Oscillations in the Winter Stratosphere: Part 2. The Role of Horizontal Eddy Heat Transport and the Interaction of Transient and Stationary Planetary-Scale Waves

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ABSTRACT

An examination of 30 mb data from eight winter seasons reveals that out-of-phase temperature oscillations occur regularly on either side of 60°N. The typical time scale of these oscillations is 1–3 weeks. Evidence is presented indicating that these out-of-phase oscillations occur because fluctuations in horizontal eddy heat transport across 60°N are a dominant mechanism controlling zonal mean temperature variations in this period range. The interaction between quasi-stationary and transient planetary-scale waves is shown to be capable of producing a large fraction of these fluctuations in eddy transport.

1. Introduction

This is the second of two papers dealing with temperature and pressure-height fluctuations in the winter stratosphere. In it we sudy the physical causes for temperature oscillations which are coherent and out-of-phase on either side of 60°N. In Part I (van Loon *et al.*, 1975), the typical time scale of these oscillations was estimated to be 1–3 weeks, based on the results of a cross spectrum analysis between middle and high latitude zonal mean temperatures at 30 mb. It was in this period range that values of the coherence squared were above zero at levels higher than the 99% probability limit. It should be noted that this is an arbitrarily chosen level of statistical significance and therefore, although the 1–3 week range represents typical periods, similar out-of-phase variations occur at periods a few days shorter than a week and up to several days longer than three weeks. Further, the 1–3 week period range is not a particularly favored one for temperature variance itself (i.e., no large spectral peaks). This suggests that, among the many factors that contribute to essentially a "red noise" spectral behavior in the zonal mean stratospheric temperatures in middle and high latitudes, the one or ones that dominate in this 1–3 week range operate in such a way as to cause the out-of-phase character in the oscillations without producing anomalous, increased variance. We argue in the following that fluctuating horizontal eddy heat transport is the dominant factor. Further, evidence is presented supporting the contention that a considerable portion of these fluctuations in eddy heat transports is the result of modulation of the forced, quasi-stationary waves by planetary-scale, transient waves whose local periods are of the order of 1–3 weeks.

The data studied are subjected to spectrum and cross spectrum analysis. A brief description of both data and the spectral methods is presented in Section 2. In addition, evidence of the 1–3 week out-of-phase temperature oscillations, supplementary to that presented in Part I, is included here. The role played by variations in horizontal eddy transports of heat in these oscillations is considered in Section 3. In Section 4 evidence is presented to support the contention that the interaction between forced, quasi-stationary waves and planetary-scale transient waves contributes significantly to the variations in eddy heat transports in the 1–3 week period range. Speculations concerning connections with the troposphere, the approximate 1–3 week period, and possible relation to the major warmings of the stratosphere are contained in Section 5.

2. Spectral analyses of 30 mb zonal mean temperatures

a. Data and methods

Stratospheric zonal mean temperatures determined from the daily maps analyzed at the Freie Universität in Berlin, along with temperature and pressure-height data taken from analyses made by the National Meteorological Center (NMC), are studied. Most attention is devoted to the NMC temperature and pressure-height data at 30 mb for the nine years, 1964–1972. This entire record was broken up into eight winter segments, each

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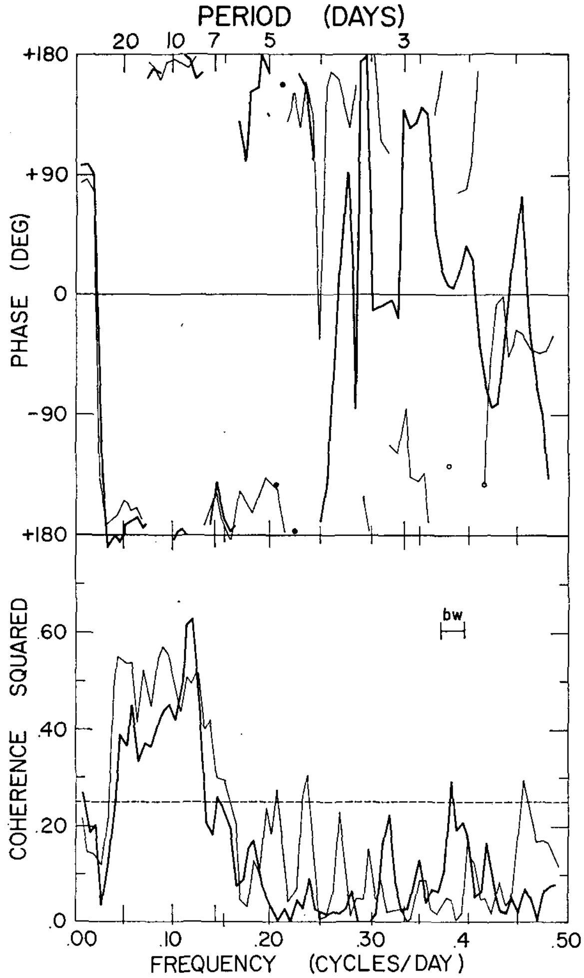

FIG. 1. Winter season coherence squared (bottom) and phase (top) between the zonally averaged 30 mb temperature for the latitude bands 40°–50°N and 70°–80°N. Positive phase means that the 40°–50°N band leads the 70°–80°N band. The 99% confidence limit is indicated by the dashed line. Results based on Freie Universität data and those based on NMC data are depicted by the heavy and light lines respectively.

beginning on 1 November and extending for 160 days. The 160-day mean was removed and 15 values at either end of each winter series were tapered with a cosine bell. A fast Fourier transform was then used to determine 81 harmonic coefficients for each of the winter series, and spectrum, cospectrum, and quadrature spectrum were estimated by averaging the appropriate squared coefficient over the eight winters. To further increase the degrees of freedom (dof) of the resulting spectral estimates, a few adjacent estimates were averaged, thus reducing the spectral resolution somewhat from the maximum of 1/160 cycles per day. Taking q to represent the number of winter segments, and L as the number of adjacent estimates averaged, the approximate dof are given by $2qL$. For a more complete discussion of the spectral methods used the reader is referred to Part I.

b. Spectral evidence of the 1–3 week oscillation

Based on the NMC analyses, it was shown in Part I that the coherence between middle and high latitude mean zonal temperature at 30 mb was above zero in the 1–3 week period range at better than the 99% significance level. Zonal mean temperatures from the 40°–50°N latitude band and those from the 70°–80°N latitude band are used to represent middle and high latitude values respectively. To further test the reliability of this result, a similar cross spectrum was estimated for zonal mean 30 mb temperatures in the 40°–50°N band and the 70°–80°N band, computed from daily analyses made at the Freie Universität in Berlin. In this case, only six winter segments, 1965–66 through 1970–71, were readily available to us. Furthermore, the data ran for only 151 days from 1 November of each year. After removing the 151-day mean, each segment was extended by adding four zeroes at the beginning of the series and five at the end. Because of the tapering procedure, this should have little effect on the spectral results.

