An Observational Study of Traveling Planetary Waves in the Southern Hemisphere[1]

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ABSTRACT

Southern Hemisphere analyses from the surface to 2 mb and from 20 to 80°S for the period May–September 1979 have been used to study the structure of traveling planetary waves. Space-time cross-spectral analysis of the height field has been employed to define the amplitude and phase for both the eastward and westward moving components of particular combinations of zonal wavenumber and frequency band. Latitude-height contour plots of power, phase and coherence squared show that westward moving waves have structure characteristic of barotropic external modes and are coherent across a broad range of latitudes and from the surface to 2 mb, the highest level analyzed. Eastward-moving waves, on the other hand, have more rapid phase variations, especially in the troposphere, and appear more baroclinic. The tropospheric structure of the moving components of wavenumbers 1–4 is as one would expect for baroclinically unstable modes of the Charney type. Wavenumbers 1 and 2 both have double amplitude maxima in the troposphere, separated by ~20° of latitude. These amplitude maxima are coherent with each other and are about 180° out of phase. The variances of the eastward components of wavenumbers 1 and 2 increase rapidly with altitude in the stratosphere, but the variance in the upper stratosphere is not coherent with that in the troposphere. To explain these observations it is suggested that two linearly independent eastward moving modes are present simultaneously in the Southern Hemisphere, and that these modes are manifestations of the baroclinic instability of the zonal mean flow. One of the modes dominates the variance in the troposphere (Charney mode) and the other dominates the variance in the stratosphere (Green mode).

1. Introduction

One of the most pervasive ideas in dynamical meteorology is that atmospheric motion can be understood, at least in part, in terms of linear wave theory. This principle has led many investigators to specifically design observational studies to look for wavelike behavior. The usual starting point for such analyses is to subtract the zonal average from the flow field, thus isolating the eddy or wave component. This wave component of the flow can then be further subdivided by an expansion in zonal Fourier modes, in spherical harmonics, or in any other orthonormal set of functions that is appropriate. A further subdivision can be achieved by subtracting the time average over a specified period from the flow field, thus isolating the transient components. This transient component can then be divided into frequency components by a Fourier analysis in time. A generalized procedure which includes all of the above divisions of the flow field is called space-time spectral analysis.

There is a substantial body of literature on the transient or traveling part of the flow field. We will discuss briefly a few of the studies which have treated extratropical or global oscillations, excluding those dealing specifically with the tropics. Many of the early observational studies were concerned with the verification of the Rossby–Haurwitz formula for the movement of planetary waves (e.g., Deland, 1964; Eliasen and Machenauer, 1965; 1969). Others have investigated the horizontal and vertical structure of waves with various space and time scales (e.g., Bradley and Wiin-Nielsen, 1968; Deland and Johnson, 1968). Pratt and Wallace (1976) showed that, after averaging over bands of wavenumber and frequency, there are two basic types of midlatitude winter season traveling waves which predominate in the Northern Hemisphere. One has the structure of a barotropic external mode with significant amplitude at the surface and little phase variation with height and moves westward. The other moves eastward, the amplitude increases rapidly with altitude from small values at the surface and has substantial westward phase tilt with altitude. The westward moving planetary scale waves have been studied thoroughly, and evidence of enhanced amplitude at the frequencies corresponding to the free solutions of Laplace's tidal equa-

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tions has been noted. Recent reviews of the literature on westward propagating planetary waves have been provided by Madden (1979) and Walterscheid (1980).

Much attention has been given to the westward traveling planetary waves, perhaps because most studies have been applied to the Northern Hemisphere where westward moving planetary-scale waves seem to be more prominent, but also because the linear theory for westward moving planetary waves has been better developed. For shorter wavelength disturbances, of course, baroclinic instability is acknowledged to be the source of an overwhelming preponderance of eastward motion. In the Southern Hemisphere, away from the surface, even the planetary waves show a preference for eastward motion. The preferentially eastward motion of the planetary waves in the Southern Hemisphere is most apparent in the stratosphere (Philpot, 1969), and has been extremely well-documented with the advent of satellite observations of the stratosphere (Deland, 1973; Harwood, 1975; Hartmann, 1976). Leovy and Webster (1976) provided a direct comparison of planetary wave behavior in the Northern and Southern Hemisphere stratospheres and suggested that the predominant eastward moving waves might be due to baroclinic instability of the Green (1960) type as elucidated by Geisler and Dickinson (1975) and Geisler and Garcia (1977).

Space–time spectral analysis of Southern Hemisphere 500 mb data by Kao *et al.* (1970) showed that most of the kinetic energy of zonal wavenumber 2 in winter at middle and high latitudes was associated with eastward motion, with wavenumber 1 showing a less dominant preference for eastward motion.

In this study, time–space spectral analysis will be applied to data from the Southern Hemisphere during the period 14 May–13 September, 1979. During this period more than 200 drifting buoys provided an unprecedented description of the surface pressure and temperature field over the Southern Hemisphere (Fleming *et al.*, 1979; Guymer and LeMarshall, 1981). In addition to the rawinsonde network of upper air observations, polar orbiting satellites provided tropospheric and middle and upper stratospheric temperature measurements. Data from this period should thus be better suited than any past data set for an attempt to trace planetary waves from the surface to the upper stratosphere. The results of space–time spectral analysis of this data set suggest that westward traveling waves can indeed be traced from the surface to 2 mb with confidence. The eastward moving zonal wavenumbers 1 and 2 seem to behave quite differently in this regard, since even though eastward moving planetary wave amplitudes increase rapidly with altitude in the stratosphere, the dominant signal in the stratosphere is linearly independent (as measured by the coherence) of the dominant signal in the troposphere. Several possible explanations for this behavior are discussed. At the time of this writing the explanation we prefer is that there are two baroclinically unstable modes present whose amplitudes dominate different regions of the atmosphere.

2. Data

The principal data source for this study is the set of U.S. National Meteorological Center (NMC) 1200 GMT daily analysis fields between 1000 mb and 2.0 mb, during the period May–September 1979. This period includes the FGGE Second Special Observing Period (SOP-2), during which there was a large number of drifting buoys providing surface data in the Southern Hemisphere (Fleming *et al.*, 1979). The 1000–100 mb fields are obtained from the NMC 1200 GMT final cycle optimum interpolation analyses. For the Southern Hemisphere, the 100–5 mb analyses include TIROS Operational Vertical Sounder (TOVS) retrievals. Between 5 and 0.4 mb, heights and temperatures were determined from the TIROS-N Stratospheric Sensing Unit (SSU) channel 25 and 26 radiances via regression. The original fields are available on a 65 × 65 polar stereographic grid and were interpolated to a 5° × 5° latitude–longitude grid for the analysis described in this paper. Missing data were obtained by linear interpolation. The pressure levels available are 1000, 850, 700, 500, 300, 250, 200, 150, 100, 70, 50, 30, 10, 5, 2, 1 and 0.4 mb.

In the troposphere, we compared the NMC analyses with the Australian Numerical Meteorological Research Center (ANMRC) analyses for the Southern Hemisphere which are available at 1100 and 2300 GMT on a 47 × 47 polar stereographic grid at sea level, 1000, 850, 700, 500, 300, 250, 200 and 100 mb. The two data sets produce almost identical results north of 50°S, but the NMC analyses seem to have larger wave variances than the ANMRC analyses south of that latitude. The discrepancy seems to be larger for temperature and the eastward moving waves than for height and westward moving waves.

