

## Stratospheric Long Waves: Comparison of Thermal Structure in the Northern and Southern Hemispheres<sup>1</sup>

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### ABSTRACT

With the aim of comparing planetary-wave behavior in the Northern and Southern Hemispheres, we have examined stratospheric temperature/thickness data for 1971–72 using Nimbus 4 Selective Chopper Radiometer (SCR) data, National Meteorological Center (NMC) gridded data, and Eole constant-level balloon data. Properties of planetary waves 1 and 2 derived from the SCR and NMC data are shown to agree well. Large-amplitude oscillations with energy in the 20–30 day period range and eastward propagating wave 2 in the Southern Hemisphere have been noted previously and are prominent in these data. Strong vertical coherence in wave phase at all levels between 200 mb and the upper stratosphere is observed. Additional features of interest in this data set include the following: 1) the upper stratosphere in mid-winter appears to satisfy the necessary condition for instability derived by Charney and Stern (1962), especially in the Southern Hemisphere; 2) wave amplification is closely associated with eastward phase propagation; 3) wavenumber 2 amplitude is highly asymmetric with respect to the solstice in both hemispheres and at least in the north the asymmetry is prominent in the upper troposphere as well as the stratosphere; and 4) the meridional extent of the wave amplitude is directly related to zonal wind speed. Some tentative interpretations of these observations are offered.

### 1. Introduction

The relatively homogeneous global coverage of satellite radiance data affords the opportunity for making detailed comparisons between temperature fields in the Northern and Southern Hemispheres. Such comparisons should provide valuable insight into the mechanisms of planetary-scale stratospheric waves. In a sense, the two hemispheres provide a kind of controlled experiment: The geometry, gas properties and radiation environments are essentially the same, but the forcing and the zonal flow upon which the planetary waves are superimposed differ between hemispheres.

The Northern Hemisphere stratosphere has been investigated for many years with the aid of conventional data and rocket data as well as satellite data. It is well-known that the westerly regime of winter is disturbed by planetary waves, predominantly waves 1 and 2; these tend to be quasi-stationary in phase, usually combining to give a stationary anticyclone in the Aleutian sector in the lower stratosphere, but the waves are subject to large amplitude fluctuations. The nature of these fluctuations in the Northern Hemisphere stratosphere as elucidated by a large conventional data set has been studied in detail by van Loon *et al.* (1975) and Madden (1975). In middle or late winter, extreme

wave amplification is commonly associated with reversal of the zonal temperature gradient and wind: this is the well-known “sudden warming” or “major stratospheric warming” phenomenon which has recently been reviewed by Quiroz *et al.* (1975). It is also known that a major cause, and perhaps the sole cause, of the stratospheric waves is forcing from below (Perry, 1967). In a general sense the response of the stratosphere to tropospheric forcing is theoretically understood (Charney and Drazin, 1961; Dickinson, 1968; Matsuno, 1970; Simmons, 1974; Holton, 1975).

The general climatology of the Southern Hemisphere lower stratosphere has been described by Phillpot (1969) who noted eastward propagation of large-scale waves over the Antarctic, and by Labitzke and van Loon (1972) and van Loon and Jenne (1972) who have constructed mean monthly and seasonal charts using conventional data. The winter mean zonal flow in the lower stratosphere is stronger than in the north. Except during the summer, planetary waves 1 and 2 are present, but have slightly lower amplitudes than in the Northern Hemisphere. Warmings of sufficient amplitude to reverse the zonal wind in the lower stratosphere have not been observed. One striking difference between the wave behaviors in the two hemispheres was noted by Deland (1973) on the basis of satellite radiance data. Unlike its quasi-stationary northern counterpart, Southern Hemisphere wavenumber 2 propagates eastward.

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The most detailed studies of Southern Hemisphere stratospheric waves are those of Harwood (1975) and Hartmann (1975), both of whom find the propagating wave 2 during different years. They also find a weaker planetary wave 3 with both stationary and propagating components.

We are puzzled by a number of aspects of the planetary waves. Why are there prominent propagating components in the south but apparently not in the north? What causes the large and long-period fluctuations in wave amplitude? Why is there such marked asymmetry between the relatively undisturbed early northern winter and the highly disturbed late northern winter? Does *in situ* instability play any role in the stratosphere? [The reader is referred to Holton (1975) for a review of this problem.] To investigate such questions, we have analyzed and compared stratospheric radiance and temperature data from both hemispheres during 1971 and 1972. The Southern Hemisphere analysis repeats portions of Harwood's (1975) work but also extends it downward as well as in time. It is complementary to the much more detailed investigation of Hartmann (1975) who used data for 1973.

Three cautions should be kept in mind in considering the interpretations in this paper. First, the analysis deals only with the temperature or thickness field. The geostrophic description of the flow also requires specification of the geopotential field and this will, in general, have a vertical structure different from that of temperature, although we believe that important properties of the waves are revealed by analysis of temperature/thickness alone. Second, the analysis deals with only a single year and it may be atypical; it is certainly atypical in at least one respect—there was no major stratospheric warming below 10 mb in the north. Nevertheless, certain major features, such as traveling waves in the Southern Hemisphere and large-amplitude oscillations, are typical winter features. Indeed, one purpose of the present study is to provide an additional basis for comparing the behavior of such features in different years. Finally, the satellite data cannot reveal features having vertical scales smaller than about two scale heights. This deficiency will hopefully be remedied as results from the infrared limb scanning technique become available (Gille and House, 1971).

## 2. Data treatment and comparisons

The principal data source is the reduced radiance data of the Oxford-Heriot-Watt Selective Chopper Radiometer (SCR) of the Nimbus 4 spacecraft. A compilation of the data for a period of a year [8 May 1971 (day 128) to 8 May 1972 (day 129)] has been published by Oxford University (1972), providing global coverage every 2 days. The data appear in the form of thickness charts for both hemispheres of the 100–10 mb and 10–1 mb layers derived by inversion of the radiance data; the two layers correspond closely to

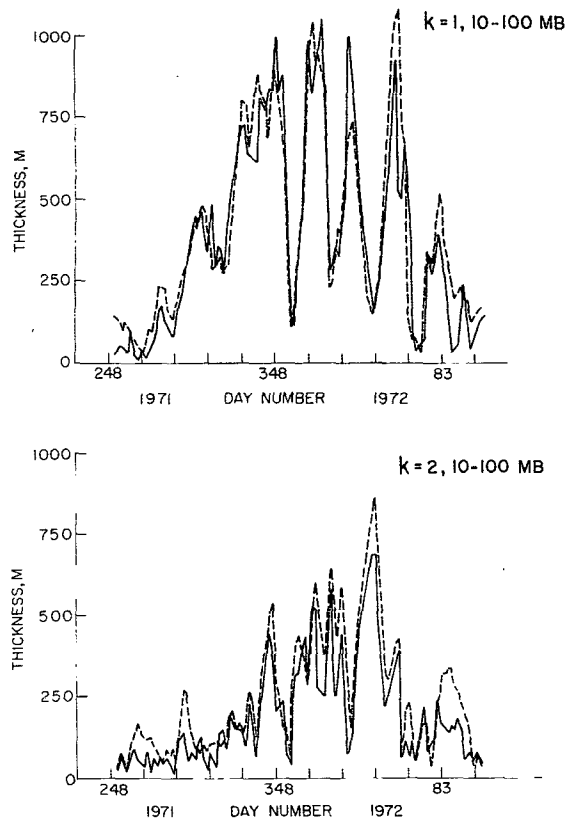


FIG. 1. Comparison between wave 1 and 2 thickness amplitudes derived from SCR data (dashed) and NMC data (solid) for the 100–10 mb layer and 60°N. The 12 hourly NMC data were averaged over 2-day periods for consistency with the SCR data. Note that 1000 m thickness amplitude corresponds closely with 15 K mean temperature amplitude over the layer.

the two uppermost radiance channels (channels A and B).

Data were extracted manually from the charts at latitudes 30°, 45° and 60° for both hemispheres at longitude intervals of 30°. Data gaps were visually interpolated and in this manner a "continuous" data set generated. A longitudinal Fourier decomposition was performed at each latitude and families of Fourier coefficients and phases were generated for wavenumbers 0–6 for each data day.

