Seasonal variation of planetary waves in the stratosphere observed by the Nimbus 5 SCR

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SUMMARY

The structure and behaviour of planetary-scale temperature waves in the stratosphere are described by the use of observations from the Selective Chopper Radiometer on the Nimbus 5 satellite during the two years from January 1973 to December 1974.

From a latitude–height diagram of monthly root-mean-square wave amplitudes, it is found that the planetary wave of wavenumber one is predominant in the upper stratosphere at middle and high latitudes throughout the year for both hemispheres. Waves of higher wavenumbers are rather weak in the summer hemisphere.

Power spectral analysis of monthly r.m.s. wave amplitude for 24 months shows that the 12-month period oscillation is prominent in middle and higher latitudes, while a 6-month periodicity is observed in tropical latitudes for wavenumber one. The phase of maximum of the 6-month cycle is about one month after the equinoxes, suggesting that planetary wave activity in lower latitudes is closely related to the semiannual oscillation of the equatorial zonal current in the upper stratosphere.

Further analyses are made of seasonal characteristics of ‘transient’ waves to find the relationship between the wave motion and the mean zonal wind velocity. The predominant period (or phase velocity) is determined by a power spectral analysis using the Doppler effect due to the east–west motion of waves. With wavenumber one in the upper stratosphere, a 15- to 20-day period standing oscillation is observed in wintertime, while a 10-day period westward moving wave is found in the summer hemisphere. During the spring and autumn, a standing oscillation with a period of about 3 weeks can be seen together with an 8- to 10-day period westward motion. Higher wavenumbers show eastward motion in winter and no significant periodicity is found in other seasons as the wave activity is weak.

These characteristic features of transient waves are explained by the theory of critical line absorption for vertical wave propagation through the mean zonal wind.

1. INTRODUCTION

Recent progress in meteorological satellite instrumentation has allowed the large-scale aspects of the stratospheric circulation, especially its thermal structure, to be investigated by means of satellite infrared radiation measurements. Among these instruments the Selective Chopper Radiometers (SCR) on Nimbus 4 and 5 have brought us a great deal of information about the temperature field up to the lower mesosphere, with near global coverage. For example, using SCR data, Barnett et al. (1971, 1972, 1973) Harwood (1975) and Barnett (1975a) studied the wintertime upper stratospheric circulation, with special emphasis on the sudden warming phenomenon associated with the vertical propagation of planetary waves through the polar-night westerlies. These studies were extensions of those for the middle and lower stratosphere based upon conventional radiosonde observations and the early satellite measurements such as those from the Nimbus SIRS (Satellite Infra-Red Spectrometer). Using continuous global observations for longer periods, further studies have described not only the circulation of winter but also of other seasons (Barnett 1974; Chapman et al. 1974; Hirota 1975) and the hemispheric coupling (Barnett 1975b).

As regards the dynamics of planetary-scale disturbances in the stratosphere and mesosphere, however, attention has been focused mainly on the stationary forced Rossby waves in the polar-night westerlies, after the pioneering theoretical work of Charney and Drazin.

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(1961) and Eliassen and Palm (1961): only a few investigations have been made into the behaviour of planetary waves in the summer, spring and autumn.

The dynamical characteristics of planetary waves in the upper atmosphere are strongly affected by the mean zonal wind distribution, so the remarkable seasonal variation in their structure and behaviour is almost certainly in response to the mean zonal wind variation in the stratosphere. It has also been conjectured that the planetary wave systems in the two hemispheres may couple near the equinoxes with wave activity in the tropics. It will therefore be interesting to investigate the half-yearly oscillation of the equatorial upper stratosphere from a viewpoint of the seasonal variation of planetary waves.

Thus the main purpose of the present study is to give a description of planetary wave activities in the upper stratosphere throughout the year with the aid of Nimbus SCR radiance observations. In the first half of this paper, the vertical and horizontal structure of radiance temperature waves and their seasonal variations are discussed, based upon monthly average values. In the second half, an analysis is made of the time-dependent behaviour of transient planetary waves to give the relationship between the wave motion and the mean zonal wind velocity for all seasons and latitudes. Discussions will be extended to account for observed features from theoretical consideration of the planetary wave dynamics.

No special attention is paid to long-term variations of the atmospheric circulation, such as the quasi-biennial oscillation, nor to differences between the two hemispheres.