3. Analysis strategy

One of the main goals of this study is to present the hemispheric structure of transient waves in the Southern Hemisphere. In particular, if possible we would like to trace the structure of traveling phenomena from the surface to the upper stratosphere. In this way some insight may be gained into the processes which originate and modify these disturbances. The principal framework through which we will attempt to achieve these aims is the space–time spectral analysis technique. The formulation of Hayashi (1971) which we used is described briefly in the Appendix. The basic mathematical technique of writing the variation of a field over longitude and time in terms of a Fourier expansion in a set of functions with particular wavenumber-frequency pairs is straightforward, i.e.,

$$w(\lambda, t) = \sum \sum_{\omega} W_{k,\pm\omega} \cos(k\lambda \pm \omega t + \phi_{k,\pm\omega}), \quad (1)$$

where k is the zonal wavenumber, ω frequency, and ϕ a phase. The positive and negative signs in (1) correspond to westward and eastward moving waves, respectively. This basic decomposition has been used in many studies of atmospheric and general circulation model data (e.g., Kao *et al.*, 1970; Deland, 1973; Hayashi, 1974; Willson, 1975; Hayashi and Golder, 1977; Fraedrich and Bottger, 1978; Pratt, 1979; Strauss and Shukla, 1981). While the expansion of any field $X(\lambda, t)$ in the form (1) is a straightforward mathematical operation, the interpretation of the coefficients $W_{k,\pm\omega}$ and the associated space-time power spectral estimates is not. There is a long literature devoted to the question of whether the expansion (1) is a physically sensible thing to do and, if so, how to interpret the results in terms of physical phenomena. As Pratt (1976) has pointed out, the division of the space-time variance implicit in (1) into eastward moving waves, westward moving waves, oscillating stationary waves and noise is not unique. We have used the technique of Hayashi (1977) to define the stationary oscillation as that part of the variance described by coherent eastward and westward traveling waves of equal magnitude. The traveling variance is then just the remainder after the standing variance has been removed. Schäfer (1979) has pointed out that a large fraction of this remaining variance may be better treated as noise and has prescribed a formulation for defining the "wave" signal as that which possesses coherence in time between the sine and cosine coefficients of the zonal spatial Fourier decomposition. This formulation treats variance with incoherent eastward and westward components as "noise," whereas we prefer to adopt the notion of Hayashi (1977) that these are independent eastward and westward moving "waves." All of the variance decompositions beyond the basic mathematical division in (1) involve specific additional assumptions which lead to different interpretations of the space-time Fourier decomposition.

In this study, we will emphasize the structure of components of the height field defined by zonal wavenumber-frequency pairs. The structure for particular zonal wavenumbers and frequency bands will be illustrated with latitude-height contour plots of power, phase and coherency (squared coherence). The question of whether the variance is associated with organized wave-like behavior will be determined from the coherence between different latitudes and

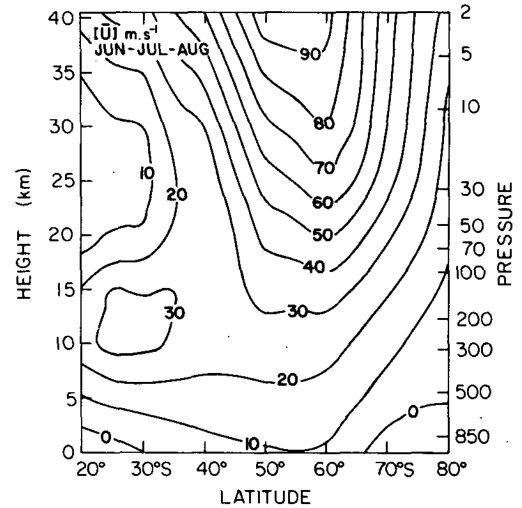

FIG. 1. Latitude-height cross section of the zonal mean geostrophic wind (m s^{-1}) in the Southern Hemisphere averaged over June–August 1979.

heights, and from the availability of rational explanations for the amplitude and phase structure obtained. This procedure is a reasonable one for the atmosphere at middle and high latitudes where isolated spectral peaks are very rare and one is forced to make physical interpretations of a very red spectrum.

4. Results

The primary results of this work are contained in the latitude-height contour plots of wave power, phase and coherency. These point out the structural differences between eastward and westward moving waves, which increase confidence in the interpretation of these Fourier decompositions. Before these figures are presented, however, we will show some selected longitude-time contour plots for individual zonal wavenumbers and some space-time power spectra for the time period under consideration.

For reference, the zonal mean geostrophic winds averaged over the 14 May–13 September 1979 period are shown in Fig. 1. These winds are very characteristic of Southern Hemisphere winter conditions (van Loon *et al.*, 1972). The vertical wind shear at middle and high latitudes is stronger than in the Northern Hemisphere and remains positive through the stratosphere. Also the midlatitude westerlies in the Southern Hemisphere are much stronger in the lower troposphere during winter than they are in the Northern Hemisphere.

a. Longitude–time plots

Fig. 2 shows a longitude-time plot of contours of the ANMRC sea level pressure field at 60°S com-

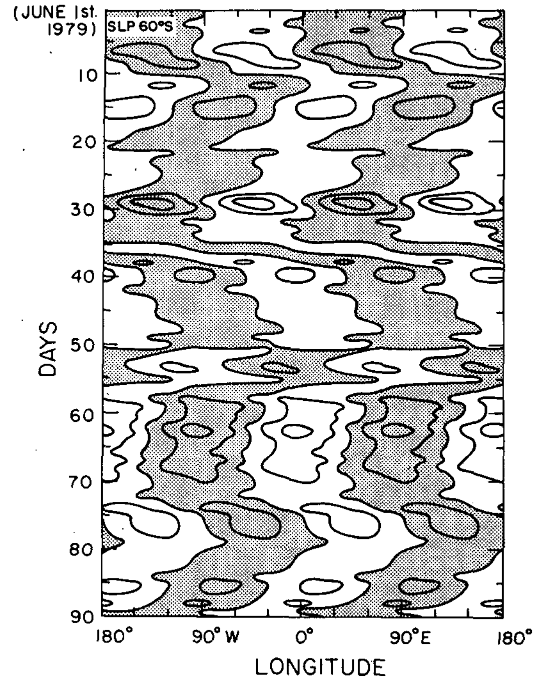

FIG. 2. Longitude–time contour plot of the zonal wavenumber 2 component of sea level pressure at 60°S. Negative values are shaded. The contour interval is 8 mb.

posed solely of zonal wavenumber 2. Wavenumber 2 at the surface is predominantly stationary, but shows periods of both eastward and westward movement. At 10 mb, 50°S, wavenumber 2 in temperature is predominantly eastward moving, as is shown by the longitude–time plot in Fig. 3. The height fields at altitudes higher than 10 mb show behavior similar to that of the 10 mb temperature. Wavenumber 3 has a significant eastward moving component in sea level pressure, together with a stationary part, as can be seen in Fig. 4. The general impressions conveyed by these plots will be confirmed and sharpened by the space–time spectral estimates described below.

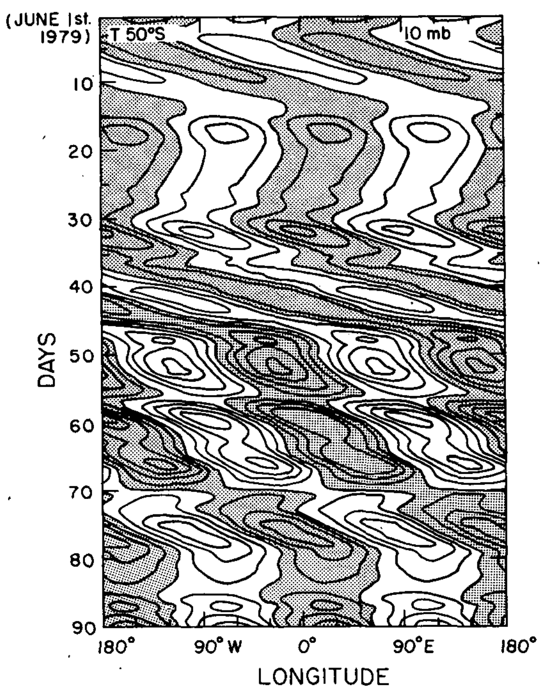

FIG. 3. Longitude–time contour plot of the zonal wavenumber 2 component of 10 mb temperature at 50°S. Negative values are shaded. The contour interval is 2 K.

b. Space–time power spectra

The space–time spectral analysis scheme we use follows the formulation of Hayashi (1971). First, zonal spectral Fourier sine and cosine coefficients are computed for each latitude, pressure and time. The lag-correlation method was then applied to these coefficients in order to obtain time-spectral estimates for each zonal wavenumber. This procedure produces an estimate of the power (variance) associated with a discrete set of zonal wavenumber–frequency band pairs. It is further possible to divide the power into that associated with eastward or westward moving disturbances as in (1) (see Appendix). One can then produce plots like those shown in Figs. 5–7, which are contour plots of spectral power in frequency versus zonal wavenumber coordinates. Fig. 5 shows the power spectra of sea level pressure at 40, 50 and 60°S. The power of the surface pressure field at these latitudes is concentrated in the low wavenumber–low frequency range. The power generally increases be-

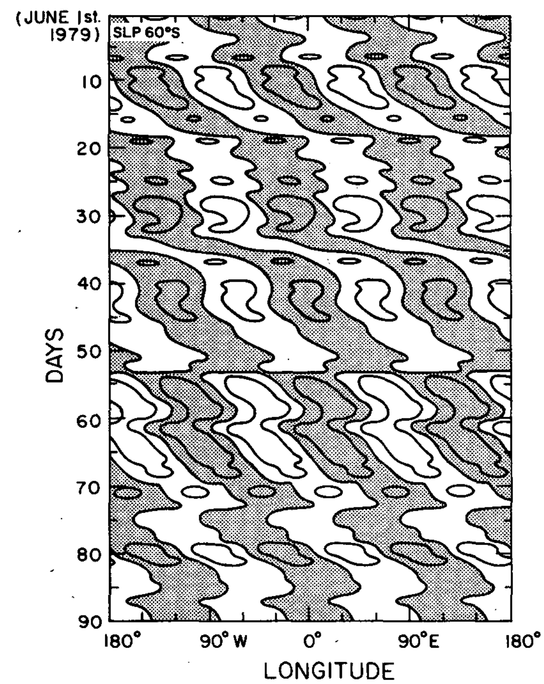

FIG. 4. As in Fig. 2, except for zonal wavenumber 3.

tween 40 and 60°S, with the westward moving variance increasing more rapidly with latitude than the eastward moving variance. There is substantial variance in zonal wavenumber 4 at 40°S which moves eastward with periods from 10 to 15 days and has a relatively constant variance between 40 and 60°S. Wavenumber 3, on the other hand, has a longer period and increases in amplitude between 40 and 60°S.

