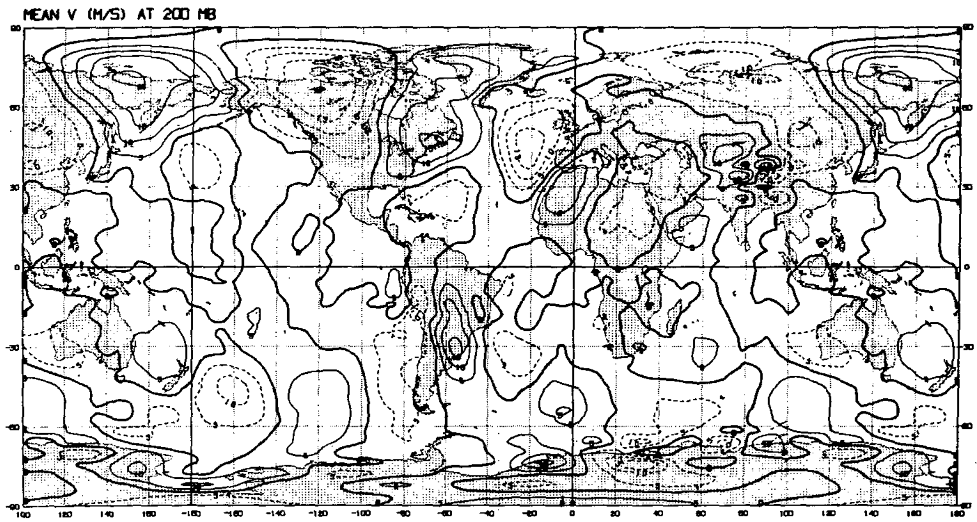
c. "Suppressed regional heating" experiments

The experiment discussed in section 5b indicated that tropical heating was an important contributor to the January waves over South America, and, indeed, over all the Southern Hemisphere.

In order to determine whether local convection, convection originating in the central Pacific (as suggested by the correlation between the SPCZ and the SACZ found in Lau and Chan, 1983) or both were necessary to maintain the South American January waves we performed two more experiments. In the first one, which we will denote "suppressed Pacific heating," we reduced the latent heat of condensation to one tenth of its value over 180° longitude centered on the dateline for all latitudes (Figure 16b). In the second experiment, denoted "suppressed Atlantic heating," the latent heat release was similarly suppressed but in the hemisphere centered on the Greenwich meridian.

The 15-day forecasts of $\bar{v}_{200\ \mathrm{mb}}$ and Hovmoller plots corresponding to the "suppressed Pacific heating" are

"Reduced tropical heating" experiment



$V_{200\ mb}$, 30°S - "Reduced tropical heating"

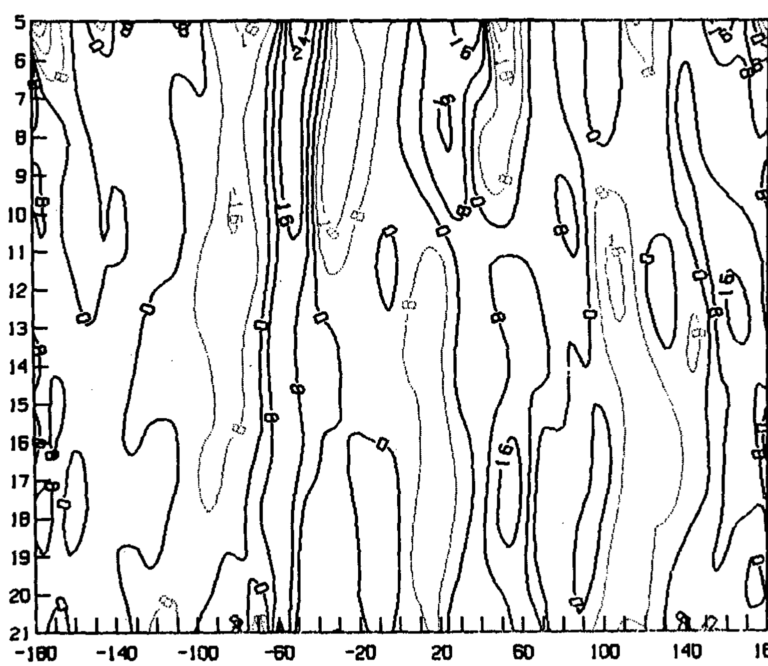
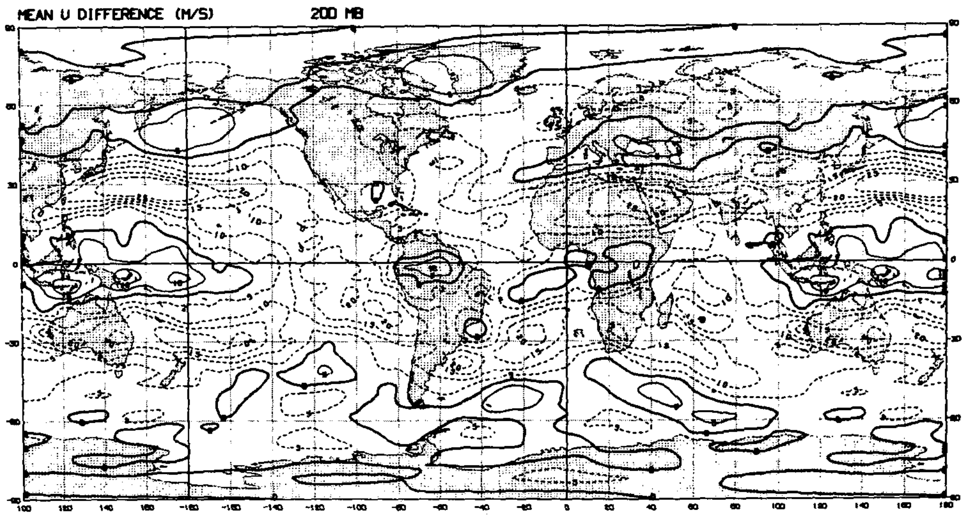