To facilitate direct comparison, a cross spectrum for the same six winters was determined from the NMC data. Resulting values of coherence squared and phase determined from the six-year averaged cospectra and quadrature spectra are shown in Fig. 1. Here $q=6$, $L=3$, and the approximate dof are 36. Assuming that the effect of the nine-day difference in segment lengths between the Freie Universität and the NMC data is small and that both analyses were based on the same observations, then differences evident in Fig. 1 must be introduced by the methods of analysis. This comparison puts in doubt the reliability of the results at periods shorter than five days, but the broad maximum in the coherence squared in the 1–3 week period range is reproduced reasonably well from both data sets. Similarly, the out-of-phase feature is further confirmed.

To underscore the uncertainty in spectral results at high frequencies, and to illustrate the fact that there is no evidence that the 1–3 week period range is a particularly important one with respect to the variance of these zonal mean temperatures, the individual spectra are presented in Fig. 2. On statistical grounds one cannot argue that at periods longer than about seven days the spectra represent anything but the same continuous decrease in variance with increasing frequency. At shorter periods, on the other hand, one could argue that the spectra based on the Freie Universität analyses are significantly different from that based on the NMC analyses. This is particularly true for the 40°–50°N band. That the relative differences in this band are greater than those between the spectra computed for the 70°–80°N band is not surprising, since considerably more of the circumference of the earth at 40°–50°N extends over data void regions than at 70°–80°N. Because there is no way to ascertain which spectrum most nearly represents the actual atmospheric conditions, we simply interpret the differences as a qualitative indication of the uncertainty in the data, and therefore must interpret results for periods less than about one week with caution.

3. Horizontal eddy heat transport and temperature variations

a. Rationale

The spectra of zonal mean temperatures in middle and high latitude bands look very much like "red noise," while the cross spectrum between the bands points to a coherent, out-of-phase behavior in the 1–3 week period range. At periods outside the 1–3 week range, factors influencing mean zonal temperatures do not consistently cause coherent behavior on either side of 60°N. Because of uncertainty in variations of the data at periods less than one week, we cannot rule out the possiblity that at these shorter periods any coherent behavior that might exist is lost in noise. At longer periods, however, the relative minimum in coherence evident in Fig. 1 is probably a reflection of the fact that there exists no regular phase relationship between temperature variations on either side of 60°N. Surprisingly, this circumstance is reflected to a degree even in the first harmonic in time, where one might expect a very coherent and in-phase behavior because of the dominance of radiational effects on the seasonal time scale. The coherence squared is lower than that in the 1–3 week range, and the middle latitudes lead high latitudes by a quarter of a cycle[2]. Dynamic effects must weaken the radiational control of temperature on the seasonal time scale.

Evidence that follows indicates that fluctuations in horizontal eddy transports of heat across 60°N, which add heat to high latitudes at the expense of the middle latitudes and vice versa, are a dominant mechanism controlling zonal mean temperature variations in the 1–3 week period range. We argue that it is this dominance that is reflected in the coherent and out-of-phase behavior of middle and high latitude temperatures in this period range.

b. Seasonally averaged horizontal eddy heat transport at 30 mb

Eddy heat transports in the stratosphere have been estimated by several investigators. For an overview of the seasonal variation of eddy transports and extensive bibliography of related studies see Newell *et al.* (1974).

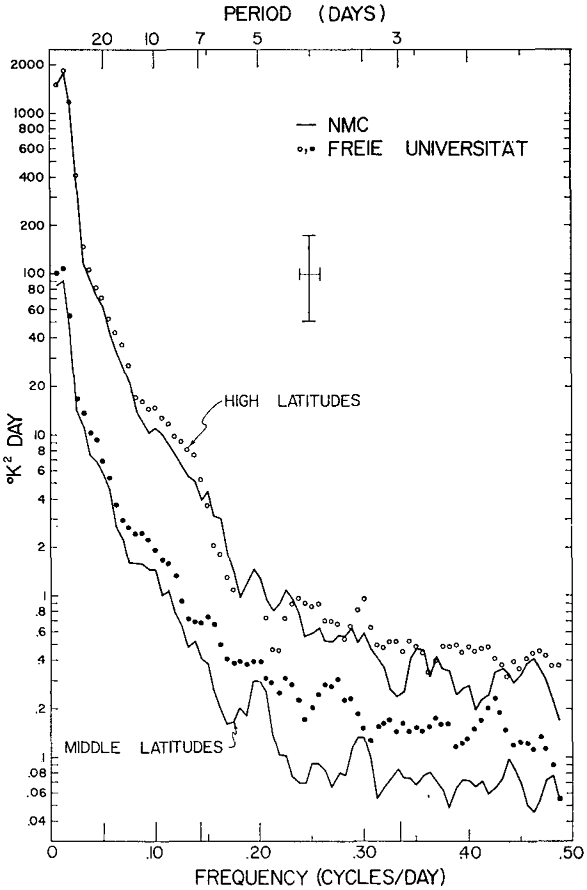

Fig. 2. Winter season variance spectra of the 30 mb zonal mean temperatures for the 40°–50°N band (middle latitudes) and the 70°–80°N band (high latitudes) based on NMC and Freie Universität data. The 99% confidence limits and bandwidth for the analyses are indicated by the cross.