Fig. 6 shows the remaining variance after the coherent standing oscillations have been removed [see Appendix and Hayashi (1977)]. A large fraction of the variance in wavenumber 3 at 40 and 50°S seems to be associated with a standing oscillation. van Loon and Jenne (1972) and Hartmann (1977) found a large stationary wavenumber 3 component during Southern Hemisphere winter. It is reasonable to suppose that the standing oscillation observed here rep-

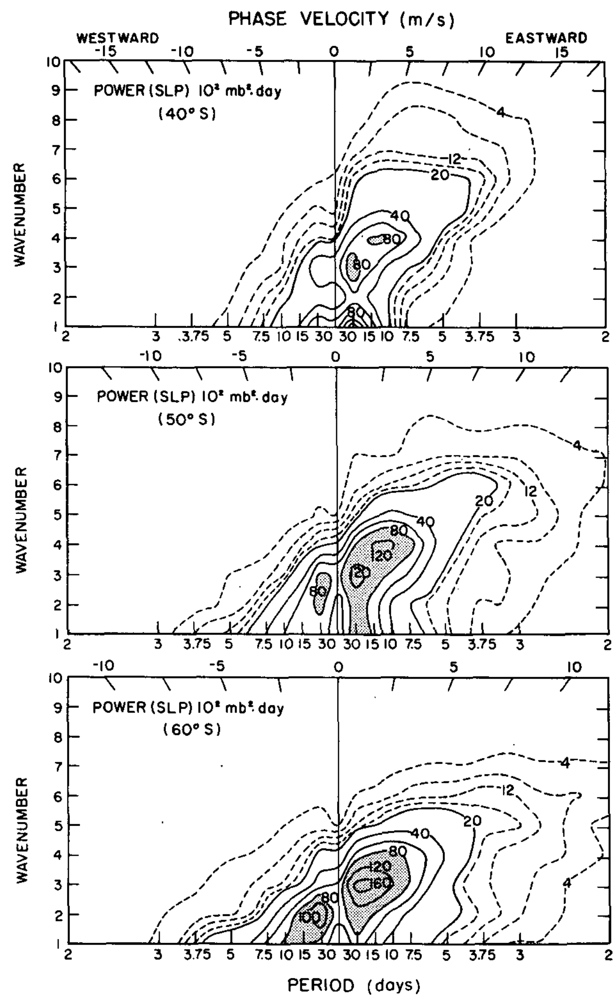

FIG. 5. Wavenumber–frequency contour plots of the power of the sea level pressure field at 40°S (top), 50°S (middle) and 60°S (bottom). Westward phase speeds are to the left, and eastward phase speeds are to the right.

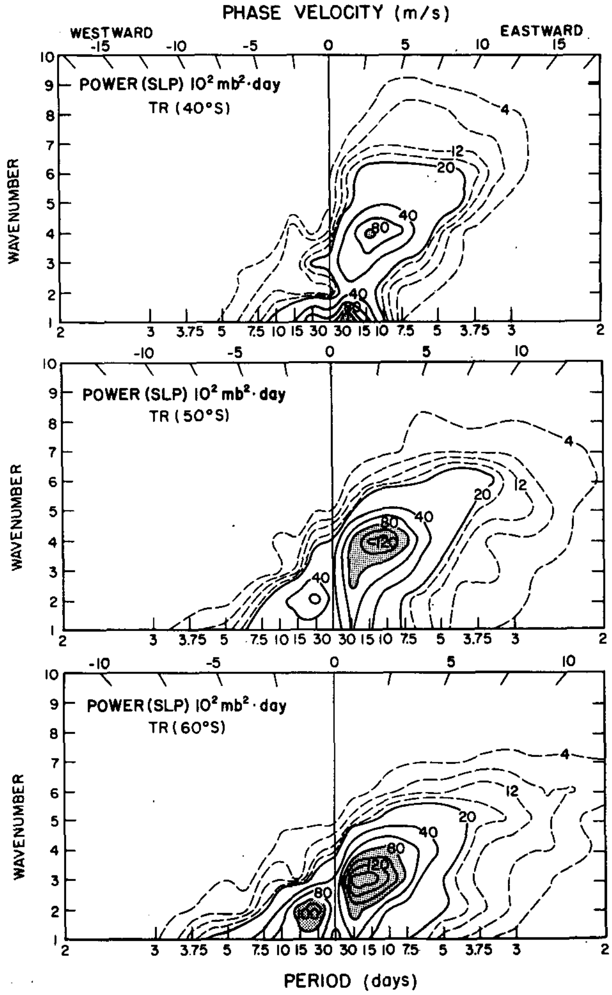

FIG. 6. As in Fig. 5, except that the power of the standing wave component has been removed.

resents time variations in this stationary wave. At 40 and 50°S, wavenumbers 1 and 2 also have a significant standing wave present. At 60°S, however, the standing wave contribution is small and the variance is composed almost entirely of eastward and westward components which move independently of each other. We shall see that the eastward and westward moving waves each have their own distinct structures which are coherent through latitude and altitude. The fact that the eastward and westward moving waves have different structures, which appear coherent over latitude and height, supports the assertion that the traveling variance can be interpreted as traveling waves rather than noise. The space–time spectra for the height field at 2, 10 and 50 mb at 60°S are shown in Fig. 7. At these levels, the power is very much concentrated in zonal wavenumbers 1 and 2. The eastward moving variance now exceeds the westward moving variance by at least a

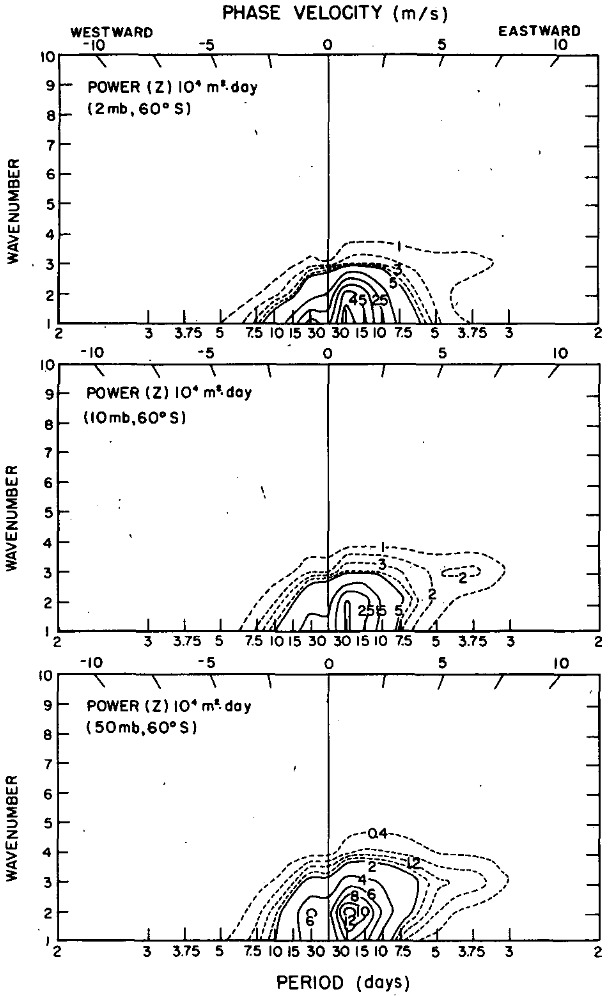

FIG. 7. Wavenumber–frequency contour plot of the power of the height field at 60°S and 2 mb (top), 10 mb (middle), and 50 mb (bottom).

factor of 2. This should be contrasted with the surface pressure where eastward and westward moving variances are about equal. It thus appears that the eastward moving variance in the height field increases more rapidly with altitude than the westward moving variance. Interestingly, at 50 mb the wavenumber 2 variance exceeds that of wavenumber 1 by more than 50%. This is the same general behavior observed by Hartmann (1976) for the winter of 1973.