Four error sources may contaminate a data set derived in the manner described above: 1) instrumentation errors of the radiometer itself such as day-night variability of the instrument, 2) errors involved in the retrieval process in which the radiance data is interpreted as thickness or layer mean temperature, 3) errors involved with the process of interpolation over the data gaps, and 4) errors in data extraction. In order to assess the validity of the original data set in describing the stratospheric long waves and also to gauge the degree of accuracy attained by the method of data treatment, the reduced data fields were compared with similar fields obtained from an independent, although

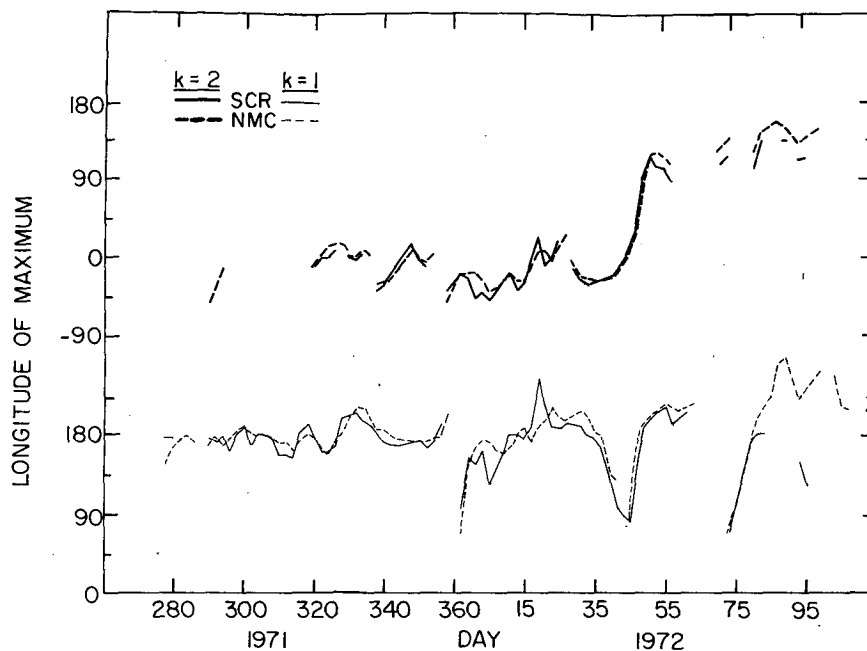


FIG. 2. Phase comparisons corresponding to the amplitudes shown in Fig. 1.

contemporaneous, data set. The comparison was made between the Northern Hemisphere Fourier-analyzed SCR thickness and a corresponding analysis of the gridded National Meteorological Center (NMC) data. Differences between the Fourier components for the two analyses will include the four error sources listed above as well as any errors in the gridded NMC data. Errors in the Fourier components resulting from systematic errors in either data set should show up clearly.

Fig. 1 shows a comparison between the amplitudes of wavenumbers 1 and 2 ( $k=1, 2$ ) as derived from the NMC data and the SCR data for the 10–100 mb layer. Extremely good agreement is obvious for both waves over nearly all the period of observation. Maximum

differences occur in autumn and spring when the amplitudes of the disturbances are small. However, even at these times the shapes of the two curves are similar although the wave amplitude appears a little larger in the SCR data than in the NMC data. Fig. 2 shows a comparison of the phases of the two waves as determined by the two data sets. Some differences in phase appear in wave 1 near the end of the analysis period in late spring. Throughout the rest of the data period the two independent determinations are nearly coincident.

In summary, it would appear that all four error sources are relatively small and that the SCR data do provide an accurate representation of at least the planetary-scale features of the stratosphere. Evidently, the noise level of the data presented here is somewhere between 100 and 150 m (average temperature 1.5–2.3 K). At 60°N, the longitudinal spacing of radiosonde stations is more regular than at other latitudes. Nevertheless, one further result of this comparison is to provide added confidence in the ability of the NMC data to successfully represent the very long stratospheric waves, at least near 60°N.

The third data set used in the study is that resulting from the Eole constant-density balloon experiment (Morel and Bandeen, 1973; Webster and Curtin, 1974, 1975). The Eole data set provides dense coverage of wind velocities and temperature at a constant-density surface closely approximating the 200 mb isobaric surface with maximum sampling occurring in middle and high latitudes. The data period is from September 1971 through June 1972, with maximum number of balloons aloft in October and November and a gradual decline in density of observations occurring during the re-

TABLE 1. Average thickness amplitudes (m) of the first six Fourier harmonics at latitude 60°N and 60°S and 30°N and 30°S for the 100–10 and 10–1 mb layers. Averaging periods were from day 324 (1971) to day 71 (1972) in the Northern Hemisphere and from day 128 to day 228 (1971) in the Southern Hemisphere.

Levels	Latitude	Wavenumber (k)					
		1	2	3	4	5	6
100–10 mb	60°N	643	288	104	91	55	45
	60°S	407	153	61	48	38	32
	30°N	53	41	32	23	18	17
	30°S	57	47	24	20	18	12
10–1 mb	60°N	560	437	139	126	61	50
	60°S	555	225	108	63	55	53
	30°N	192	163	59	51	35	33
	30°S	221	153	69	50	34	30

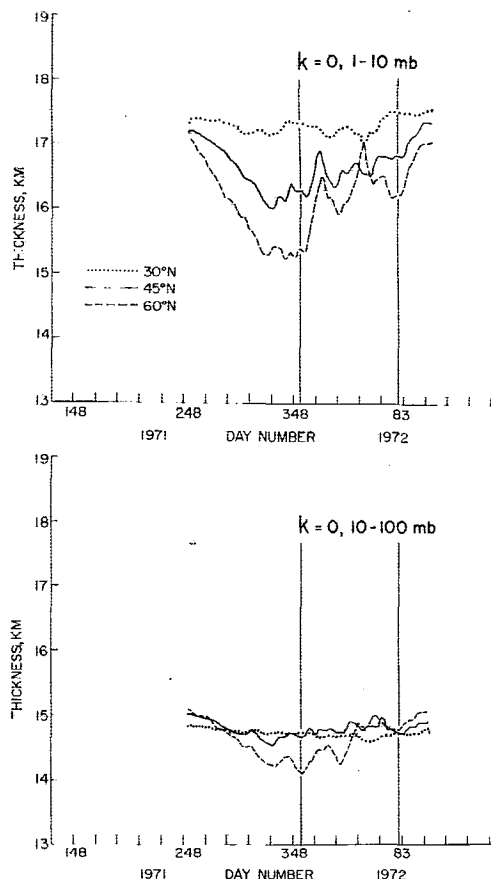


FIG. 3. Zonally averaged thickness, Northern Hemisphere, as given by the SCR data for latitudes 60°N (dashed curve), 45°N (solid curve) and 30°N (dotted curve). Thin vertical lines on this and subsequent figures indicate winter solstice and spring equinox.

mainder of the Eole period. From September through November (Southern Hemisphere spring), the SCR and Eole data sets overlap and show coherence in the vertical both in amplitude and phase (Figs. 11, 14 and 15). The coherence between these two independent data sets adds to our confidence in the use of the SCR data in the Southern Hemisphere, just as the NMC data supported our confidence in the SCR data in the Northern Hemisphere. The generally close correspondence between satellite-derived temperatures and *in situ* temperature measurements averaged over layers of 10–15 km depth have been noted elsewhere (Aanensen, 1973; Finger *et al.*, 1973; Hartmann, 1975). Our comparison verifies the validity of the SCR data in the present application.

### 3. Results

Table 1 shows average amplitudes for the first six Fourier harmonics at 60° and 30° for both hemispheres at the two levels, 100–10 mb and 10–1 mb. The averaging period was from day 324 (1971) to day 71 (1972) in the Northern Hemisphere and from day 128 to day

228 (1971) in the Southern Hemisphere. At 60° in both hemispheres, an amplitude decrease of about a factor of 3 is evident between  $k=2$  and 3 at both levels. A similar amplitude reduction is apparent in the upper layer at 30° but is less obvious in the lower layer. The decrease in temperature amplitude with increasing wavenumber is much more rapid than in the troposphere (see, e.g., Saltzman, 1958). This behavior is consistent with the theory of vertical propagation of planetary waves (Charney and Drazin, 1961; Matsuno, 1970). It should also be noted that the amplitudes for  $k \geq 3$  fall near or below the uncertainty limit determined from the comparisons between the SCR and NMC data sets. Consequently, only the zonal mean,  $k=0$ , and harmonics 1 and 2 will be discussed further.