FIG. 17. As in Fig. 15 except for the "Reduced tropical heating" experiment.

presented in Figs. 19a and b. The reduction in amplitude and change of the South American waves is even stronger than in the "reduced tropical heating," experiment. In the Hovmoller diagram, it is apparent that eliminating the convection over Indonesia and the Central Pacific as well as in the subtropical SPCZ results in the eastward propagation of the previously stationary SACZ waves, presumably through a change in the Walker circulation. When the Atlantic hemisphere heating is suppressed, the corresponding stationary waves and Hovmoller plots are those of Figs. 20a and b. The South American waves weaken and start propagating immediately.

The fact that the weakening of the South American waves in these two experiments is much stronger than in the "reduced tropical heating" experiment suggests

"Reduced tropical heating" minus "January control"



"Reduced tropical heating" minus "January control"

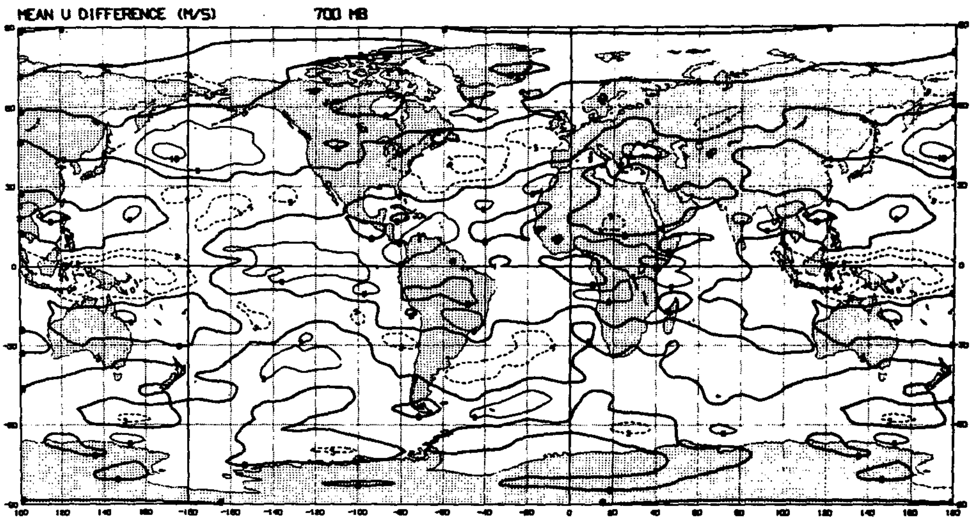


FIG. 18. Difference in the zonal velocity between the reduced tropical heating experiment and the January control forecast at (a) 200 mb level and (b) 700 mb level; contour interval is 5 m s^{-1}.

that subtropical convection in the SPCZ and SACZ plays a role in their maintenance, and they are not just a tracer of a circulation determined by equatorial convection over South America and Indonesia.

d. *"Easterly deceleration" experiment*

We performed an experiment in which we decelerated the initial zonal flow by adding a solid body rotation velocity corresponding to -5 m s^{-1} at the equator. The sea level pressure was also modified so as to maintain geostrophic balance with the change in zonal flow.