Fig. 8a shows the space–time spectra for the meridional geostrophic velocity at 300 mb 60°S. This is in excellent agreement with the results of Kao *et al.* (1970), in that it shows most of the variance of the meridional velocity associated with eastward motion, and the variance maximum elongated in a direction from low wavenumbers and low frequencies to high wavenumbers and higher frequencies corresponding to eastward motion. Figs. 8b and 8c show the space–time cospectra at 60°S of northward momentum transport $\overline{u'v'}$ and heat transport $\overline{v'T'}$, respectively. The momentum flux is equatorward for low-frequency planetary-scale wavenumbers, while the heat flux is predominantly poleward for the lowest wavenumbers. The heat flux accomplished by the westward moving waves is very small, suggesting that these waves have little phase tilt with height. This expectation of a fairly barotropic structure will be confirmed by the phase and amplitudes shown below for these waves.

As shown by Andrews and McIntyre (1976) and Edmon *et al.* (1980), northward flux of heat by eddies is the best measure of upward energy flux for quasi-geostrophic waves. Thus, Fig. 8c suggests that most of the upward energy flux by transient waves

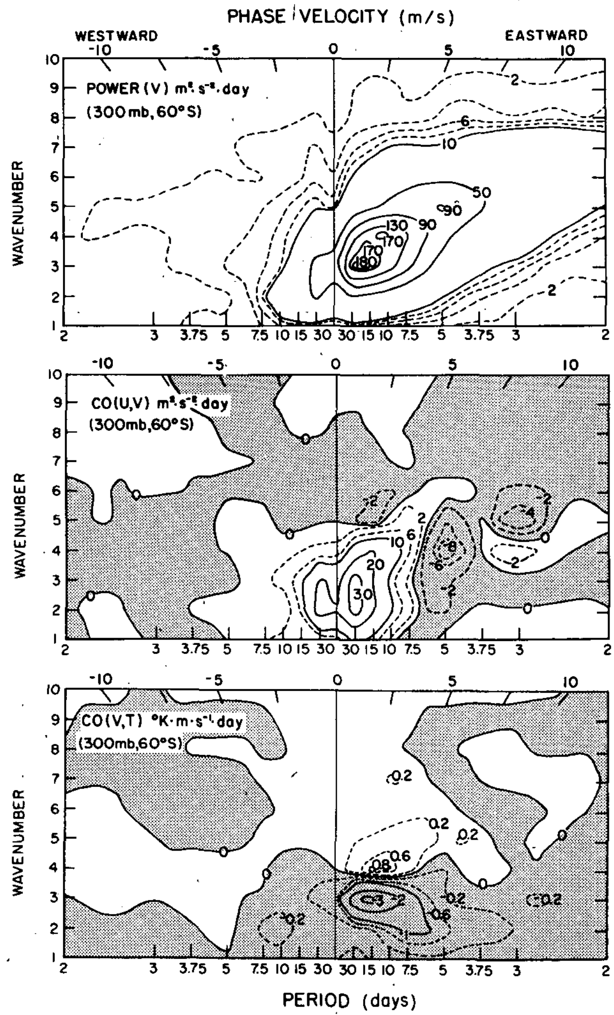

FIG. 8. Wavenumber–frequency contour plots at 300 mb, 60°S of the power in the meridional wind (top), the cospectra of the zonal and meridional wind components $\overline{u'v'}$ (middle), and the cospectra of meridional wind and temperature $\overline{v'T'}$ (bottom).

at 300 mb 60°S is taking place in the low-frequency eastward traveling planetary waves.

c. Wave structure: amplitude, phase and coherency cross sections

Latitude–height contour plots of the amplitude, phase and coherency (squared coherence) of particular wavenumber–frequency pairs in the domain from 20 to 80°S and 100 to 2 mb will be presented in this section. The phase and coherency are calculated relative to a single reference latitude/pressure point which is chosen on the basis of the amplitude structure. Positive phase changes indicate an eastward shift in the longitude by an amount equal to the value plotted divided by the zonal wavenumber.

1) WESTWARD MOVING WAVES

The amplitude, phase and coherency for zonal wavenumber 1 moving westward with a period of 5 days is shown in Fig. 9. The reference point for the phase and coherency in this case is 10 mb, 50°S. The coherency is high over most of the domain shown, and the phase is relatively constant. The minimum coherency required to indicate a meaningful relationship between the points at the 99% confidence level is 0.3 (see Appendix). The 5-day period corresponds to the theoretically predicted period for the gravest symmetric Rossby mode (e.g., Longuet-Higgins, 1968). Geisler and Dickinson (1975, 1976), Schoeberl and Clark (1980) and Salby (1981a,b) have examined the dependence of the structure of this mode on realistic horizontal and vertical wind shears. This mode stands out quite clearly in most data sets (Deland, 1964; Eliasen and Machenauer, 1965, 1969). Madden and Julian (1972) examined long time series at a number of stations and were able to demonstrate a spectral peak near 5 days for wavenumber 1 and show that there was very little phase variation with height or latitude. Thus, their study strongly supported the identification of this disturbance with the gravest Rossby mode. Subsequent studies have reaffirmed this interpretation (Madden and Julian, 1973; Madden and Stokes, 1975; Madden, 1978). Rodgers (1976) found a strong westward 5-day peak in stratospheric temperature data.

The westward moving wavenumber 1 with a period of 15 days (Fig. 10) shows considerably less horizontal coherency in the troposphere than the 5-day wave, but does have good coherency in the stratosphere. In the area where the coherency is large for this wave the phase is relatively constant. There are many studies which report coherent westward moving waves ~16 days, but the evidence that this is a pure Rossby normal mode signature is less conclusive than that for the 5-day wave [see, e.g., reviews by

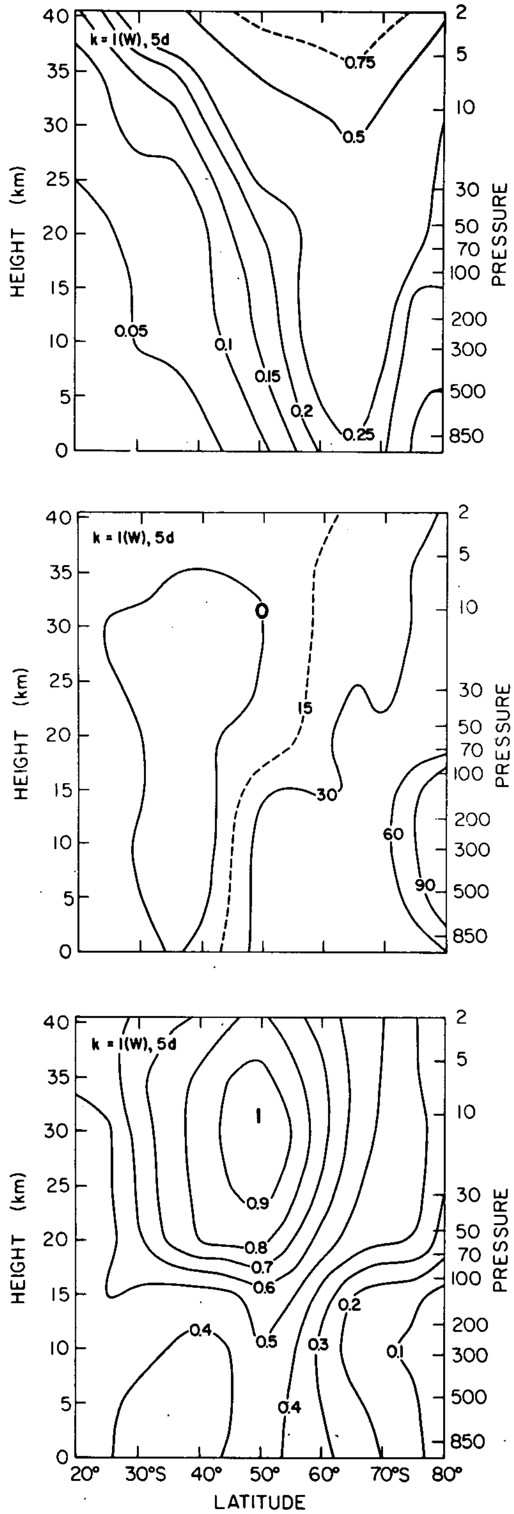

FIG. 9. Latitude–height contour plots of the power (top, units 10^4 m^2 day), phase (middle, degrees), and coherency (bottom) of the westward moving wavenumber 1, 5-day period component of the height field. The reference point is at 10 mb, 50°S, as indicated by the boldface 1 on the coherency plot.