#### a. Zonal mean fields

Fig. 3 shows the variation of the zonal mean thickness ( $k=0$ ) for the 10–100 mb and 1–10 mb layers of the Northern Hemisphere from day 250 (1971) to day 103 (1972). Considering first the upper level, large variations are apparent throughout the time period. While the thickness remains nearly constant at 30°N, the thickness at higher latitudes is seen to decrease smoothly

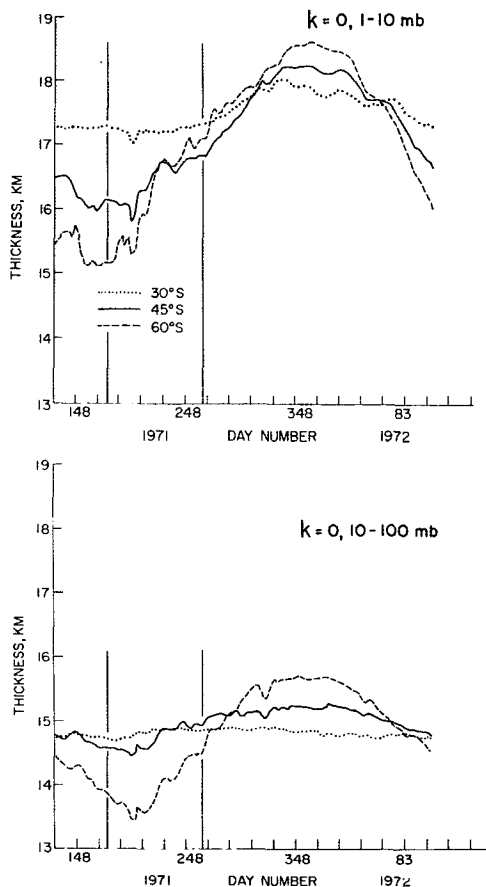


FIG. 4. As in Fig. 3 except for the Southern Hemisphere.

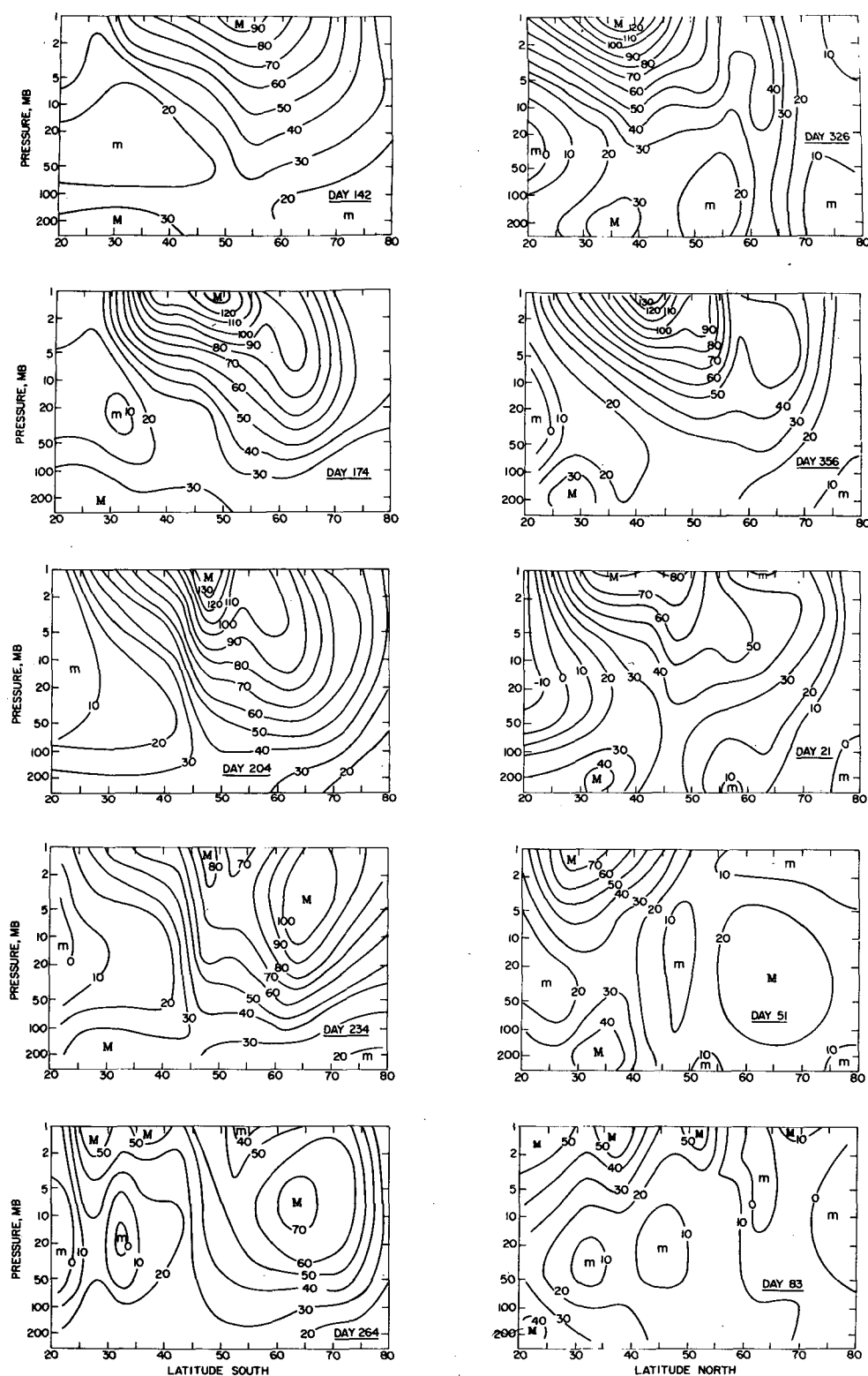


FIG. 5. Zonal wind cross sections ( $\text{m s}^{-1}$ ) derived from SCR data for the Southern Hemisphere during 1971 (left) and the Northern Hemisphere during 1971-72 (right).