2. Data

The Nimbus 5 SCR radiance data are used in this study for the period of two years from 1 January 1973 to 31 December 1974. Fourier components of radiance around latitude circles were available on a daily basis, from the analysis of gridpoint values (every 10° in longitude) with zonal linear interpolation across small gaps. The lowest three zonal wavenumbers are subject to this analysis since we are interested in planetary-scale phenomena.

The weighting functions of the Nimbus 5 SCR channels are described by Ellis et al. (1973) and the comparison of their data with radiosonde and rocketsonde data is made by Barnett et al. (1975). The measurements from the top channel (B12), which represent the atmospheric temperature field of a layer just below the stratopause (weighting function peaks at 1.5 mb ≈ 43 km) are mainly used, together with the additional use of channels B34, B4 and A2, peaking approximately at 8 mb (33 km), 32 mb (21 km), and 51 mb (17 km). North–south coverage is from 80°N to 80°S and values have been taken at 8° latitude intervals.

Days of missing data, although very rare, were excluded from the monthly mean computation and values were obtained by linear interpolation for the daily analysis.

3. Monthly-mean waves

In order to see the vertical and latitudinal distribution of planetary waves in the stratosphere, we define the monthly averaged value of wave amplitude in the following way: suppose $A_m$ is a radiance wave amplitude obtained from the Fourier analysis as a function of latitude, channel, wavenumber and day, i.e. $A_m = A_m^L (\text{Lat.}, \text{Ch.}, \text{WN}; \text{day})$. Then the 30-day average of the wave amplitude is defined as

$$\bar{A} (\text{Lat.}, \text{Ch.}, \text{WN}) = \left\{ \frac{30}{\sum_{\text{day}=1}} A_m^2/30 \right\}^{1/2}$$

for every calendar month beginning the first day of the month.

This is a measure of planetary wave activity, and hereafter we call it monthly r.m.s.
Figure 1. Meridional distribution of monthly r.m.s. wave amplitude $A$ of wavenumber one for (a) January, (b) April, (c) July and (d) October 1973. Broken lines indicate the maximum. Units are the radiance unit $(\text{W} \cdot \text{m}^{-2} \cdot \text{ster}^{-1} \cdot \text{cm}^{-1})^{-1}$. 
wave amplitude. Note that the wave amplitude thus defined includes both the 'standing wave' and 'transient wave' components.

Fig. 1 shows the meridional distribution of the monthly r.m.s. wave amplitude $\tilde{A}$ of wavenumber 1 for four typical months of 1973. The unit used for wave amplitude is a radiance unit which is almost equivalent to an interval of one degree Kelvin.

In the winter stratosphere (northern hemisphere in Fig. 1(a) and southern hemisphere in Fig. 1(c)), a large wave amplitude is observed around 60° latitude, the value in the northern hemisphere being larger than that in the southern hemisphere. On the other hand, in the summer stratosphere, where the zonal easterly wind is predominant, another maximum of amplitude is observed in the middle latitude, though the magnitude itself is very small compared with that in the winter hemisphere, as was pointed out in a previous study of Hirota (1975). It is of interest to note that for July (Fig. 1(c)) the maximum of wave amplitude in the northern hemisphere seems to have its origin in the subtropical troposphere, reflecting the Southwest Indian monsoon.

Wave amplitudes in spring and autumn (Fig. 1(b) and (d)) show an almost symmetric distribution with respect to the equator, the maxima in both hemispheres being located also around 60° latitude.

Throughout the period of analysis the minimum wave activity is observed in the equatorial lower stratosphere. This may be partly because the vertical wavelength of equatorial waves in the lower stratosphere is too small for them to be detected by the SCR.

The meridional distribution of monthly r.m.s. wave amplitude for wavenumbers 2 and 3 shows similar features to those of wavenumber 1, except for the summertime stratosphere, where no marked maximum of wave activity is observed.

The magnitude of each wave in middle latitudes is summarized in Table 1, where the average is taken over 2 years for both hemispheres with respect to three latitude circles 40°, 48° and 56°. Winter denotes the months from December to February in the northern hemisphere and from June to August in the southern hemisphere and so on. Figures in parentheses are ratios between channels B12 and B4.

| TABLE 1. AVERAGED WAVE AMPLITUDE OF CHANNELS B12 AND B4 OVER 2 YEARS (1973–74) FOR MIDDLE LATITUDES (40°–56°) |
|---------------------------------------------------------------|---|---|---|
| Wavenumber | 1 | 2 | 3 |
| Season |
| Winter |
| B12 | 6.3 (2.0) | 4.5 (2.2) | 1.9 (2.0) |
| B4 | 3.1 | 2.1 | 0.9 |
| Spring and autumn |
| B12 | 3.7 (1.8) | 2.1 (1.9) | 0.9 (1.4) |
| B4 | 2.1 | 1.1 | 0.7 |
| Summer |
| B12 | 1.1 (1.7) | 0.5 (1.1) | 0.4 (1.0) |
| B4 | 0.6 | 0.5 | 0.4 |