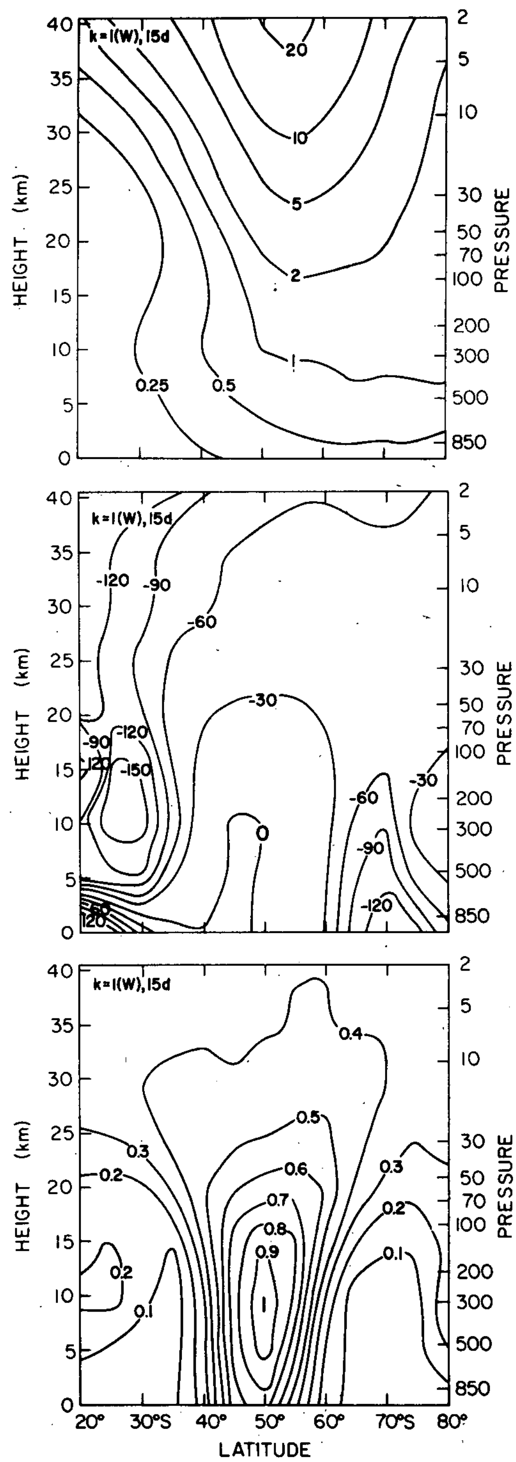

FIG. 10. As in Fig. 9, except for westward moving wavenumber 1, 15-day period. Reference point is 300 mb, 50°S.

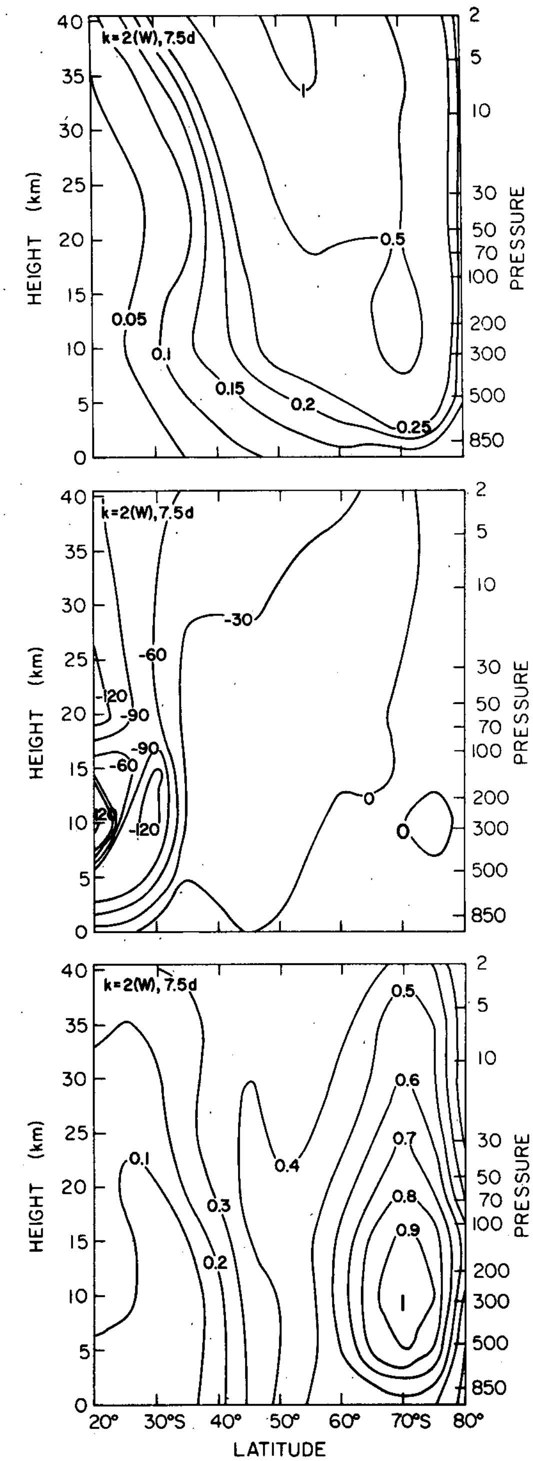

FIG. 11. As in Fig. 9, except for westward moving wavenumber 2, 7.5-day period. Reference point is 300 mb, 70°S.

Madden (1979) and Walterscheid (1980)]. It should be remembered that Fig. 10 presents amplitude, phase and coherency for a band of frequencies corresponding to periods from ~13 to 17 days which may not be dominated by the so-called 16-day wave, and that the Parzen data window introduces considerable smoothing in the frequency domain. The main reason for showing the structures of the westward moving variance is to contrast them with eastward moving disturbances shown in the next section. For this same reason, we show the structure of westward moving wavenumber 2 with a period of 7.5 days in Fig. 11. Again the phase is almost constant where the coherency is >0.3 and the coherency poleward of 45°S is >0.3 at all levels.

2) EASTWARD MOVING WAVES

In this section, the structure of eastward moving zonal wavenumbers 1–4 in the height field will be described. The structure of the eastward and westward moving disturbances can then be compared with each other and with theory. Fig. 12 shows the structure of the wavenumber 1 component moving eastward with a period of 15 days. The amplitude in the troposphere has two maxima, one each at 45°S and 65°S. The coherency shows that there is a coherent relationship between these two maxima, since the coherency drops below the significance level of 0.3 at 60°S but then increases to >0.4 at 70°S. There is a suggestion of another coherency maximum at 25°S, but it is much weaker. The phase indicates that the 45 and 65°S maxima are ~180° out of phase with each other. The tropospheric structure revealed in Fig. 12 is very similar to that of low zonal wavenumber baroclinically unstable modes of the Charney–Eady type, which also have two amplitude maxima in middle and high latitudes with a rapid phase shift of about 180° between the two maxima (Hartmann, 1979).

The eastward moving wave structure in Fig. 12 can be compared with that of a westward moving wave of the same zonal wavenumber and period shown in Fig. 10. The westward moving wave shows no evidence of a double amplitude maximum as the eastward moving wave does. The westward moving wave also does not show secondary increases in the coherency away from the reference point at 300 mb, 50°S. In the stratosphere, the eastward moving wave amplitude increases with altitude roughly twice as fast as the westward moving wave. Somewhat surprisingly, however, the eastward moving wave does not show significant coherency between the troposphere and the upper stratosphere, whereas the westward moving wave does. Fig. 13 shows the phase and coherency of the eastward moving wave relative to 10 mb, 50°S. The coherency with the troposphere is remarkably small, but there is a good region of coherency in the stratosphere. The meridional scale appears to be larger in the stratosphere than in the troposphere. The phase in the stratosphere indicates poleward heat flux and momentum flux.