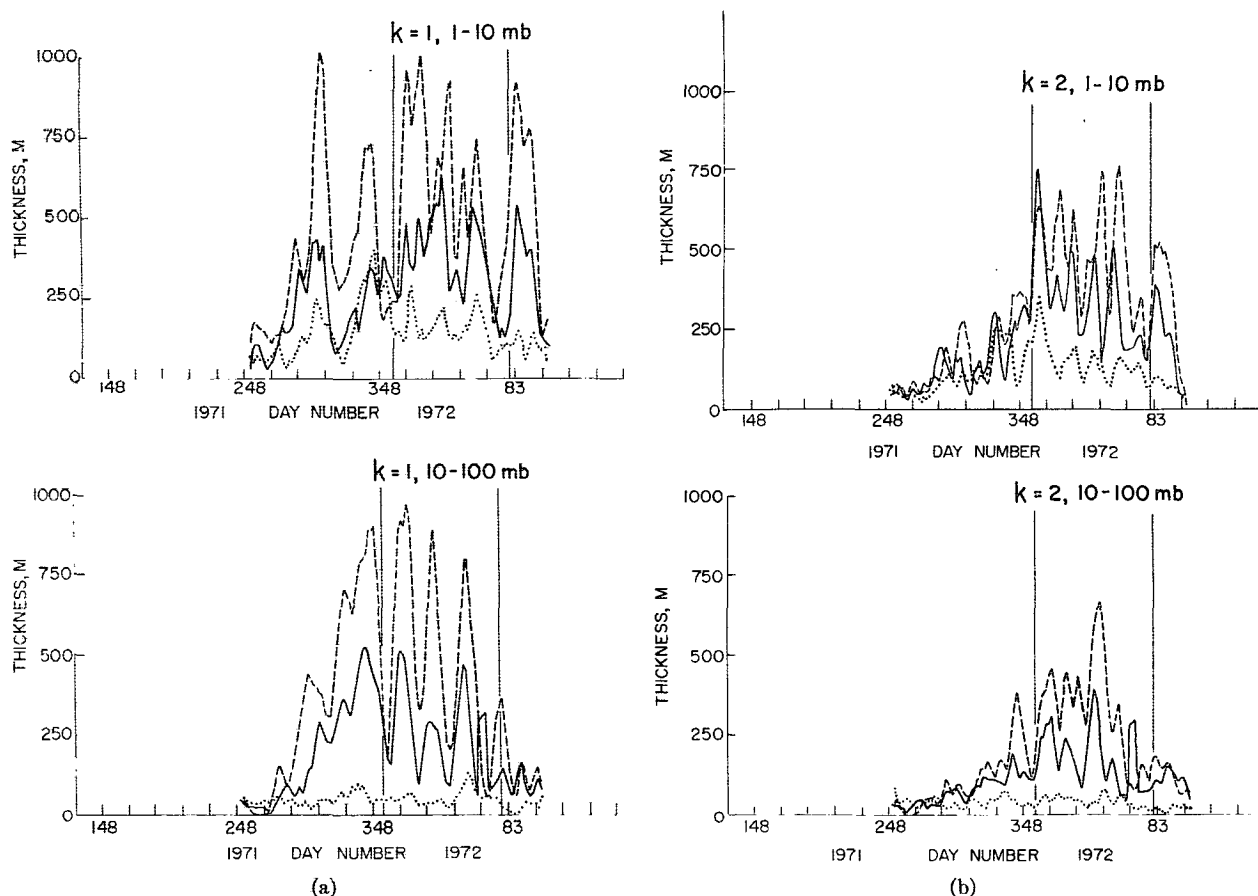


FIG. 6. Northern Hemisphere thickness amplitudes derived from SCR data for latitudes  $60^\circ$ ,  $45^\circ$  and  $30^\circ\text{N}$  designated as in Fig. 3. A 3-point running mean smoother has been applied to the amplitude data. The effect of the smoother can be seen by comparing with the unsmoothed amplitudes in Fig. 1. (a) wave 1, (b) wave 2.

through late fall and early winter and then increase in a more irregular manner from mid-winter through spring. The variation of mean thickness in the lower layer (100–10 mb) follows the same trend but with much smaller amplitude. The maximum thickness difference between  $30^\circ$  and  $60^\circ\text{N}$  in mid-winter is less than 0.5 km ( $\sim 7^\circ\text{C}$ ) compared to 2 km ( $\sim 30^\circ\text{C}$ ) in the upper layer. This general behavior of the northern stratosphere winter temperatures is well known (Adelfang, 1970; Barnett, 1974; Labitzke 1974). During late winter there are two rapid warming events in the 100–10 mb layer at  $60^\circ\text{N}$ . Neither of these satisfies the criterion of Julian (1967) for a major stratospheric warming; that is, the zonal circulation does not reverse direction. The first such event occurs around day 3; the other warming event occurs near day 43 (1972). Both of these events will be referred to later when the behavior of wavenumbers 1 and 2 is discussed.

The zonal mean thickness fields for part of this period in the Southern Hemisphere have been discussed by Harwood (1975). They are displayed in Fig. 4 for the period between day 129 (1971) and day 107 (1972). The period begins during early winter and extends into

the following autumn. The rate of temperature decrease in the fall is almost identical to that in the north at the corresponding seasonal date. This is true at all three latitudes and in both layers. During early winter, up to 20 days before the solstice, mean temperature behaves in a similar way in both layers and in both hemispheres. The temperature decrease begins to level off in the northern 100–10 mb layer before the solstice, but the decrease continues in this layer until after the solstice. In the 10–1 mb layer, southern temperatures remain low longer than in the south, but they rise more regularly and more rapidly in late winter, so that by the spring equinox the horizontal temperature gradient is weaker in the southern upper stratosphere than in the northern. Similar behavior has been noted by Briggs (1965) and Labitzke and Barnett (1973). The irregular temperature rise during northern late winter and spring is characterized by rapid coolings as well as by rapid warmings.

Some zonal mean wind cross sections based on inversions of the SCR radiance data by the Oxford group are shown in Fig. 5. Winds were derived by applying the thermal wind equation to the SCR results, using

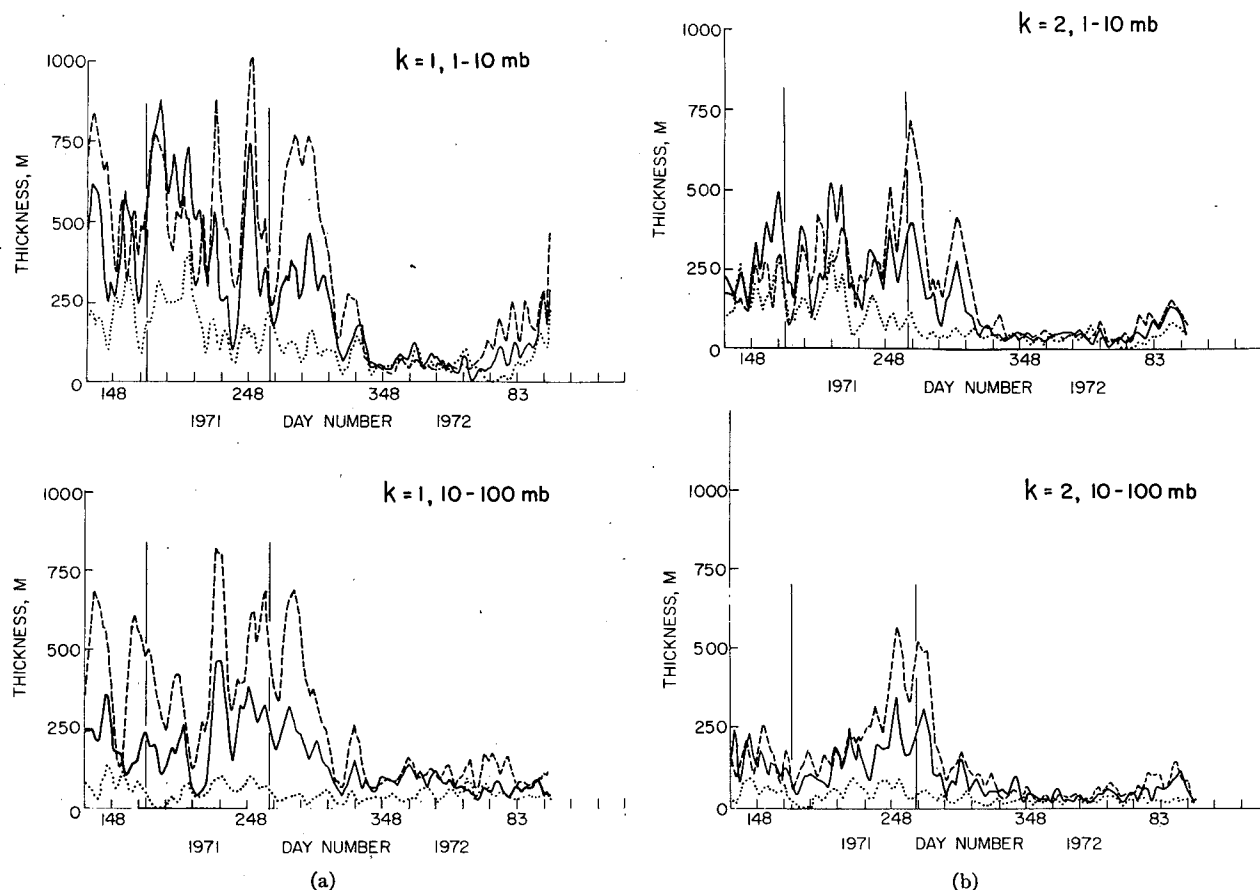


FIG. 7. As in Fig. 6 except for the Southern Hemisphere.

the 200 mb level as a base. Observed geostrophic mean zonal winds from the NMC data set provide the base level data in the north. Except for the last two cross sections, for which Eole data were available, 200 mb climatology had to be used in the Southern Hemisphere. However, Fig. 5 shows that the 200 mb winds make a relatively small contribution to the stratospheric mean zonal winds. Some significant features of these cross sections are the following: 1) during early winter the cross sections are similar in both hemispheres, but the strongest winds are found 5–10° latitude closer to the pole in the south than in the north; 2) during late winter the strongest westerly winds shift downward and poleward and decrease very slowly in the south, while they shift equatorward and possibly upward as well in the north; and 3) based on our calculations of the potential vorticity gradient these winds sometimes appear to satisfy the necessary condition for free jet instability (Charney and Stern, 1962), on the tropical side of the stratospheric jet. This is particularly evident on days 204 and 234 in the south. The potential vorticity gradient changes sign because of the dominance of the horizontal curvature term ( $\partial^2 \bar{u} / \partial y^2$ ) and the relatively small apparent values of the other factors influencing the gradient of zonally averaged potential

vorticity. Thus, if instability arises, we would expect it to be essentially barotropic in character.