The purpose of this experiment was to determine whether the South American waves were sensitive to a shift in the position of the critical surface separating easterlies and westerlies, as argued in section 3.

The result of this experiment was rather unexpected, and is apparent in Fig. 21. The forecast of the stationary waves in the Northern Hemisphere is not very much affected by the change in zonal flow, whereas the Southern Hemisphere changes dramatically. The intensity of the short subtropical stationary waves over the Amazon in the control January forecast is weaker, but it is clear that the change in rotation has resulted

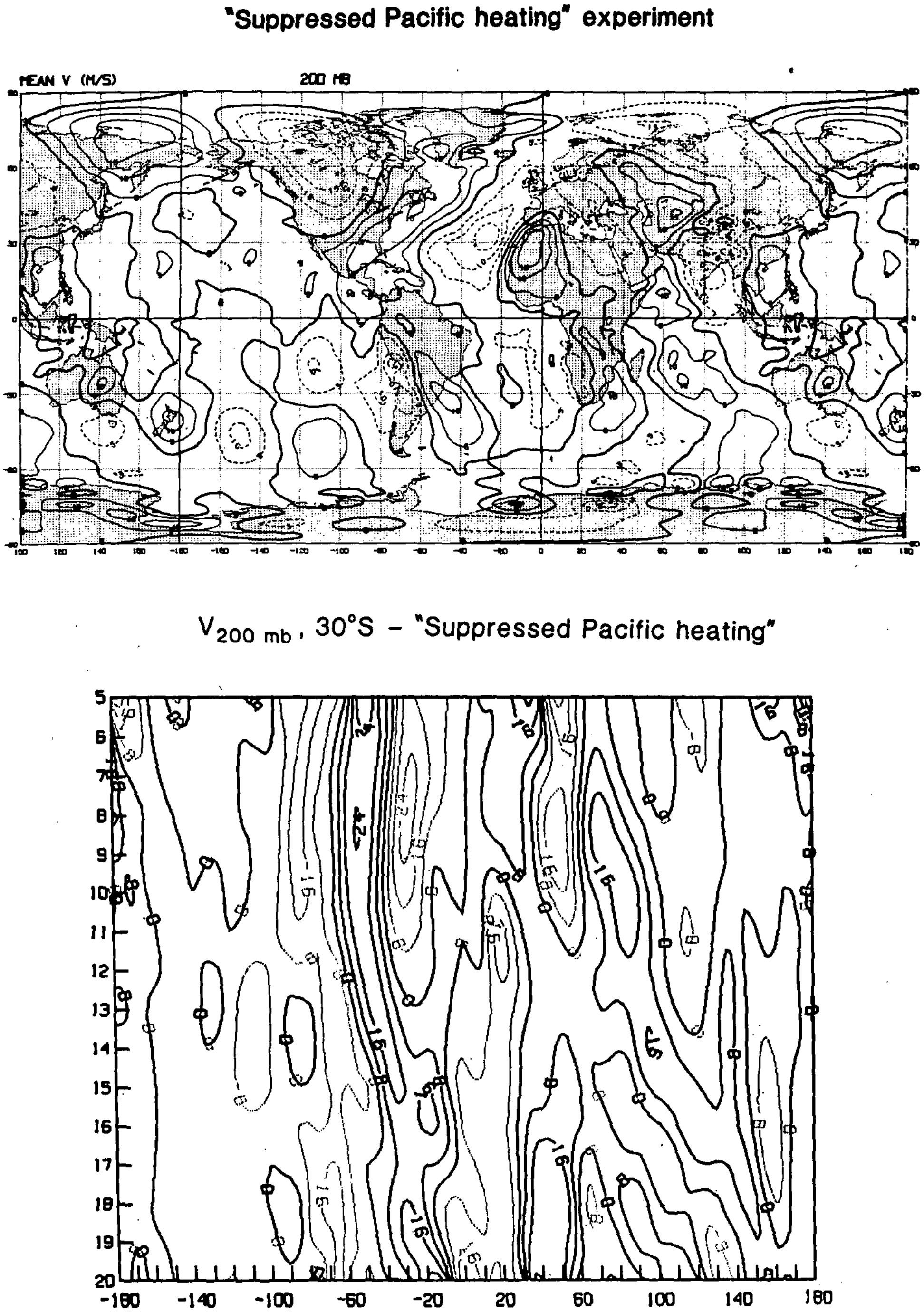


FIG. 19. As in Fig. 15 except for the "Suppressed Pacific heating" experiment.

in the very abrupt generation of almost stationary waves of zonal wavenumber 5 centered at 45°S. This result is reminiscent of the "ubiquitous" pentagonal wave in the Southern Hemisphere observed during certain periods of the southern summer and discussed by Salby (1982), Hamilton (1983), and Randel and Stanford (1983).