To put the data studied here in perspective, the average horizontal eddy transport of heat at 30 mb was computed for each of the eight, 160-day winter segments. Temperature and height data were harmonically analyzed along latitude lines and the sine and cosine coefficients for the first six zonal waves were retained. On any given day the northward eddy heat transport across some latitude ϕ is estimated by

$$[V^*T^*]\approx k\sum_{m=1}^{m=6}\{ZS_mTC_m-ZC_mTS_m\}m. \qquad (1)$$

Here, in the left-hand term, the bracket denotes the average of a quantity with respect to longitude and the asterisk denotes the departure of a quantity from its longitudinal average. Equation (1) states that the product of the longitudinal deviations of the meridional wind, V, and the longitudinal deviations of the temperature, T, averaged over all longitudes is given approximately by the sum of transports accomplished by the first six zonal wave-numbers of the geostrophic

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[2] The averaging of three adjacent spectral estimates, used in estimating the coherence squared and phase results in some leakage to the first harmonic from harmonics zero and two. This leakage does not materially affect the results, however, since the coherence squared at the first harmonic estimated from the NMC data by simple averaging of the squared, raw coefficients over the eight winters gives a value of 0.26, and the estimated phase put the 40°-50°N band 0.4 cycle ahead of the 70°-80°N band.

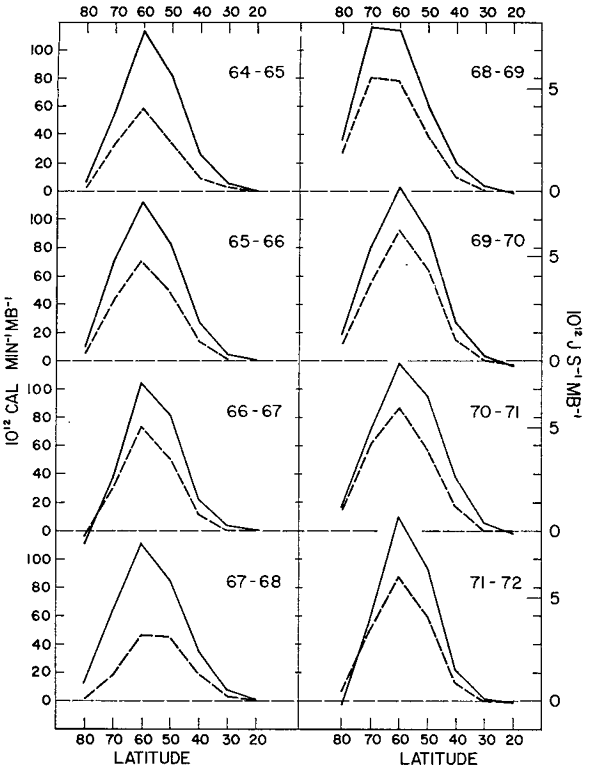

Fig. 3. Average northward transport of heat accomplished by horizontal eddies (first six zonal wavenumbers) during eight winter seasons at 30 mb. Solid and broken lines indicate total and standing eddy transport respectively.

meridional wind. The constant k determines the units and is a function of the latitude, ϕ. ZS_m and ZC_m are the sine and cosine coefficients of the pressure-height for zonal wavenumber m at latitude ϕ, and TS_m and TC_m the corresponding coefficients of the temperature. Coefficients are defined with respect to longitude increasing eastward from Greenwich.

Eddy transports of heat from 20° to 80°N, determined by averaging (1) over each 160-day winter segment, are presented in Fig. 3. Maximum northward transport occurs at 60°N in every winter but that of 1968–1969. That portion of the eddy transport accomplished by standing eddies is indicated and was computed from

$$[\overline{V^*}\,\overline{T^*}] \approx k \sum_{m=1}^{m=6} \{\overline{ZS_m}\,\overline{TC_m} - \overline{ZC_m}\,\overline{TS_m}\} m. \qquad (2)$$

Here the overbar ($\overline{\ \ }$) denotes the 160 d time average.

At 60°N, approximately 90% of the eddy transport is accomplished by zonal wavenumbers one and two and the average horizontal convergence of heat over the pole produced contributes to about a 2° increase in temperature per day (Fig. 4).

c. *Daily values of horizontal eddy heat transport and zonal mean temperature*

With this seasonally-averaged picture in mind, we proceed to look at daily values of eddy transports of heat across 60°N and relate them to the 1–3 week, out-of-phase oscillations between middle and high latitude zonal mean temperatures. Figure 5 shows the daily values of eddy heat transport for three Januaries. These particular Januaries were selected to illustrate the variable behavior that occurs from year to year and even from month to month. During the second two-thirds of January 1972, zonal wavenumber two accomplished nearly all the eddy heat transport. In contrast, wave one dominated in 1969 and by the end of January 1968, a month when the polar westerly vortex broke down, transport by both wave one and two falls to near zero.

Along with the eddy heat transport, the temperature differences between high and middle latitudes are in-

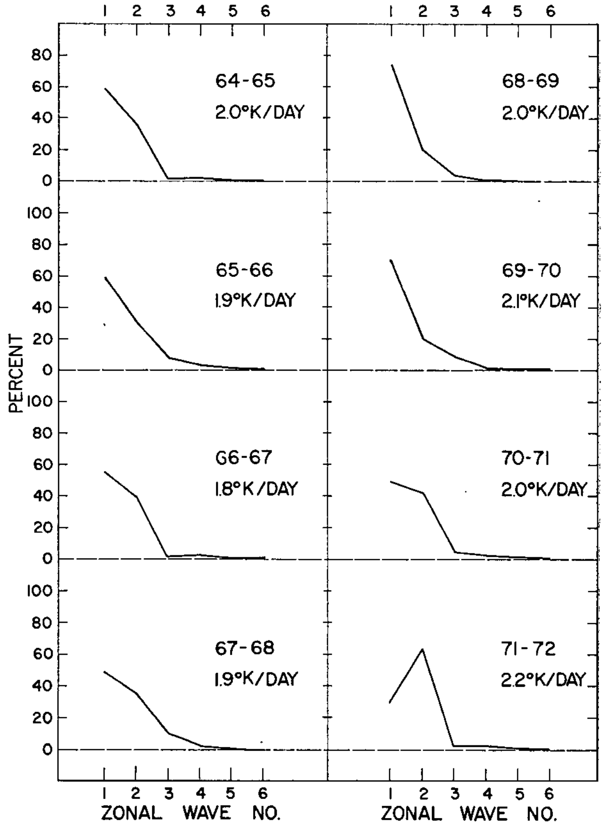

Fig. 4. Percent of the total horizontal eddy heat transport across 60°N, presented in Fig. 3, that is contributed by each of the first six zonal wavenumbers. The temperature change per day over the polar cap that would result from this transport alone is indicated; it was obtained by dividing the transport across 60°N as shown in Fig. 3 by the specific heat of air and the area of the polar cap north of 60°N, and then multiplying by the number of minutes per day and the acceleration of gravity. It is a point value applying at 30 mb.