#### b. Wave amplitudes

The variation of the amplitudes of wavenumbers 1 and 2 for both the 100–10 mb and 10–1 mb layers are shown for the Northern and Southern Hemispheres in Figs. 6 and 7, respectively. Discussion of the phase properties of the various modes is left to the next section.

Table 1 provides a comparison of the average wave amplitudes between the hemispheres. The amplitude of wavenumber 1 is larger in the Northern Hemisphere in the 100–10 mb layer, but the amplitudes are nearly the same in both hemispheres in the 10–1 mb layer. Wavenumber 2 is more intense at 60°N than it is at 60°S in both layers.

The familiar distinction between disturbed winter conditions and placid summer conditions is clearly shown. The amplitudes in the summer are generally below the 100–150 m noise level. The most striking winter features, common to both hemispheres, are the very large amplitude variations in wave 1 which typically recur at intervals of 20–30 days. These ampli-

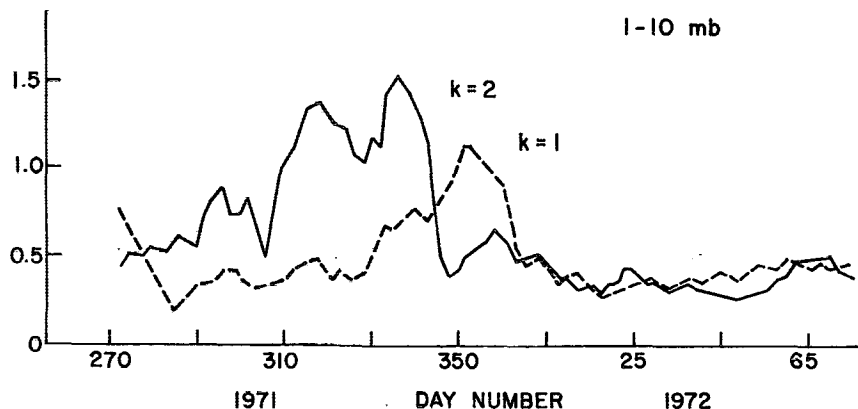


FIG. 8. Ratios of wave amplitude at 30°N to the average of the 45° and 60° amplitudes. A 12-day running mean smoother has been applied.

tude oscillations are particularly regular in the Northern Hemisphere in the 100–10 mb layer. The amplitude variations are coherent both in height and latitude and it will be shown that similar coherence appears in the phase variations. Large-amplitude wave oscillations which are not associated with the meridional temperature reversal of a stratospheric warming have been reported for both hemispheres for other years (Hirota and Sato, 1969; Hirota *et al.*, 1973; Hartmann, 1975). Harwood (1975) has also reported these oscillations in the Southern Hemisphere for this particular season. During the limited period of overlap with the Eole data set the stratospheric variations will be shown to be coherent with the 200 mb oscillations discussed by Webster and Keller (1975). The latter oscillations were seen to persist through summer and into the following winter and were still evident at the end of the Eole experiment.

Maximum amplitudes occur at 60° for both wavenumbers, both layers and both hemispheres (with the exception of Southern Hemisphere wave 2 in the 10–1 mb layer during early winter). This wave has maximum amplitude near 45°. The similarity in meridional amplitude structure in the two hemispheres is surprising in view of the differences in zonal winds shown in Fig. 5 and the strong dependence of amplitude on zonal wind structure indicated by theory (Dickinson, 1968; Simmons, 1974). The amplitudes shown are for predominantly stationary waves in the north but it will be shown in the next section that wave 2 in the south is predominantly transient. A noteworthy feature is the decrease in equatorward extent of the disturbances in the 10–1 mb layer which occurs near day 210 in the Southern Hemisphere and between days 350 and 365 in the Northern Hemisphere. This is illustrated by the sharp drop in the ratio of the amplitude at 30° to amplitudes at 45° and 60° in the Northern Hemisphere shown in Fig. 8. The structure change appears in both wavenumbers. The timing of these changes in structure coincides with marked weakening of the mean zonal flow, especially equatorward of 60° and above the 20 mb

level. This can be seen by noting the periods of rapid weakening of the horizontal temperature gradient in Figs. 3 and 4 and the changes in zonal flow in Fig. 5.

Another feature worth noting is the seasonal asymmetry in the waves. Amplitudes of wave 1 are generally only slightly asymmetric with respect to the winter solstice in the north with a slight shift in maximum activity toward spring. Lack of data during the 1971 southern fall makes it difficult to compare this Northern Hemisphere behavior with that of wave 1 in the Southern Hemisphere but the increasing activity after day 83 (1972) in the 10–1 mb layer suggests near symmetry in the south as well. In sharp contrast, wave 2 is highly asymmetric with respect to the solstice in both layers and in both hemispheres. It is very weak in early winter but activity grows over the winter and peaks during spring. We shall return to this point when considering the relationship between stratospheric and tropospheric behavior.

### c. Phase variations

Fig. 9 illustrates phase variations of the Northern Hemisphere modes. Although the waves tend in general to be quasi-stationary, there are fluctuations in phase. Two periods of rapid eastward phase propagation are evident, one centered near day 265, the other near day 42. For wavenumber 1, these are most marked in the 10–100 mb layer. For wavenumber 2, the first of these is evident at 200 mb, the second is most evident in the 10–100 mb layer. Fig. 10 shows that the propagation in wavenumber 1 is even more evident at 200 mb than in the stratosphere and also shows a third period of rapid eastward propagation at 200 mb centered near day 17. Inspection of Fig. 6a shows that these three periods coincide with the onset of three very large mid-winter amplifications of wave 1 which occur in both stratospheric layers but are most regular in the 100–10 mb layer. The first and third of these events also coincide with the two rapid zonally averaged warmings at 60°N which were noted earlier.