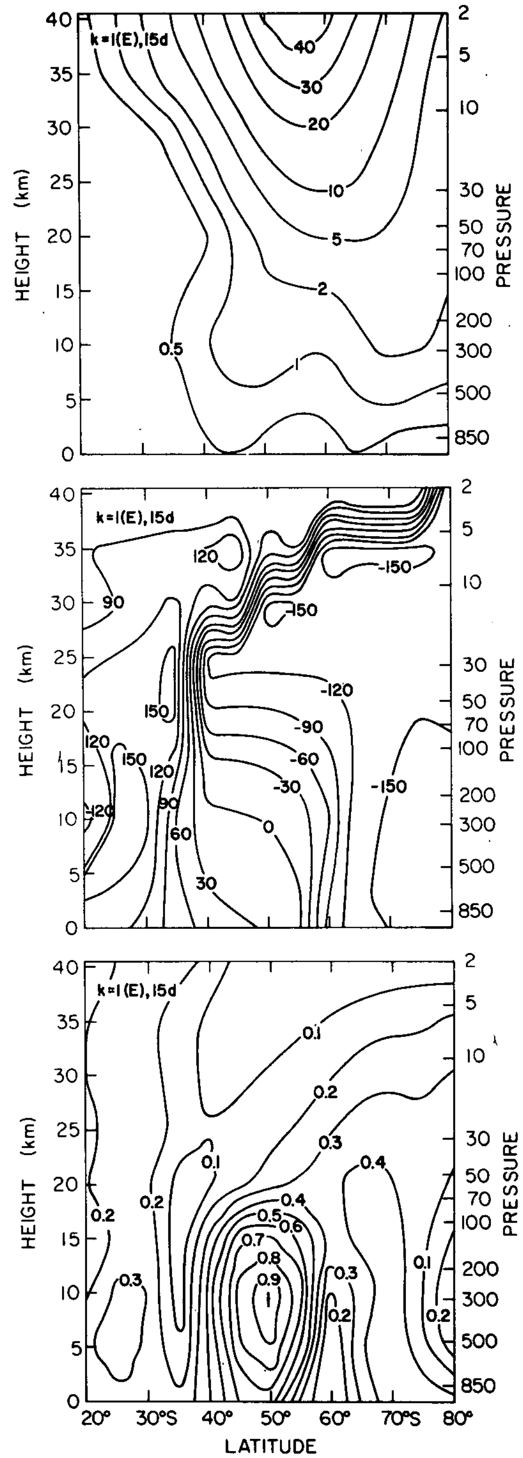

FIG. 12. As in Fig. 9, except for eastward moving wavenumber 1, 15-day period. Reference point 300 mb, 50°S.

The structure of the eastward moving wavenumber 2 with a period of 7.5 days is shown in Fig. 14. Again there is a double amplitude maximum in the troposphere, though less marked than for wavenumber 1. The coherency between these two amplitude maxima is again above the 0.3 level required for significance and the phase shift is again ~180°. The contrast between the eastward and westward moving

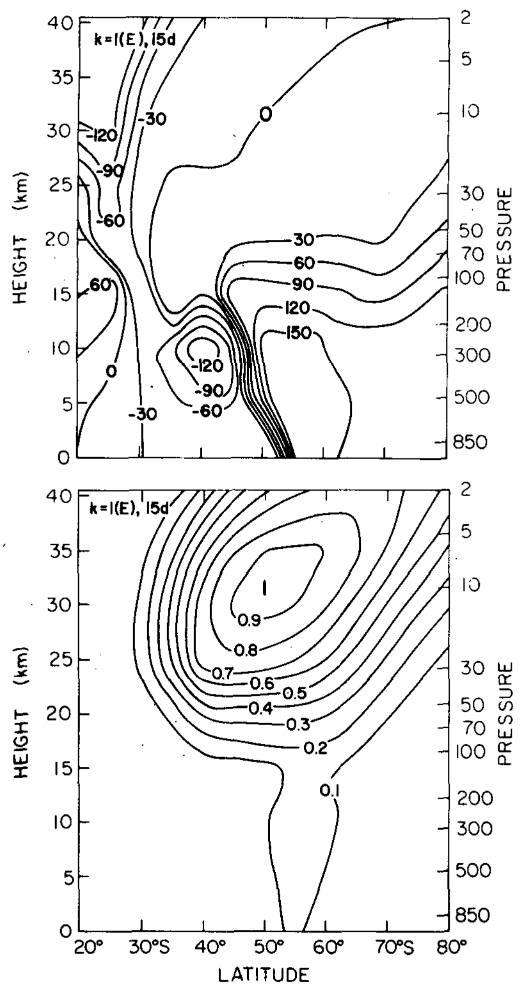

FIG. 13. As in bottom two-thirds of Fig. 12, except for a reference point at 10 mb, 50°S.

wavenumber 2 is very similar to the contrast in wavenumber 1. The eastward moving wave has two maxima in the troposphere, with rapid phase variation in between, while the westward moving wave has a single broad amplitude maximum with uniform phase everywhere that the coherency is significant. The eastward moving wave amplitude increases very rapidly with altitude but there is little coherence between the troposphere and the upper stratosphere, while the westward moving wave amplitude increases more slowly with height but has significant coherency from the surface to the highest data level considered at 2 mb. The narrow meridional scale of the geopotential height found in the troposphere for eastward moving wavenumbers 1 and 2 is consistent with the kinetic energy spectra derived by Kao *et al.* (1970) for the Southern Hemisphere. They found that for planetary waves at middle and high latitudes most of the kinetic energy was contained in the zonal component of wind and in the eastward moving component. If the winds are approximately geostrophic, this suggests predominance by eastward waves with height perturbations whose meridional scales are much shorter than their zonal scales.

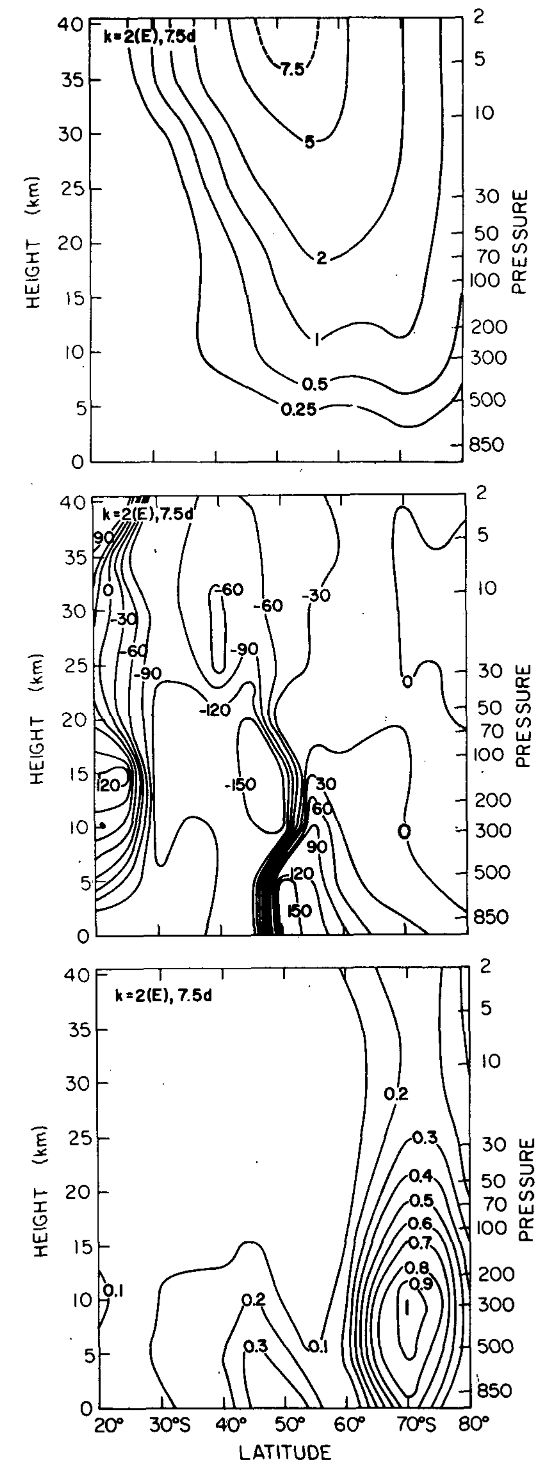

FIG. 14. Same as in Fig. 9, except for eastward moving wavenumber 2, 7.5-day period. Reference point 300 mb, 70°S.

The structure of wavenumber 3 moving eastward with a period of 10 days is shown in Fig. 15. In this case the amplitude does not increase with altitude in the stratosphere, but rather remains roughly constant above ~300 mb. The phase shifts westward with altitude at all levels, but most rapidly near the surface. The wave appears to be coherent from the surface to above 2 mb. This structure is similar to the structure of baroclinically unstable waves growing on a zonal mean state similar to that in Fig. 1 (Hartmann, 1979).