In general, the wave amplitude decreases with increasing wavenumber. The amplitude in summer is about 1/5 to 1/10 of that in winter. It should be noted, however, that the wave amplitude is reduced by the limitation of the SCR technique when the vertical wavelength is small, because the single channel radiance represents the average temperature of an atmospheric layer with a considerable depth. Hence the wave amplitude may be somewhat modified for each wavenumber after the estimate of their vertical wavelengths.

It is interesting to compare the amplitude ratio between the upper and lower stratosphere with that obtained from a simple theoretical consideration. If we assume that the
wave energy remains constant with height, the ratio of wave amplitude between the two levels \( Z_1 \) and \( Z_2 \) must be given by \( r \approx \exp[(Z_1 - Z_2)/2H] \), where \( H \) denotes the scale height of the atmosphere. Assuming that \( H \approx 7 \text{km} \) in the stratosphere, \( Z_1 = 43 \text{km} \) and \( Z_2 = 21 \text{km} \), corresponding to the peaks of weighting function of SCR channel B12 and B4, we have a value of \( r \) about 4.5. The observed ratios are less than half of this value, even in winter, indicating that the wave energy is not conserved in the vertical but reflected, refracted or absorbed somewhere in the stratosphere. This may be associated with the vertical and horizontal variation of the mean zonal wind (Dickinson 1968; Matsuno 1970; Simmons 1974).

As was noted before, the wave amplitude shown in Fig. 1 and Table 1 includes both standing and transient wave components. To see the magnitude of the former only, we define the standing wave amplitude as \( A_s \) (Lat., Ch., WN) from the 30-day average of Fourier coefficients themselves, since the transient wave components whose characteristic time-scale is usually less than one month can be almost removed by this procedure. The ratio of the standing wave amplitude to the monthly mean (total) r.m.s. wave amplitude, i.e., \( R = A_s/A \), is a measure of relative activity of the different wave types. \( R = 1 \) for a perfectly standing wave, while \( 0 < R \ll 1 \) indicates that the wave is almost completely transient.

Table 2 gives \( R \) for channel B12 averaged as in Table 1.

<table>
<thead>
<tr>
<th>Season</th>
<th>Wavenumber</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td></td>
<td>0.63</td>
<td>0.42</td>
<td>0.27</td>
</tr>
<tr>
<td>Spring and autumn</td>
<td></td>
<td>0.56</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Summer</td>
<td></td>
<td>0.24</td>
<td>0.25</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Thus the standing wave component of wavenumber one is predominant in winter, spring and autumn, when the mean zonal wind in the mid-latitude stratosphere is westerly, while most waves are transient in the summer easterly current.

In order to see the three dimensional structure of planetary waves on a monthly basis, an analysis is made of the latitudinal distribution of phase angle for the three channels B12, B34 and B4. It should be noted, however, that the geographical location of the monthly mean phase angle cannot be defined with respect to waves including both standing and transient components. Instead we compute the monthly mean of daily values for the phase angle relative to an arbitrary reference value, in this case the phase angle of the channel B12 component on the equator.

The result of such an analysis for wavenumber one for four typical months in 1973 is shown in Fig. 2. It is found in general that the wave axis is tilted westward with height, except in the tropics. A strong westward tilt in the vertical is observed in middle latitudes of the northern hemisphere in January and of the southern hemisphere in October, where the vertical wavelength is approximately 60 km. Another interesting feature of the phase angle distribution is the westward tilt with decreasing latitude, which indicates a poleward transport of eddy momentum and, in turn, an equatorward energy flux in the relative westerly current, in as far as the temperature wave is representative of the geopotential height wave in a geostrophic motion. This is seen in winter and spring of both hemispheres and a tendency to penetrate into the opposite hemisphere can be observed in spring, in good agreement with
Figure 2. Latitudinal distribution of the monthly mean phase angle for wavenumber 1, channel B12 (solid line), B34 (broken line) and B4 (dotted line) relative to B12 phase at the equator.

Figure 3. Latitude-time diagram of (a) monthly r.m.s. wave amplitude and (b) the ratio of standing wave to r.m.s. amplitude for wavenumber 1 at Ch.B12.
the evidence of hemispheric coupling pointed out by Barnett (1975b) based on the standing wave statistics.