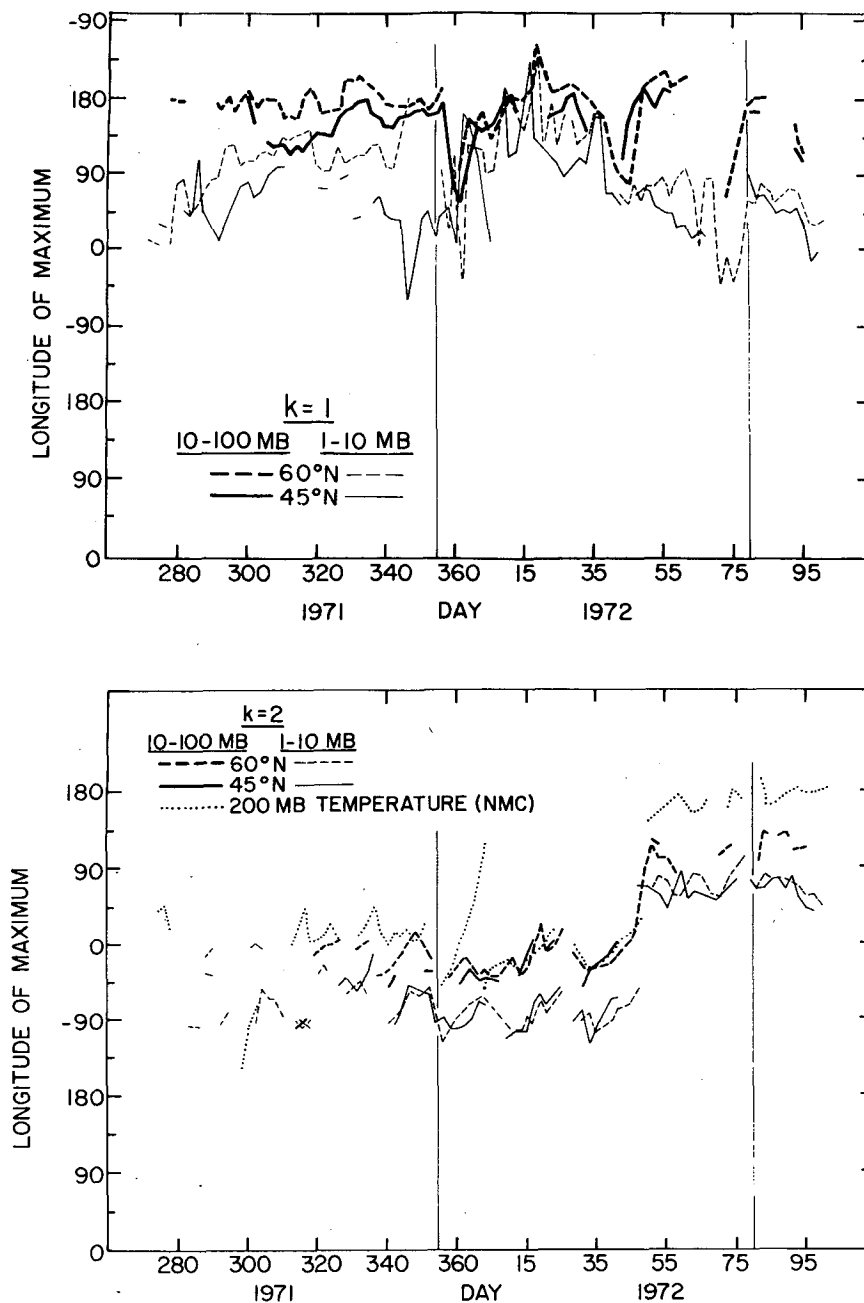


FIG. 9. Northern Hemisphere phases (longitude of thickness maximum). Top: wave 1, bottom: wave 2. Only one of the two wave 2 maxima is shown. Phases are not shown for amplitudes below 150 m.

Figs. 9 and 10 also illustrate the phase relationships between temperature/thickness at different heights and latitudes. Wave 2 shows a consistent westward tilt in the vertical, with the thermal ridge displaced about  $60^\circ$  farther west in the 10–1 mb layer than in the 100–10 mb layer, although there is no evidence for a consistent phase shift with latitude. During the early winter there is also a westward tilt with height of wave 1 averaging about  $80^\circ$  between the two layers. There is also a sub-

stantial phase shift with latitude, the wave tilting eastward with latitude in both layers. During the rapid propagation period on day 265 the horizontal and vertical phase shifts decrease to very small values and they remain small until after day 42. After day 42, the latitudinal phase shift remains small, but vertical phase shift increases to about  $180^\circ$ . These phase and amplitude relationships appear consistent with the results of van Loon *et al.* (1975) and Madden (1975) performed

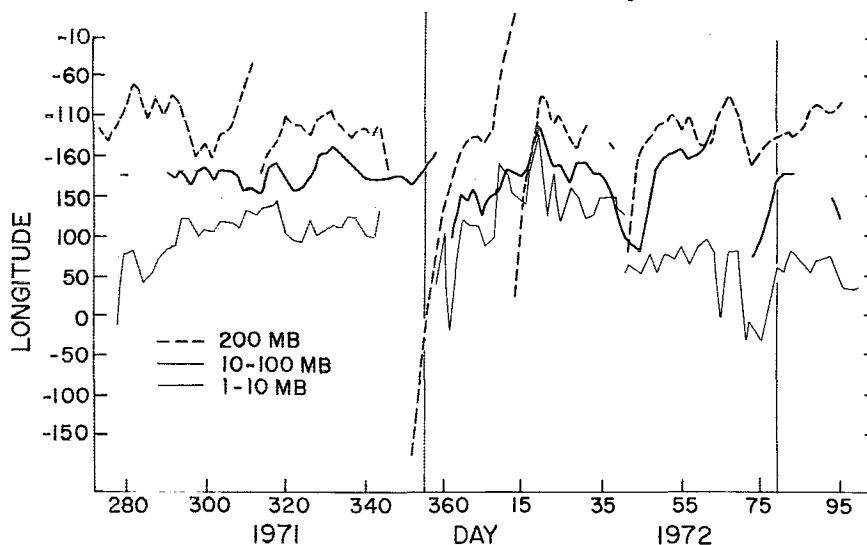


FIG. 10. Northern Hemisphere wave 1 stratospheric thickness phases compared with 200 mb temperature phases (NMC). Longitude of maximum is shown. Phases are not plotted for thickness amplitudes below 150 m or temperature amplitudes less than 5.5°C.

using long series of Northern Hemisphere conventional data. Of particular interest is the preference for similar long-period oscillations in the long waves.

In the south, wave 1 generally tends to remain quasi-stationary, but there are three periods of rapid eastward propagation centered near days 162, 220 and 243 (Fig. 11). Inspection of Fig. 7a shows that these immediately precede major wave 1 amplitude peaks occurring near days 175, 228 and 250. Except during these propagation periods, there is a consistent westward tilt of the wave of about  $150^\circ$  between the two stratospheric layers which is larger than that in the north. The latitude phase shift is small, but during the early winter it is consistently eastward with increasing latitude, as in the north. Wave 2 shows an eastward phase progression, averaging about  $15^\circ \text{ day}^{-1}$  (phase speed  $\sim 10 \text{ m s}^{-1}$  at  $60^\circ$ ). This has been documented by Harwood (1975), and it was observed in other years by Deland (1973) and Hartmann (1975). There is a consistent westward tilt of about  $60^\circ$  between the two stratospheric layers. Both stratospheric waves are coherent with the corresponding 200 mb Eole temperature waves, and the westward tilt continues down to the 200 mb level, although magnitude of the tilt is much smaller below the 100–10 mb layer for wave 1. These data do not show a clear indication of a latitude phase shift of wave 2 in the Southern Hemisphere.

#### d. Coherence between stratosphere and troposphere

The time-longitude sections (Figs. 12–15) illustrate the amplitude/phase relationships between the 200 mb level and the stratospheric layers at latitude  $60^\circ$ . Northern Hemisphere wave 1 shows only a weak relationship between temperature amplification at 200 mb and temperature amplification in the stratosphere (Fig. 12). The correspondence between the stratospheric amplitude peak occurring just after day 365

and the period of rapid eastward phase progression at 200 mb is evident. Note that there is no amplitude peak at 200 mb at this time. The correlation between strato-

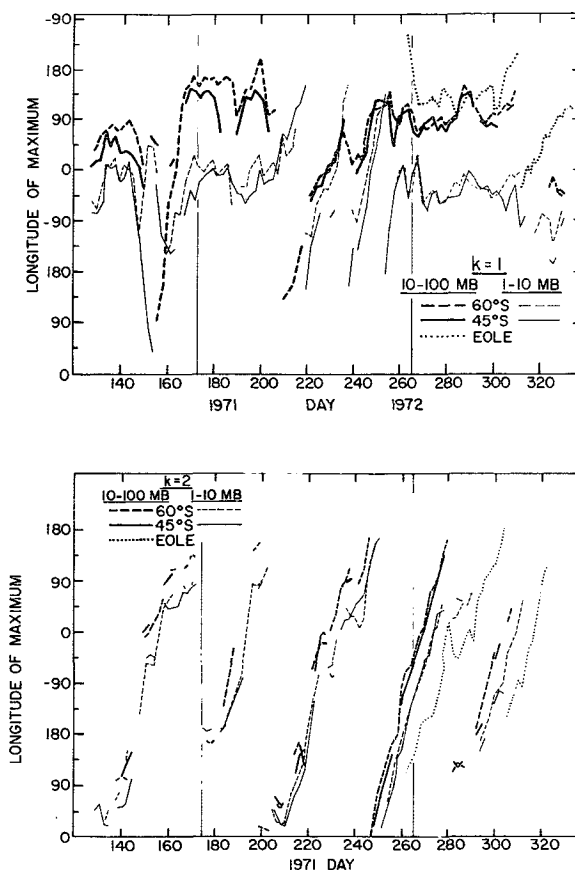


FIG. 11. Southern Hemisphere thickness phases and Eole temperature phases (longitude of maximum). Only one of the two wave 2 maxima is plotted. Thickness phases are not plotted for amplitudes below 150 m. Top: wave 1, bottom: wave 2.