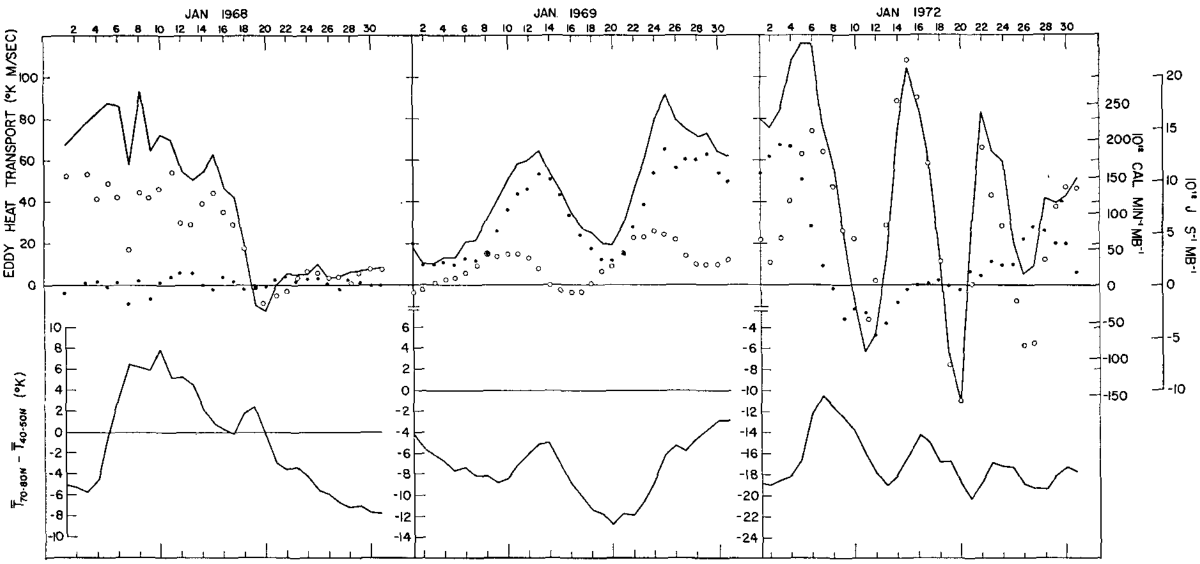

FIG. 5. Zonal mean temperature difference at 30 mb between the 70°–80°N band and the 40°–50°N band (values>0 mean 70°–80°N warmer than 40°–50°N) for three selected Januaries (bottom). Total horizontal eddy heat transport across 60°N (solid line), that accomplished by zonal wavenumber one (dots), and that accomplished by zonal wavenumber two (open circles) (top).

dicated. The out-of-phase oscillations are manifested clearly in the regular variation of this temperature difference in the Januaries of 1969 and 1972. They are not clearly evident during January of 1968.[3] In the former Januaries each maximum (least negative value) in the temperature difference follows a few days after a maximum in the horizontal eddy transport of heat across 60°N.

d. Cross spectrum between horizontal eddy heat transport and zonal mean temperature

Cross spectrum analysis was used to demonstrate that the relationship between eddy heat transport and temperature difference evident in January 1969 and 1972 was, on the average, a regularly occurring feature during the eight winters studied. One time series was taken to be the total horizontal eddy heat transport across 60°N determined by (1), and a second was the area-weighted temperature difference between high and middle latitudes. Eddy transports across 60°N can be considered as the eddy convergence of heat over the polar cap, and since eddy transports at 30°N are nearly always small, they also represent the horizontal eddy divergence of heat from the 30°–60°N region. For that reason the high latitude temperatures were weighted by the area over the polar cap north of 60°N, and middle latitude temperatures by the area between 30° and 60°N.

The coherence squared and phase between these two series, determined by averaging over the eight winter segments and three adjacent estimates, are presented in Fig. 6. The dof are approximately 48 ($2qL=2\cdot8\cdot3$). The relative maxima of coherence squared in the 1–3 week range corresponds reasonably well to that of the cross spectra between middle and high latitude temperatures shown in Fig. 1 here, and in Fig. 6, Part I. The two series are in quadrature, with the area-weighted temperature difference trailing the eddy heat transports. The quadrature relationship is a feature that has recently been reported to occur in laboratory experiments (Pfeffer *et al.* 1974).

e. Quantitative comparison of horizontal eddy heat convergence temperature change

From Fig. 6 it is seen that, in the 1–3 week period range, fluctuations in eddy heat transports at 60°N are correlated with the varying temperature difference across 60°N. Figure 7 is presented to demonstrate that it is reasonable to assume that these fluctuations in the eddy transport are adequate to account for the variations in temperature. The eddy convergence of heat indicated is that occurring over the polar cap north of 60°N. Again, because horizontal eddy transports of heat are small at 30°N, it is also proportional to divergence over the 30°–60°N latitude band.[4] The smooth lines are the result of a low pass filtering operation that will be discussed further in the following

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[3] The out-of-phase oscillations present in other months of the 1967–1968 winter can be seen in Fig. 7.

[4] Since the area in the 30°–60°N band is 2.7 times larger than that over the polar cap north of 60°N, the temperature scale of Fig. 7 for middle latitudes was chosen to be 2.7 times that for high latitudes. Relative middle latitude temperature changes judged by the right hand scale of Fig. 7 can, therefore, be related directly to the negative of the indicated eddy convergence.