6. Summary and conclusions

We have presented observational evidence that during January 1979, large amplitude, short wavelength stationary waves dominated the subtropical circulation over South America and the South Atlantic for more than 30 days. These waves were shorter and stronger

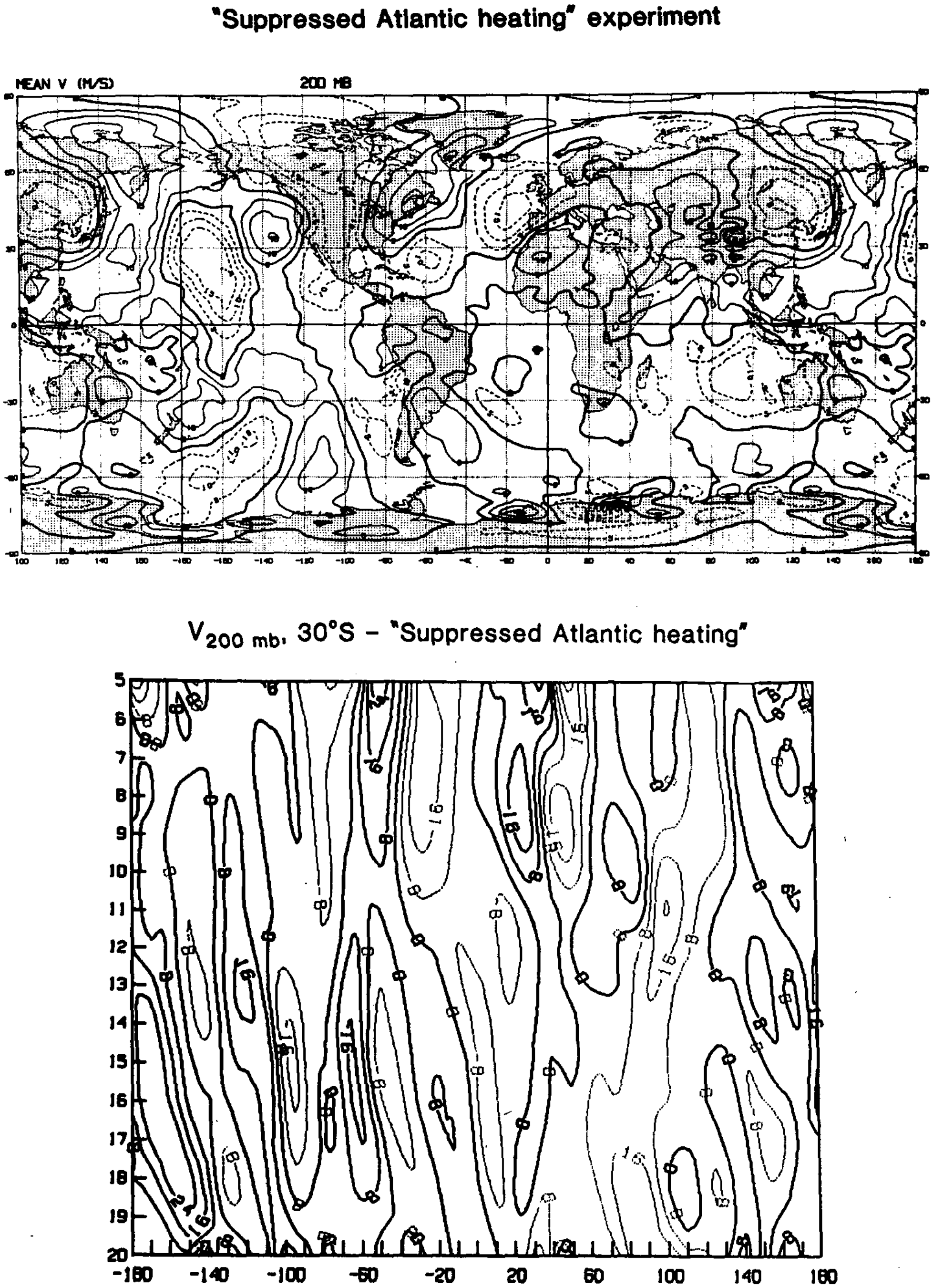


FIG. 20. As in Fig. 15 except for the "Suppressed Atlantic heating" experiment.

than the climatological stationary waves described by Newell et al. (1972) and Taljaard et al. (1972). Synoptically, they correspond to a split-jet blocking anomaly, with a cold cyclonic vorticity center behind a stationary front located at about 30°S, 40°W and an anticyclonic center at about 45°S (Fig. 3a).