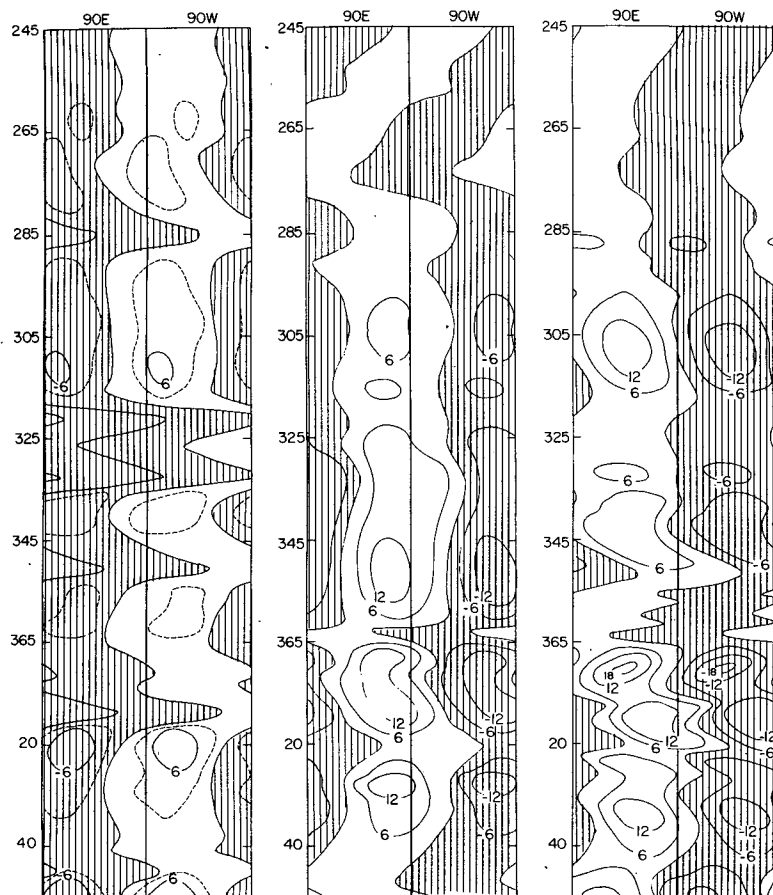


FIG. 12. Northern Hemisphere wave 1 longitude-time section at 60°N. Longitude 180° runs down the center of each panel. Left: 200 mb temperature, °C (NMC); center: 100–10 mb thickness, hundreds of meters (SCR); right: 10–1 mb thickness, hundreds of meters (SCR).

spheric and tropospheric amplitudes is much more striking for wave 2 (Fig. 13). In particular, the seasonal asymmetry in stratospheric amplitudes is also very marked at 200 mb. Fig. 13 reveals another interesting feature: there is a tendency at all levels for winter wave 2 amplitude maxima to occur during periods of eastward phase progression.

In the south, the short period of overlapping data gives only a hint that 200 mb wave 1 amplitude is well correlated with stratospheric wave 1 amplitude (Fig. 14). The most interesting feature here is the correspondence between strong wave intensification occurring with eastward phase progression in the 10–1 mb layer on two occasions. These periods of amplification coincide with the amplitude maxima which we have already noted on days 228 and 250. The longitude-time section for wave 2 (Fig. 15) shows that periods of maximum amplitude coincide with the most clearly defined eastward phase progression. There is strong correspondence between wave 2 amplitude maxima at 200 mb and those in the stratosphere, particularly those in the 10–1 mb layer.

#### 4. Interpretations

The results presented here confirm many of the features of winter stratospheric disturbances which have been discussed before in the literature. The large-amplitude oscillations in the 20–30 day period range and the eastward propagating southern wave 2 are especially noteworthy. Returning to the questions raised in the introduction, we single out four features of the data for particular discussion. Again, note that inferences should be treated with particular caution because only temperature/thickness data have been analyzed.

- 1). DESPITE STATIONARY FORCING, EASTWARD PHASE PROGRESSION OCCURS FOR WAVE 2 IN THE SOUTH, AND DURING THE AMPLIFICATION PHASE OF WAVE 1 IN BOTH HEMISPHERES.

The regular eastward phase progression of wave 2 in the Southern Hemisphere, despite presumably stationary forcing, is strongly suggestive of normal mode re-

sponse. Geisler and Dickinson (1975) have explored normal modes for cases having vertical shear but without horizontal shear of the mean wind. They find, in addition to the counterpart of the neutral Rossby wave, several baroclinically unstable modes which derive their energy from the horizontal temperature gradient near the lower boundary. The lowest of these decays rapidly with height above the troposphere. This was the mode first investigated by Charney (1947). They also find higher modes with one or more modes in the vertical which become possible because of reflection by the strong winds of the upper stratosphere.

The identification of the cause of the propagating component of wave 1 is more tenuous. It is significant that phase propagation occurs during periods of amplitude growth. Geisler (1974) and Simmons (1974) have found eastward propagation during the amplification phase of stratospheric waves produced by switch-on of stationary forcing from below. Trenberth (1973a, b), Hirota (1971) and Geisler (1974) have investigated models in which large-amplitude oscillations arise as a result of interactions between standing and transient wave components. Hirota's model is particularly interesting in this regard. Amplitude oscillations arise from

interaction between a standing wave and a westward propagating wave forced by periodic variations in the tropospheric zonal wind. Webster and Keller (1975) have reported such quasi-periodic variations of 200 mb Southern Hemisphere zonal wind and have related them to periodic variations in the meridional flux of zonal momentum. The present analysis suggests that the models of Trenberth, Hirota and Geisler may be close to the truth.

## 2) THE UPPER STRATOSPHERE IN MID-WINTER CONTAINS REGIONS OF APPARENT BAROTROPIC INSTABILITY, ESPECIALLY IN THE SOUTH.

This is a rather unexpected finding, and it will be of interest to see whether barotropically unstable mean zonal flow appears in other years and in other data. We have identified no effects that can clearly be attributed to barotropic instability, but this may be due to limitations of vertical and/or horizontal resolution in these data. The indications that the meridional tilt of wave 1 does change as the wave goes through its amplification and decay cycle (Figs. 9 and 11) are suggestive of an important role for barotropic energy exchange between the mean zonal flow and wave 1, however.