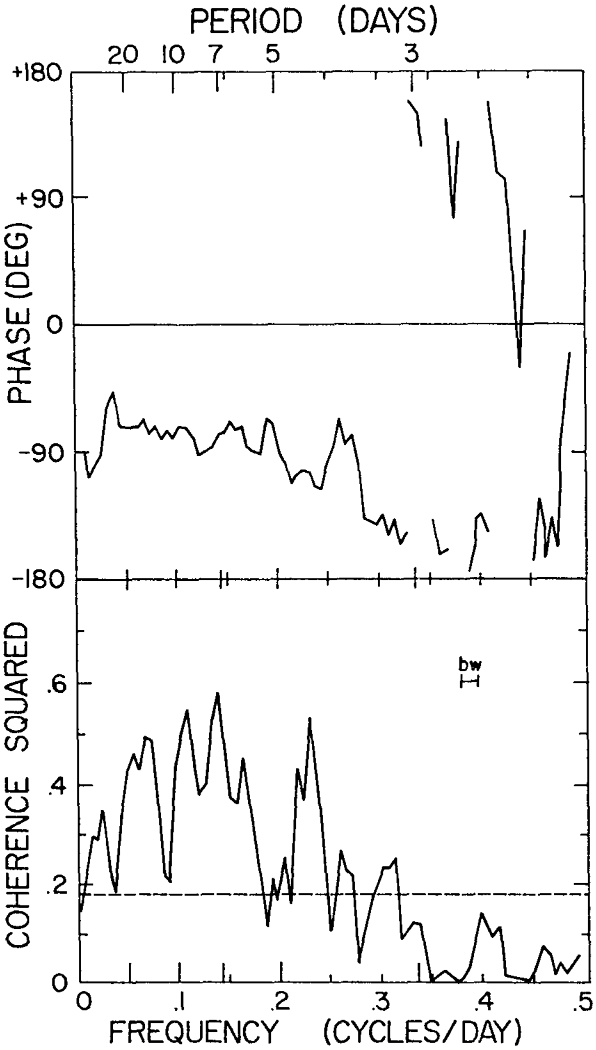


FIG. 6. Winter season coherence squared (bottom) and phase (top), between total eddy heat transport across 60°N and the area-weighted temperature difference between the 70°–80°N and 40°–50°N bands at 30 mb. Positive phase angles mean area-weighted temperature difference leads eddy heat transports. The 99% confidence limit is indicated by the dashed line.

section. It will suffice to say here that fluctuations in temperature and eddy convergence about the low-pass data comprise much of the higher frequency variations that reflect the coherent, out-of-phase temperature changes suggested by Fig. 1, and also those changes in area-weighted temperature difference that are coherent and in quadrature with the eddy heat transport as suggested by Fig. 6.

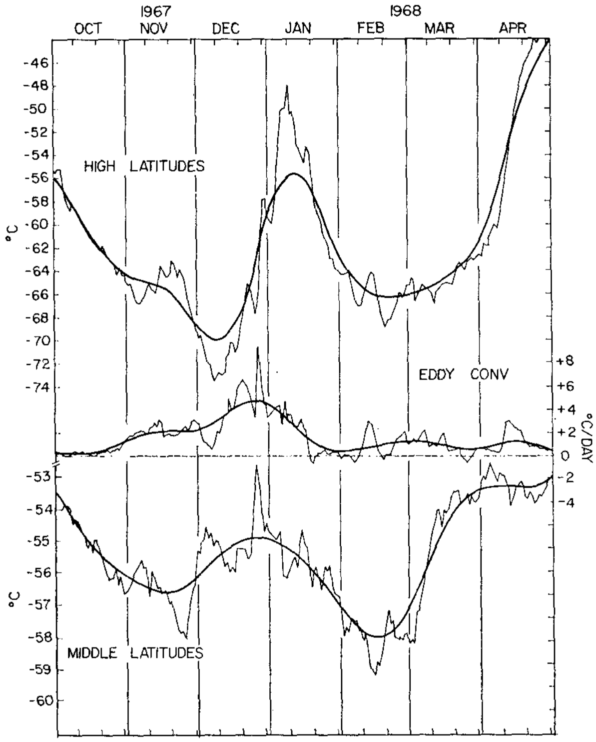
Fluctuations in eddy convergence of heat about the low-pass values typically exceed 2°C/d, while only the steepest slopes in the high latitude temperature curve suggest temperature changes as large as 2°C/d. It is concluded that the eddy transports across 60°N are more than adequate to explain the out-of-phase temperature variations on either side of 60°N. In a case study of the sudden warming of January 1958, Mahlman (1969) has clearly demonstrated that the increasing eddy heat flux into the polar region during the warming was offset in large measure by a corresponding increase in the rising motion over the pole associated with mean cell. It is likely that, here too, changes in the strength of the mean cell (rising to the north of 60°N and sinking to the south; e.g., Reed *et al.*, 1963; Julian and Labitzke, 1965; Vincent, 1968) tend to compensate to a degree, but in the 1–3 week period range they do not eliminate the effects of the fluctuating eddy heat transports.

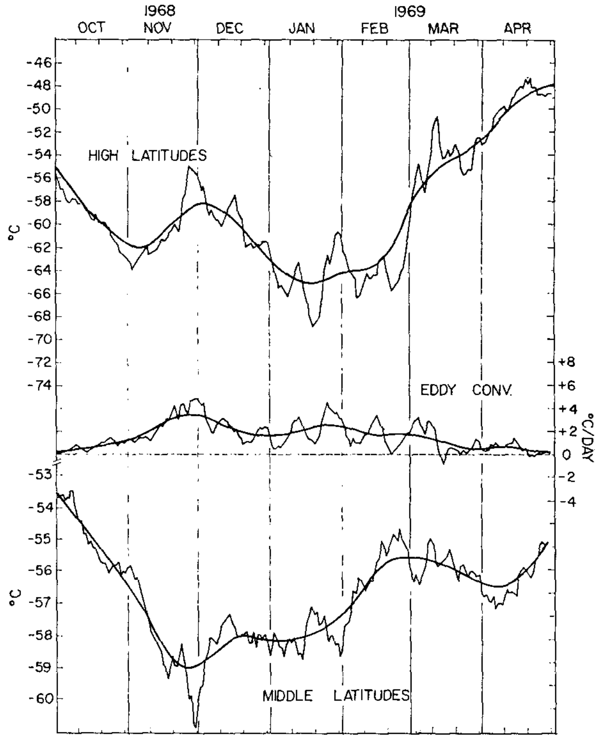
4. The role of transient planetary-scale waves in the time fluctuations of eddy heat transports