Fig. 16 displays the structure of wavenumber 4 moving eastward with a period of 10 days. The amplitude maximum is equatorward of those of the lower wavenumbers and the amplitude decays rapidly into the stratosphere. These features are both consistent with the shorter zonal scale of wavenumber 4, as is, perhaps, the suggestion that wavenumber 4 has a broader meridional scale than wavenumbers 1–3. Wavenumber 4 has a broad region of significant coherency with the reference point at 300 mb, 50°S, which extends to 5 mb.

5. Discussion

In this study we have examined the characteristics of transient waves in the Southern Hemisphere from 14 May to 13 September 1979. This period was chosen because of the simultaneous availability of data from both a large number of surface buoys and from satellite instruments which provide information on the stratosphere. The central focus of the study has been on latitude versus height contour plots showing the power, phase and coherency of components of the height field for particular zonal wavenumber–frequency band pairs. A comparison of the structure of eastward and westward moving waves results in the following observations for zonal wavenumbers 1 and 2.

- The amplitude of the eastward moving component increases much more rapidly in the stratosphere than the westward moving component.
- In the troposphere the eastward moving component has two amplitude maxima separated in latitude by a relative minimum. These two maxima are coherent with each other and are ~180° out of phase with each other. The westward moving component has a single broad amplitude maximum with little variation in phase.
- For the eastward moving components of wavenumbers 1 and 2 there is little coherence between the troposphere and the upper stratosphere, whereas the westward moving components show coherence from the surface to 2 mb, the highest level studied.

For the eastward moving components of zonal wavenumbers 3 and 4 structures were found which are characteristic of baroclinically unstable modes

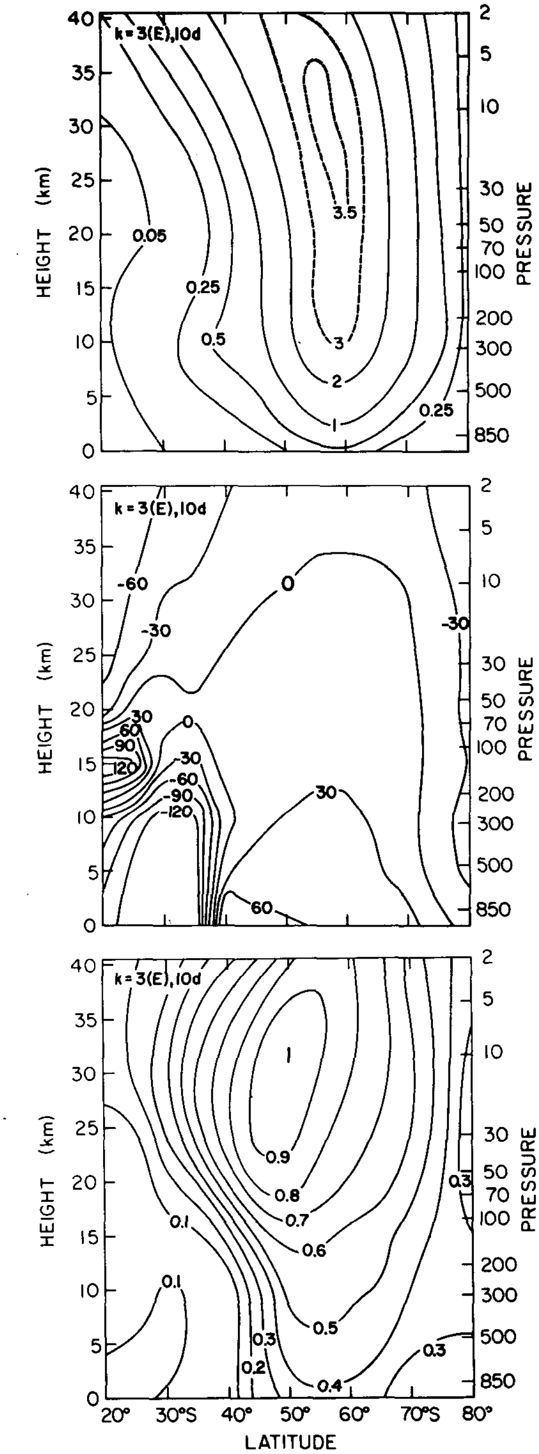

FIG. 15. As in Fig. 9, except for eastward moving wavenumber 3, 10-day period. Reference point at 10 mb, 50°S.

of the Charney (1947) type. In contrast to zonal wavenumbers 1 and 2, the eastward components of wavenumbers 3 and 4 did not show an increase in amplitude with height. They did, however, show good

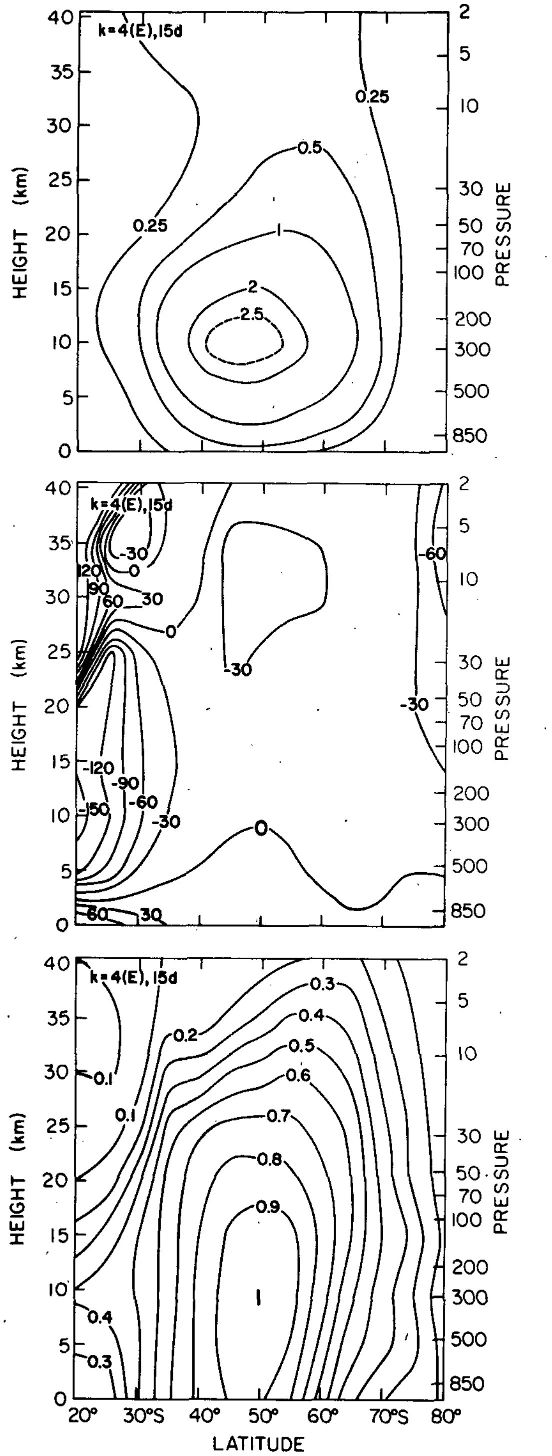

FIG. 16. As in Fig. 9, except for eastward moving wavenumber 4, 15-day period. Reference point is 300 mb, 50°S.

coherence between the troposphere and stratosphere, which the eastward components of wavenumbers 1 and 2 did not show.

The behavior of the westward moving waves described in this study supports interpreting them as essentially barotropic Rossby waves which are predominantly either forced or free depending on how close the wavenumber–frequency pair in question is to a normal mode. The structure of the eastward moving zonal wavenumbers 3 and 4 is perfectly consistent with the structure of baroclinically unstable waves on a sphere (see, e.g., Gall, 1976; Simmons and Hoskins, 1976). The most interesting problems arise in trying to understand the behavior of the eastward moving components of zonal wavenumbers 1 and 2. The structure of the eastward moving planetary waves in the troposphere is consistent with that of baroclinically unstable waves of the Charney–Eady type. As discussed by Hartmann (1979), a narrow meridional scale is preferred for baroclinically unstable waves of planetary wavelengths so that the advection of relative vorticity may play its normal important role in the vorticity balance of unstable modes of the Charney–Eady type. The distribution of phase and coherency in the troposphere shown in Figs. 12 and 14 of this paper is similar in many respects to the phase and amplitude of the normal mode shown in Fig. 12 of Hartmann (1979). One can then tentatively conclude that the dominant eastward moving components of wavenumbers 1 and 2 in the troposphere are associated with baroclinically unstable modes of the Charney–Eady type. It should be pointed out, however, that if they are to have the observed eastward phase speeds, any quasi-nondivergent zonal wavenumber 1 and 2 components must have relatively narrow meridional scales, regardless of their source of excitation. Therefore, we cannot entirely exclude the possibility that these are primarily forced waves. Antarctica has topography with significant zonal wavenumber 1 and 2 components. The topography of Antarctica also has important effects on the structure and growth rates of unstable waves (Hartmann, 1979; Mechoso, 1980).