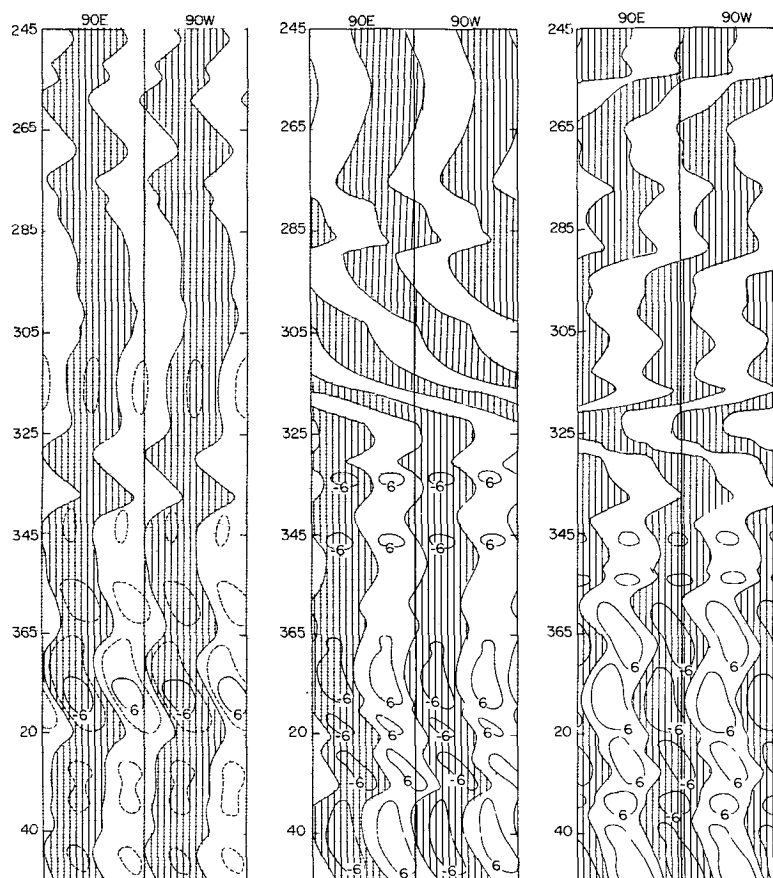


FIG. 13. As in Fig. 11 except for Northern Hemisphere wave 2.

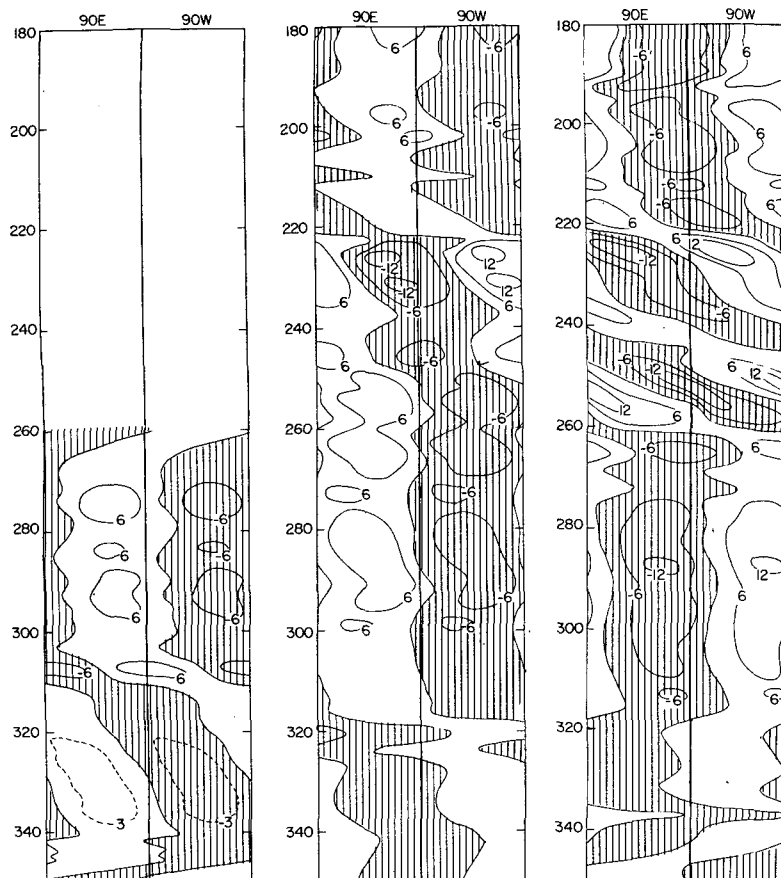


FIG. 14. Southern Hemisphere wave 1 longitude-time section at 60°S. Longitude 180° runs down the center of each panel. Units as in Fig. 11. Left: 200 mb temperature, °C (Eole); center: 100-10 mb thickness (SCR); right: 10-1 mb thickness (SCR).

- 3) WAVENUMBER 2 AMPLITUDES GROW FROM VERY LOW VALUES IN EARLY WINTER TO HIGH VALUES IN LATE WINTER.

This is true in both hemispheres, and accounts for the major part of the asymmetry with respect to the solstice of the disturbed character of the stratospheric flow in this particular year. At least in the north, the seasonal growth of wave 2 is closely related to seasonal growth of wave 2 in the troposphere. Evidently this seasonal asymmetry is due either to seasonal variation in wave 2 forcing, which we assume originates in the troposphere, or to changes in the response characteristics of the stratosphere. To the extent that wave 2 represents normal mode response, the latter mechanism is indicated, but an implication of that conclusion is that stratospheric response characteristics strongly influence waves at 200 mb.

- 4) THE MERIDIONAL AMPLITUDE STRUCTURE IS SIMILAR IN THE UPPER STRATOSPHERE IN BOTH HEMISPHERES, AND THE EQUATORWARD EXTENT OF WAVES IS DIRECTLY RELATED TO ZONAL WIND SPEED IN THE UPPER STRATOSPHERE.

The latter effect could again be due to the response characteristics of the stratosphere for non-dissipative

waves. Alternatively, it could be a consequence of photochemically accelerated radiative damping which has an increasingly dissipative affect on planetary waves as the Doppler-shifted wave frequency decreases (Dickinson, 1969; Holton, 1975). Since the meridional wave amplitude structure is very similar in both hemispheres, despite differences in the zonal winds and differences between stationary waves in the north and transient waves in the south, we believe that photochemically accelerated radiative damping may be the more important factor.

In emphasizing such possible processes as normal mode response, instability and photochemically accelerated radiative damping, we do not mean to imply that forcing from the troposphere is not important. Indeed, there is abundant evidence that it is the dominant cause of stratospheric disturbances much of the time. Nevertheless, this analysis suggests that other mechanisms may also be important. Answers to this question will require detailed analysis of the geopotential structure as well as analysis of the energetics along the lines of the analyses of Perry (1967) and Hartmann (1975), but for more extensive periods.

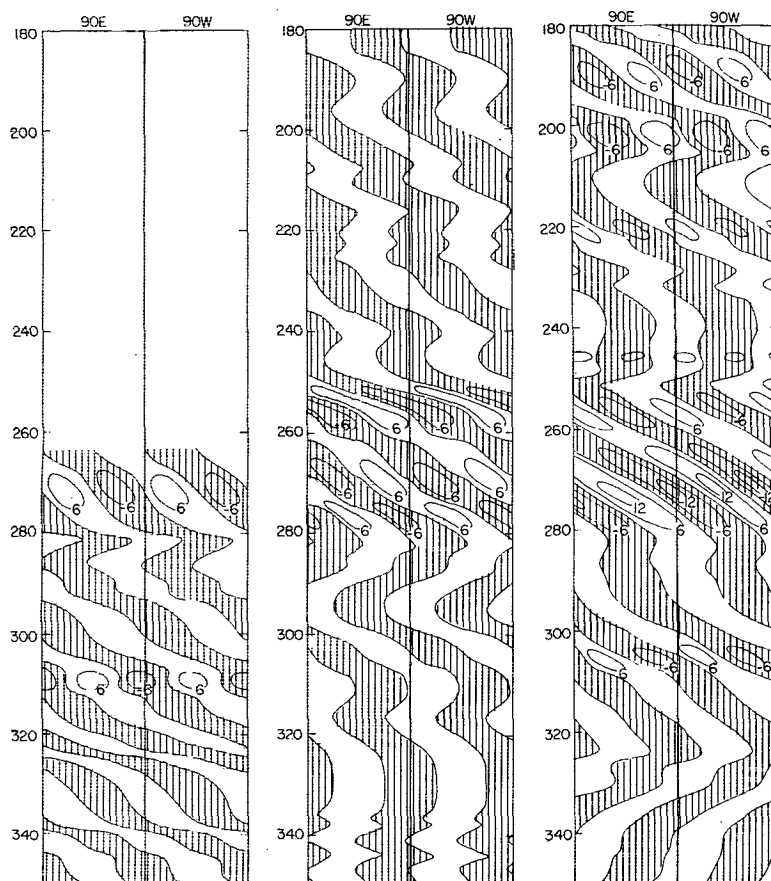


FIG. 15. As in Fig. 14 except for Southern Hemisphere wave 2.

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