a. *Evidence of transient, planetary-scale waves*

There have been many observational studies of transient, planetary-scale waves reported in recent years. Among them, Deland and Johnson (1968), Hirota (1968), Fritz (1970), and Deland (1973a and 1973b) have presented evidence for the existence of transient planetary-scale, wave-like disturbances in the stratosphere. Their results indicate that disturbances of scale zonal wave one generally move westward. Both eastward and westward propagation are indicated for zonal wave two disturbances. Cross spectrum analysis is again used to establish the *mean* character of transient planetary-scale waves during the eight winters studied here. One time series is taken as the sine coefficient of the height or temperature wave (ZS_m or TS_m) and the second as the corresponding cosine coefficient (ZC_m or TC_m). Since most of the eddy heat transport is accomplished by zonal waves one and two, the following analyses concern only those two largest scale waves. The cross spectrum is computed, as before, by averaging over the eight winter segments and three adjacent estimates. Resulting coherences squared and phase angles for zonal wavenumbers one and two are presented in Figs. 8 and 9. Where the values of coherence squared are highest, the sine and cosine series tend to be out of phase by one quarter cycle. Of course, this means most of the covariability is in the quadrature spectrum, so the technique reduces, essentially, to the quadrature spectrum method used by Deland (1964). Inspection of plots of the sine versus cosine coefficients of zonal waves one and two indicated some periods with and some without regular propagation. The apparent direction of propagation for a given wave is not always the same either. Because of this variability in time we have chosen not to use more sophisticated techniques capable of resolving waves into eastward and westward propagating components, but attempt only to establish the dominant behavior of the planetary scale transient waves over the eight-year period.

For zonal wave one in the height field a relative maximum in the coherence squares occurs at periods near seven days, and the sine coefficient leads the cosine coefficient by approximately a quarter of a cycle in the





1–3 week period range, suggesting a dominant westward movement (Fig. 8a). The coherence of wave one in the temperature field is not large in the 1–3 week range, with the exception of the peak near 10 days (Fig. 8b). Surprisingly, the phase angle here suggests a dominant eastward movement. At the University of Washington, Pratt and Wallace[5] have found a similar relationship between wave-one height and temperature in their study of planetary-scale waves in the troposphere. Their work indicates that there is a relatively large amplitude westward propagating wave in the height field with little or no associated temperature variations, and a smaller amplitude eastward propagating wave in the height field with correspondingly larger associated temperature variations. It seems likely that their interpretation may well explain these stratospheric results also. Because of the larger coherence squared we assume that the westward propagating height wave is the more important feature.

Coherences squared for wave two in the heights have a relative maximum in the 1–3 week range, as do those for wave two in the temperatures (Fig. 9). The values of coherence squared associated with the temperature wave are larger and the phase angles for both reflect a dominant eastward movement of wave two.

From Figs. 8 and 9 it is concluded that transient planetary-scale waves were present often at 60°N and 30 mb during the eight winters studied. In the 1–3 week range, westward propagating wave one in the heights

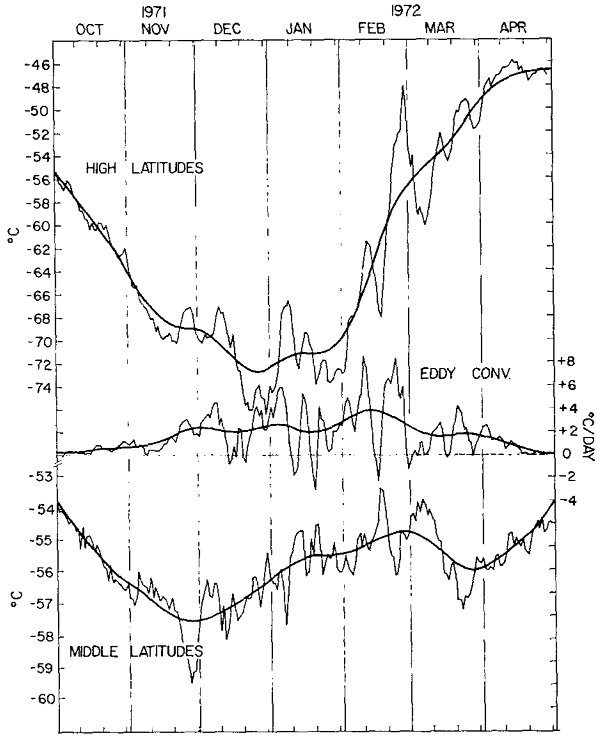


FIG. 7. For three winter half-years (1967–68, 1968–69, 1971–72), the horizontal eddy convergence of heat at 30 mb over the polar cap north of 60°N (middle), zonal mean temperatures for the 70°–80°N band (high latitudes), and for the 40°–50°N band (middle latitude). Also see footnote 4.

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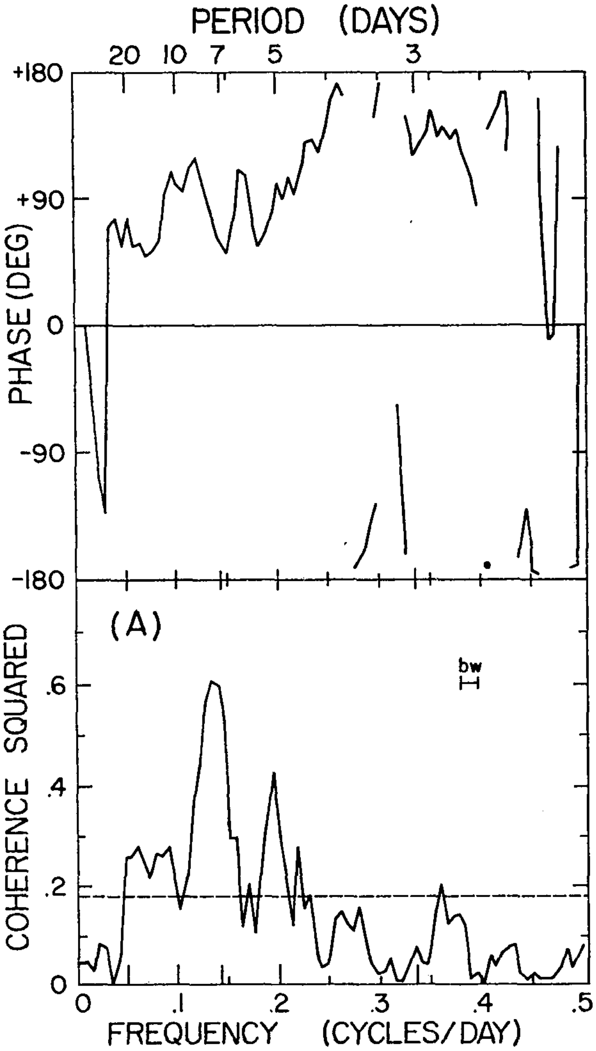
[5] Personal communication.

and eastward propagating wave two in the temperature appear to have been the dominant transients.

b. Interaction between forced, quasi-stationary waves and transient planetary-scale waves

Planetary-scale, time-averaged or stationary waves in stratospheric pressure-height and temperature have been well-documented (e.g., Hirota and Sato, 1969; van Loon *et al.*, 1973). The quasi-stationary waves considered here are defined by the time-averaged values of the zonal coefficients ZS_m, ZC_m, TS_m, and TC_m, plus a slowly varying contribution determined by a low-pass, time-filter (LP) operation applied to the zonal coefficients. Similarly, transient waves are determined by a band-pass, time filter (BP) operation applied to the zonal coefficients. The amplitude responses of the two filters are plotted in Fig. 10. Actual filtering was accomplished by multiplying the Fourier transform of a 3008-day time series (1 March 1964–25 May 1972) of the zonal coefficients by the appropriate amplitude response. The filtered data are obtained after an inverse transform of this product.