Similar features can be seen for wavenumber 2, except that the phase inclination with height and latitude is rather small compared with that of wavenumber one.

4. Annual and semiannual variations of wave amplitude

As was mentioned in the previous section, planetary wave activity shows a notable seasonal variation. It may be conjectured from Table 1 that the monthly mean wave amplitude shows an annual cycle (12-month oscillation) in middle and high latitudes with its maximum in winter. Conversely, in tropical latitudes, there appears to be an effect from middle latitudes twice a year, during the winter-to-spring period of each hemisphere, since Fig. 2 shows rapid phase variations across the equator at these times. This may cause a six-month variation of wave amplitude in the equatorial region. It is, therefore, interesting to investigate the long-term variation of planetary wave activity in more detail, based on monthly means.

Fig. 3 gives the monthly r.m.s. wave amplitude $\tilde{A}$ and the proportion of standing wave, $R = A / \tilde{A}$, for wavenumber one of channel B12. Inspection of this figure reveals that large amplitudes are observed in the winter hemisphere associated with the large value of $R$ whereas in the equatorial region two maxima in a year can be seen after the equinoxes in both $\tilde{A}$ and $R$.

In order to separate these two types of oscillation quantitatively and more clearly, we apply a power spectral analysis to the time series of the monthly r.m.s. wave amplitude. The method of analysis used here is the 'maximum entropy method', M.E.M. (see Ulrych and Bishop 1975). Although we have only 24 (month) data for each latitude, the predominant periodicity is significantly detected because of the excellent properties of the M.E.M.; in this case the length of the prediction error filter is 12 which is half the data length.

Fig. 4 shows the result of the power spectral analysis: strong concentration of power

![Figure 4. Power spectra of monthly mean wave amplitude of wavenumber one for (a) middle latitudes and (b) low latitudes during the period of 1973-1974. Units are $(K^2 \cdot \text{month})$.](image-url)
spectral density at the 12-month period is obtained for middle latitudes (48°N and 48°S), while another sharp peak of power density is found with a period of six months for the tropics (8°N and 8°S).

The latitudinal distribution of power spectral density for the annual and semiannual cycles is presented in Fig. 5. Note that the 6-month period component is comparable with or larger than the 12-month period component in the region between 15°N and 15°S. An additional large power density of the 6-month cycle around 30°–40°N may be a manifestation of the Indian monsoon in the summertime of the northern hemisphere as was noted before in connection with Fig. 1(c).

![Figure 5. Latitudinal distribution of power spectral density of 12-month period and 6-month period component for wavenumber 1 at Ch.B12 during the period of 1973–1974. Units are (K² month).](image)

Higher wavenumbers also show the annual cycle in middle and high latitudes, but no marked 6-month periodicity was found for them.

Fig. 6 shows the relationship between the semiannual variation of the mean zonal current and wave activity of wavenumber 1 in the equatorial region. The wave amplitude shown in this figure is an average for 8°N and 8°S, and for the two years. Roughly speaking, components of the annual and quasi-biennial oscillation are removed by this averaging process. The equatorial zonal wind at 50km height is taken from Belmont et al. (1975) based on meteorological rocket observations for 11 years. It is found that the maximum wave amplitude appears about one month after the equinoxes with a significant time-lag after the appearance of maximum westerlies on the equator. The fact that the wave activity

![Figure 6. Semiannual cycle of monthly r.m.s. wave amplitude of wavenumber 1 at Ch.B12 (averaged for 2 years), and mean zonal wind at 50 km height on the equator (after Belmont et al. 1975).](image)
is strongest when the zonal westerly wind intensity is decreasing suggests that the planetary wave of wavenumber one is responsible for taking the westerly momentum away from the equator at this stage. Although we cannot estimate the magnitude of eddy momentum transport from radianc data alone, the phase angle distribution shown in Fig. 2 seems to support the hypothesis of a poleward flux of westerly momentum associated with the planetary wave. It is, of course, another problem to account for the westerly acceleration of the equatorial zonal current after the solstice.

5. Transient Wave Analysis

We have hitherto discussed the long-term variation of planetary waves in the stratosphere on a monthly-mean basis. In the following, an attempt is made to investigate dynamical characteristics of transient planetary waves in terms of their east–west phase velocities as a function of latitude and season. The relationship between the phase velocity of travelling waves and the stratospheric mean zonal wind velocity is a subject of interest.