The results show that for eastward moving wavenumbers 1 and 2 there is no significant coherence between the dominant signal in the troposphere and the dominant signal in the stratosphere. This occurs despite the fact that the amplitudes in both regions are considerable. Thus we cannot directly associate the eastward-moving variance in the stratosphere with the dominant mode in the troposphere. There are several possible explanations for this lack of coherence which come to mind.

1) A lack of coherence does not mean, necessarily, that there is no physical connection between these regions, but simply that variations in the two regions are linearly independent. Thus it may be that the lack of coherence results from nonlinearities in the system. If the waves undergo a life cycle and modify the zonal mean wind during this life cycle, and if one takes into account the finite time it takes the waves to propagate from the troposphere to the 2 mb level,

then it is easy to imagine that the signal at 2 mb may be linearly independent of the signal in the troposphere. Webster and Keller (1975) have reported oscillations in the zonal wind and eddy energy in the Southern Hemisphere on time scales comparable to the periods of the waves discussed here. In addition, since the waves increase in amplitude by several orders of magnitude between the troposphere and 2 mb, there may be a stronger interaction with the stationary component and other wave components at 2 mb than at the surface.

2) A large amplitude wave component at 2 mb which is linearly independent of the troposphere may suggest an *in situ* stratospheric source for the wave. Most theoretical studies of *in situ* instabilities of planetary scale waves in the stratosphere have not been encouraging however (Fleagle, 1958; Murray, 1960; McIntyre, 1972), even though integral criteria suggest stratospheric winds may be unstable (Charney and Stern, 1962; Leovy and Webster, 1976).

3) It is possible that there are two linear modes present which are independent of each other. One of these could dominate in the troposphere and the other could have larger amplitudes in the stratosphere. There are, of course, two linear baroclinically unstable modes with just these characteristics—the Charney modes and the Green modes of beta-plane theory. The Charney modes for zonal wavenumbers 1 and 2 must have narrow meridional scales in the troposphere and usually have more rapid growth rates than the Green (1960) modes for the corresponding zonal wavenumber (Hartmann, 1979; Hoskins and Revell, 1981). While Hartmann (1979) has shown that the meridional scale of the Charney modes increases with altitude in the stratosphere and that these modes do have substantial amplitude in the stratosphere, the growth of amplitude with altitude of the normal mode is weak and does not approach the rapid increase of amplitude with altitude of a freely propagating wave. Strauss (1981) was able to show that Green modes can exist on a sphere and can have growth rates which are competitive with the Charney–Eady modes. The structure of these waves indicates a very rapid increase in amplitude from the troposphere to the stratosphere, much in accord with the beta-plane results of Geisler and Garcia (1977). Taking all of this into account, one might legitimately suggest that Charney modes and Green modes for zonal wavenumbers 1 and 2 exist simultaneously in the Southern Hemisphere. The Charney modes have the largest amplitude and hence dominate the structure in the troposphere, while the Green modes, whose amplitudes increase dramatically with height, dominate the variance in the stratosphere. Since these two waves are each assumed to be linear and independent of one another, the coherence between them would be zero, as observed.

Which, if any, of these interpretations will prove to be the correct one is open to question. The weight of evidence seems to swing in favor of the third, the multiple linear mode argument, however, since the strong zonality of Southern Hemisphere flows is suggestive of a high degree of linearity, and since *in situ* stratospheric instability of planetary waves appears so unpromising.

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APPENDIX

Space–Time Spectral Analysis

Any function of longitude (λ) and time (t) can be written as a double Fourier expansion

$$X(\lambda, t) = \sum_{k} \sum_{\pm\omega} W_{k,\pm\omega} \cos(k\lambda \pm \omega t + \phi_{k,\pm\omega}), \quad \text{(A1)}$$

where k is the zonal wavenumber, ω the central frequency, ϕ a phase, and plus and minus signs correspond to westward and eastward moving components, respectively.

The space–time power spectrum of the field $X(\lambda, t)$ can be written (Hayashi, 1971) as

$$P_{k,\pm\omega}(X) = \tfrac{1}{2} W_{k,\pm\omega}^2, \quad \text{(A2)}$$

where again the plus sign gives the power in westward moving components and the minus sign that in eastward components at zonal wavenumber k and average over a frequency band centered at frequency ω.

If we have two variables $X(\lambda, t)$ and $X^*(\lambda, t)$ (for example, the height field at different latitude–pressure coordinates), then we can define the cospectra between X and X^* as

$$K_{k,\pm\omega}(X, X^*) = \tfrac{1}{2} W_{k,\pm\omega} W_{k,\pm\omega}^* \cos(\phi_{k,\pm\omega}^* - \phi_{k,\pm\omega}), \quad \text{(A3)}$$

and the quadrature spectra between X and X^* as

$$Q_{k,\pm\omega}(X, X^*) = \tfrac{1}{2} W_{k,\pm\omega} W^*_{k,\pm\omega} \sin(\phi^*_{k,\pm\omega} - \phi_{k,\pm\omega}). \quad \text{(A4)}$$

The coherency (squared coherence) between X and X^* for wavenumber k and frequency $\pm\omega$ is then

$$\mathrm{Coh}^2_{k,\pm\omega}(X, X^*) = \frac{K^2_{k,\pm\omega}(X, X^*) + Q^2_{k,\pm\omega}(X, X^*)}{P_{k,\pm\omega}(X) P_{k,\pm\omega}(X^*)}. \quad \text{(A5)}$$

In practice, the coefficients $W_{k,\pm\omega}$ and phases $\phi_{k,\pm\omega}$ are obtained by first performing a zonal spatial Fourier transform,

$$X(\lambda, t) = \sum_k C_k(t) \cos k\lambda + S_k(t) \sin k\lambda, \quad \text{(A6)}$$

and then performing a time Fourier analysis of the cosine $C_k(t)$ and sine $S_k(t)$ coefficients of the spatial Fourier transform, i.e.,

$$C_k(t) = \sum_\omega A_{k,\omega} \cos\omega t + B_{k,\omega} \sin\omega t, \quad \text{(A7)}$$

$$S_k(t) = \sum_\omega a_{k,\omega} \cos\omega t + b_{k,\omega} \sin\omega t. \quad \text{(A8)}$$

The four coefficients of this last transform, A, B, a and b, can then be related to the coefficients $W_{k,\pm\omega}$ and phases $\phi_{k,\pm\omega}$ through a simple manipulation (Hayashi, 1971).

Coherent westward and eastward moving waves of equal amplitude do not produce two traveling waves but a standing wave whose amplitude oscillates in time. Pratt (1976) and Hayashi (1977) have suggested separating the standing component from the total power spectrum (A2) by defining it as that part of the variance which describes eastward and westward moving components which are coherent with each other. The standing (ST) part of the variance can be related to the coherence between progressive and retrogressive waves which can in turn be related to the cospectra and power spectra in time of the cosine and sine coefficients in (A7) and (A8), i.e.,

$$\mathrm{ST}_{k,\omega}(X) = \{\tfrac{1}{4}[P_\omega(C_k) - P_\omega(S_k)] + K_\omega{}^2(C_k, S_k)\}^{1/2}. \quad \text{(A9)}$$

The traveling (TR) parts are then just the eastward or westward variance minus one-half the standing variance (Hayashi, 1977),

$$\mathrm{TR}_{k,\pm\omega}(X) = P_{k,\pm\omega}(X) - \tfrac{1}{2}\mathrm{ST}_{k,\omega}(X). \quad \text{(A10)}$$

The zonal Fourier expansion of the spatial dependence is straightforward, but in order to explain how the critical coherency was determined, a detailed description of the spectral analysis in time is required. The time spectra were computed using the lag-correlation technique with a maximum lag of 15 and using a Parzen window (Jenkins and Watts, 1968). The frequency bandwidth for 123 daily observations and a maximum lag of 15 days is 0.033 day^{-1}, so that the central frequencies correspond to periods of 30, 15, 10, 7.5, 6, 5, . . . and 2 days. The number of degrees of freedom for each spectral estimate for a sample of length 123 days, treated with a Parzen window and a maximum lag of 15 days, is ~30 (Jenkins and Watts, 1968). For this number of degrees of freedom a coherency $\geqslant 0.3$ is required to reject a null hypothesis of zero coherency at the 99% level, according to the formula favored by Julian (1975).

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