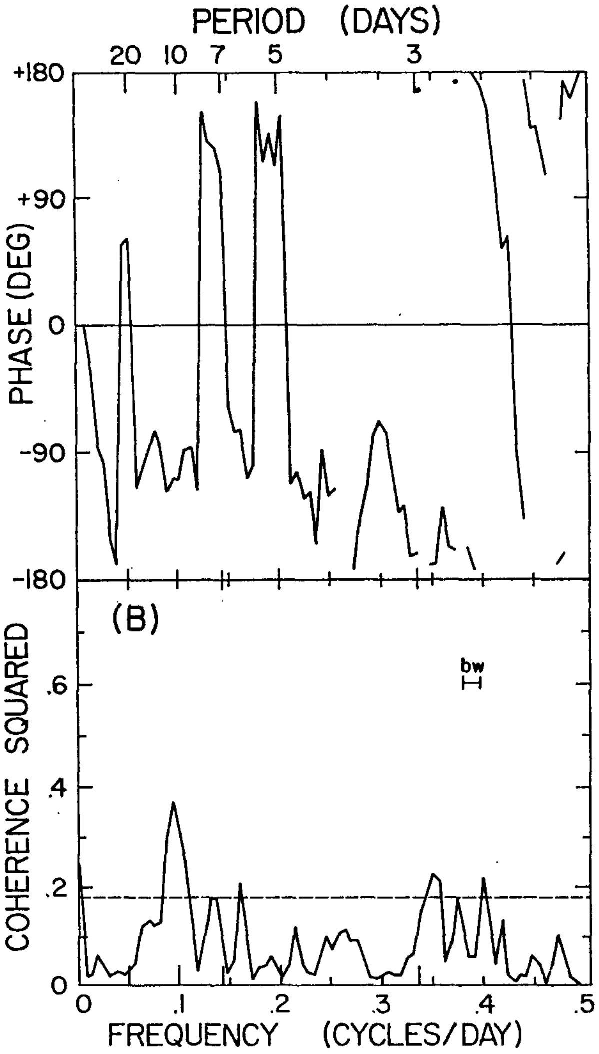
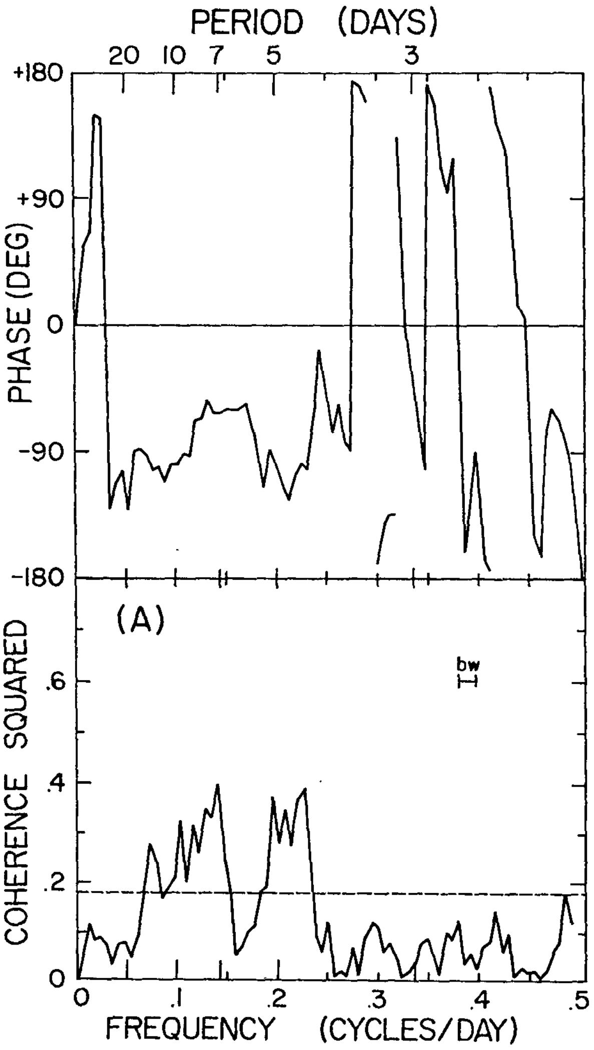


FIG. 8. Winter season coherence squared (bottom), and phase (top), between zonal wave-one sine and cosine coefficients at 60°N and 30 mb for pressure-height (A), and temperature (B). Positive phase means the sine leads the cosine coefficient. The 99% confidence limit is indicated by the dashed line.

The half-power point of the LP is near 50-day periods and it has near zero response at periods shorter than 25 days. It is presumed that the quasi-stationary waves made up of the mean plus the LP data are essentially features forced by topography and heat sources, and thus the reference to forced, quasi-stationary waves.

The half-power points of the BP are near the 1- and 3-week periods. It passes most of the variations whose time scales correspond to that of the relative maxima in the coherence squared evident in Figs. 1 and 6. Because the BP also includes relative maxima in the coherence squared values of Figs. 8 and 9, it is assumed that it can be used to effectively isolate important transients. The use of time filters to separate quasi-stationary and transient wave components is similar to the approach proposed by Iwashima and Yamamoto (1971).