The method of analysis used in the present study is a power spectral estimate in space and time with the aid of the Doppler effect due to the horizontal motion of waves. We define here the transient wave simply as a deviation from the monthly mean.

Using daily values of the deviation of Fourier coefficients for wavenumber one at a given latitude, we have a data set of the radianc temperature $T(\theta, t)$ which represents the behaviour of the transient wave, where $\theta$ is longitude (every 10 degree, measured positive to eastward) and $t$ is day. Next we construct another set of data series $\mathbf{T}(i)$ from $T(\theta, t)$ in such a way that $\mathbf{T}(i) = \{T(0^\circ, 1), T(10^\circ, 1), \ldots T(350^\circ, 1), T(0^\circ, 2), T(10^\circ, 2), \ldots \}$ (For wavenumber 2, we have $\theta = 0^\circ, 5^\circ, \ldots 175^\circ$ to cover one wavelength.)

No smoothing is made for a small discontinuity between $T(350^\circ, n)$ and $T(0^\circ, n+1)$. Then a power spectral analysis, with use of the m.e.m. again, is applied to this data series $\mathbf{T}(i)$ to find the periodicity in $i$.

If the wave is perfectly stationary and steady in amplitude, the peak of $\mathbf{T}(i)$, corresponding to the wave ridge of $T$, appears every 36 in $i$. Therefore the power spectrum must show a strong concentration of power density into the frequency of one cycle per 36 in $i$. On the other hand, if the wave moves westward with a phase velocity, say $30^\circ$ longitude/day, the peak-to-peak distance in the $\mathbf{T}(i)$ series should be shortened due to the Doppler effect so as to give a maximum power spectral density for the frequency of one cycle per 33 in $i$. In short, a concentration of power spectral density into the frequency of one cycle per $i_0$ means that the wave has a period of $P = 36/(36-i_0)$. (Unit is days, positive westward, negative eastward.) The basic idea of this method is almost the same as that used in the travelling wave analysis by Chapman et al. (1974), except that they applied a power spectral analysis to a data series obtained from satellite measurements on successive orbits.

Results of computations using this technique for wavenumber one of channel B12 are shown in Figs. 7(a)–(d) for some selected latitudes and months of 1973. The length of the prediction error filter for the m.e.m. is chosen to be one-third of the data length in this case. These figures reveal that:

(i) In the winter stratosphere (32 and 48°N in Fig. 7(a) and 32 and 48°S in Fig. 7(c)), a pair of strong power density peaks is observed for the period range of 15 to 20 days. The fact that the pair shows an almost symmetric pattern with respect to $P = \infty$ indicates that this is a reflection of the standing oscillation. (Note that the superposition of eastward and westward moving waves with the same speed and amplitude makes a standing wave of varying amplitude.)

(ii) In the summer stratosphere (32 and 48°S in Fig. 7(a) and 32 and 48°N in Fig. 7(c)), most of the power density is concentrated in a westward motion with a period of
Figure 7. Power spectra of transient waves of wavenumber 1. (See text for detail.) Units are (K^2 day).
about 10 days. This type of wave has been found by Hirota (1975) from the analysis of day-to-day variation of phase angle.

(iii) In spring and autumn (Figs. 7(b) and (d)), there appears a pair of oscillations, i.e. a standing oscillation, with a period of about 3 weeks or more in middle latitudes, and in addition a fast westward motion is found with a period of 8 to 10 days. In lower latitudes the eastward component disappears.

Further computations were carried out for typical months in 1974 as well as in 1973, and characteristic features of transient planetary waves of wavenumber one at channel B12 are summarized in Fig. 8. Some small differences between the northern and southern hemispheres and between the two years are ignored.

![Figure 8](image-url)  
Figure 8. Schematic diagram of seasonal characteristics of transient waves for wavenumber 1 at Ch.B12 levels. Thin full lines denote critical lines, \((U - e) = 0\), at 45 km height. (See text for detail.)

A similar computation for higher wavenumbers shows, however, that the periodicity associated with transient waves is irregular, except for the wintertime, because of the weakness of wave activity. The schematic presentation for higher wavenumbers is, therefore, not given here. An example of the behaviour of wavenumbers 2 and 3 in the winter stratosphere of the southern hemisphere is shown in Fig. 9, where a concentration of power spectral density in an eastward motion is found, in good agreement with the result of phase angle analysis by Harwood (1975) for the 1971 winter in the southern hemisphere. Wavenumber 2 in the northern hemisphere winter seems to have a component of standing oscillation, probably due to the large effect of the surface topography of the hemisphere on the forced stationary wave.