We have argued that the January waves were not produced by SST anomalies. The observed correlation between the cold SST anomalies and low-level cyclone vorticity in the South Atlantic suggests that the atmospheric stationary waves were the cause of the ocean anomalies which in turn provided a negative feedback to the atmosphere. There is observational evidence indicating that the presence of the South American waves, apparent in the satellite observations as a band of clouds originating in the Amazon basin and tilted over the

"Easterly deceleration" experiment

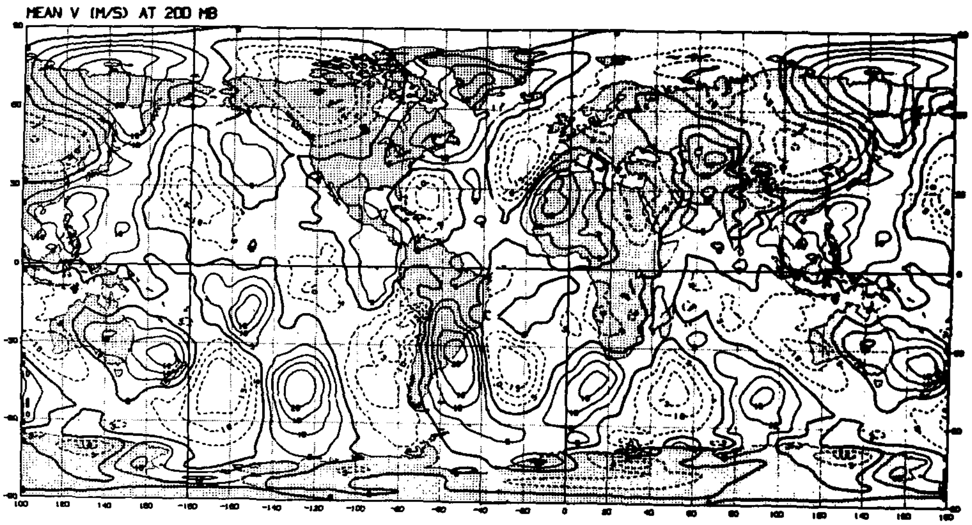


FIG. 21. As in Fig. 15a except for "Easterly deceleration" experiment.

Atlantic from northwest to southeast, is connected to the position and intensity of the South Pacific Convergence Zone.

Through the use of a comprehensive general circulation model, we have been able to determine the mechanisms that maintain the January waves. The model control forecast represents well the maintenance of the waves for about nine days, after which barotropic instability results in their sudden disappearance.

Several mechanistic experiments are performed. The "No Andes" forecast shows that the waves exist independently of the orographic forcing of the Andes.

Several experiments modifying the coefficient of latent heat lead to the conclusion that tropical heating is important in the maintenance of the waves. However, the convection in the subtropical waves themselves is important in sustaining their amplitude and phase, and the Walker type of circulation associated with the SPCZ is also a contributor to the maintenance of the South American waves. These results confirm the existence of a relationship between the occurrence of a strong SPCZ, somewhat eastward from its climatological position, and the strong "South Atlantic Convergence Zone" observed in outgoing long wave radiation maps.

A "pentagonal" stationary wave was the unexpected result of an experiment in which the zonal flow was decelerated by a solid rotation of -5 m s^{-1} at the equator. This phenomenon, probably related to the observed presence of waves with zonal wavenumber 5 in the Southern Hemisphere summer, will be studied in further detail.

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The experiments performed in this study were made possible because of the collaboration of J. Pfaendtner, L. L. Takacs and R. Balgovind who contributed to the development of the GLA fourth-order GCM. R. Dlouhy and M. Almeida helped in setting up the experiments. Most of the computer plots were developed and computed by R. Rosenberg. We are very grateful to all of them for their enthusiastic help.

The manuscript was expertly typed by D. Sabatino and Mary Ann Wells, and the figures were prepared with the collaboration of L. Rumburg and B. Sherbs.

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