6. **Some theoretical considerations**

As various theoretical and observational studies show, the wave energy in the stratosphere and mesosphere is mainly supplied from the lower atmosphere. It is also well known
that the vertical propagation of wave energy depends critically upon the vertical and horizontal structure of the mean zonal current of the upper atmosphere (Charney and Drazin 1961; Dickinson 1968; Matsumo 1970; Simmons 1974).

According to the theory of Charney and Drazin for quasi-geostrophic motion on a mid-latitude $\beta$-plane, vertical propagation of a wave with horizontal phase velocity $c$ is possible only when the zonal wind velocity relative to the wave, $(U - c)$, is positive (westerly) and smaller than a critical value $(U_c)$, i.e. $0 < U - c < U_c$, where $U_c$ is a function of latitude, thermal structure of the atmosphere and wavenumber.

Fig. 8 gives also the time, $P$ (days), for the mean zonal wind at 45 km (from the 1972 CIRA atmosphere) to go round the latitude circle. Winds are averaged for both hemispheres and for two months: January and February of the northern hemisphere and July and August of the southern hemisphere for winter and so on. The region above the curve denotes $(U - c) > 0$.

It is quite interesting to find from this diagram that almost all predominant waves lie in the region where $(U - c) > 0$. It may be said, therefore, that if we assume the wave energy of the lower atmosphere occurs in a wide range of periods the seasonal variation of the mean zonal wind in the stratosphere has a 'filtering' effect on the vertical propagation of planetary waves. That is to say, the absence of eastward travelling and stationary eddies in the summer stratosphere is clearly accounted for by the critical line considerations discussed above.

Regarding the upper criterion of vertical wave propagation, a rough estimate of $U_c$, which is valid for middle latitudes only, gives a value of $P \approx 10$ days (westward) for winter as an upper limit corresponding to the observed mean zonal wind velocity shown in Fig. 8 for wavenumber one. For other seasons, the upper limit is beyond the diagram. This also accounts for the absence of fast westward motion in the winter stratosphere.

On the excitation mechanism of transient planetary waves and the atmospheric selectivity for periodic motions, Hirota (1971) made a theoretical consideration to give an idea of the 'maximum response period'. Although the model used in that paper is rather simple, the fundamental concept is still applicable to the interpretation of observed wave characteristics.

7. CONCLUSIONS AND REMARKS

The seasonal characteristics of planetary waves in the stratosphere have been described from global analyses of Nimbus 5 SCR data. It is found that the planetary wave activity
shows a remarkable seasonal variation in response to that of the mean zonal wind: the monthly r.m.s. wave amplitude exhibits an annual cycle in middle and higher latitudes with its maximum in winter corresponding to the polar-night westerlies. In lower latitudes, on the other hand, a six-month oscillation is prominent for the monthly r.m.s. wave amplitude of wavenumber one, probably associated with the semiannual cycle of the mean zonal wind in the equatorial upper stratosphere. The result of phase angle analysis suggests that this sort of oscillation is due to the influence of mid-latitudes during the late winter and spring of both hemispheres.

Transient planetary waves, defined as deviations from the monthly mean, also show significant seasonal changes: in winter a 15- to 20-day standing oscillation is predominant for wavenumber one, in contrast to a fast westward motion with a period of about 10 days in the summertime easterlies. Waves in spring and autumn show characteristics between those in the two extreme seasons. These observed features of transient waves can be explained, at least qualitatively, in the light of some theoretical considerations of critical lines for the vertical wave propagation.

Throughout the present work, no special attention has been paid to the long-term variation over years, nor to the difference between the hemispheres. However, as has been shown by many studies, the stratospheric circulation shows notable year-to-year variations such as the quasi-biennial oscillation and the irregular occurrence of sudden warmings. The mean zonal wind distribution in the stratosphere also shows a large difference between the hemispheres. Therefore it is desirable to make an analysis of the mean zonal wind itself, by the application of retrieval techniques to radiance measurements, especially in the southern hemisphere where only a few meteorological rocket data are available.

Concerning the dynamical interaction between the planetary wave and the mean zonal current, it is also desirable in future to estimate the energy and momentum transport associated with waves in a quantitative manner.

Further observational studies thus should be continued extensively for the purpose of understanding the upper atmospheric circulation. The analysis of the mesospheric circulation with the aid of the Nimbus 6 Pressure Modulator Radiometer promises to be of great importance.

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