We now demonstrate that a significant portion of the fluctuations in eddy-heat transport that are responsible for the out-of-phase temperature variations in the 1–3 week period range can be explained by interactions between the forced, quasi-stationary and transient components of zonal waves one and two. To begin, consider the sum of the LP and BP components of some variable function of time, $X(t)$. That is, $\overline{X(t)}+\tilde{X}(t)$, where the overbar and tilde represent LP and BP component, respectively. This sum can be considered as an approximation to a complete Fourier representation of $X(t)$ with the time average and lower harmonics included in the LP component. The included lower Fourier harmonics are, however, weighted by the LP amplitude response. Similarly other Fourier harmonics, weighted by the BP amplitude response, are contained in the BP component. Considering only the LP and BP compo-



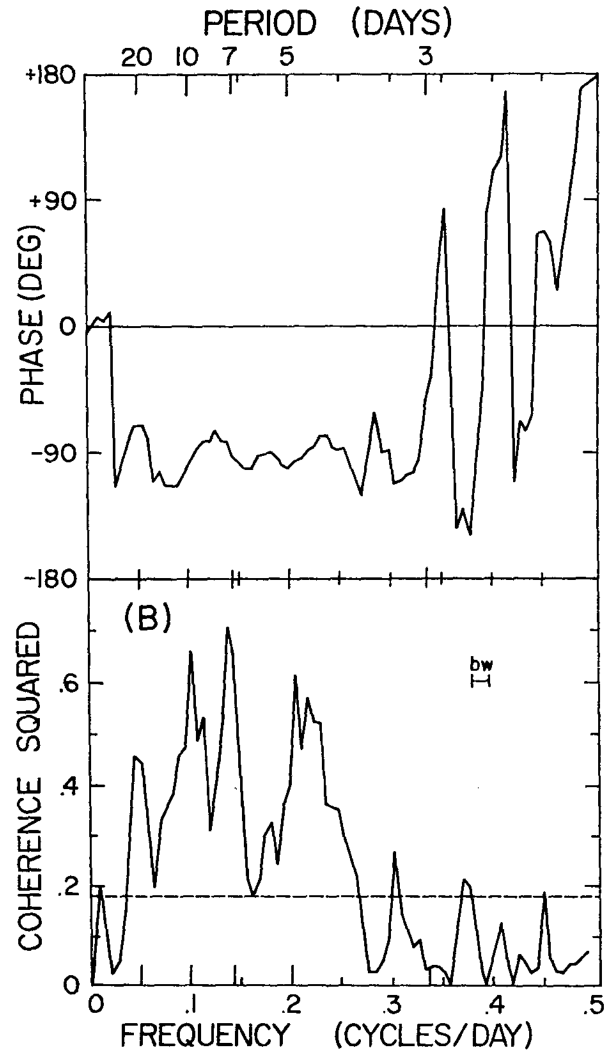


Fig. 9. Same as Fig. 8 except for zonal wave two.

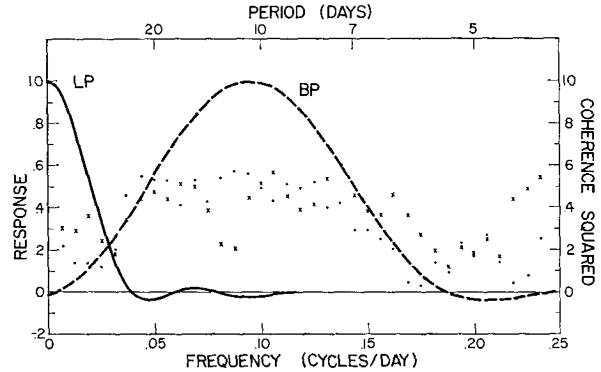


Fig. 10. Amplitude response (left-hand scale) of low-pass filter (LP) and band-pass filter (BP). Coherence squared values (right-hand scale) based on NMC data from Fig. 1 (dots) and those from Fig. 6 (crosses) are also indicated.

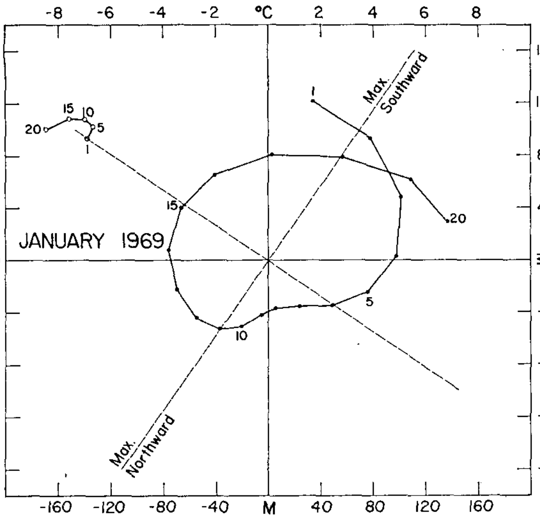


FIG. 11. Harmonic dial (zonal sine coefficient-ordinate and zonal cosine coefficient-abscissa) of the transient wave one in the heights at 60°N and 30 mb (connected dots) and the corresponding quasi-stationary temperature wave (connected open circles). Every fifth day indicated by the numbers. Scale for transient height wave at bottom and right-hand side in meters. Clockwise rotation suggests westward propagation. Scale for quasi-stationary wave at top and left-hand side in °C. Diagonal dashed line indicates approximate location for transient height wave to be one quarter of a wavelength away from quasi-stationary temperature wave, producing relative maxima in the horizontal eddy heat transport.

nents of the coefficients of zonal wavenumbers one and two in the pressure-height and temperature, and following (1), the resulting component of the eddy heat transport is given by

$$k\sum_{m=1}^{m=2}\{\overset{1}{\overline{ZS}_m\cdot\overline{TC}_m}-\overset{2}{\overline{ZC}_m\cdot\overline{TS}_m}+\overset{3}{\overline{ZS}_m\cdot\widetilde{TC}_m}-\overset{4}{\overline{ZC}_m\cdot\widetilde{TS}_m}$$

$$+\overset{5}{\overline{TC}_m\cdot\widetilde{ZS}_m}-\overset{6}{\overline{TS}_m\cdot\widetilde{ZC}_m}+\overset{7}{\widetilde{ZS}_m\;\widetilde{TC}_m}-\overset{8}{\widetilde{ZC}_m\;\widetilde{TS}_m}\}m.$$

The first two terms give the transport accomplished by the quasi-stationary waves. Terms 3 and 4 represent interaction between the quasi-stationary height wave and the transient temperature wave. Interaction between the quasi-stationary temperature wave and the transient height wave is given by terms 5 and 6, and the transport accomplished by the transients alone is given by terms 7 and 8. When averaged over all time the interaction terms 3, 4, 5, and 6 produce almost no net transport; however, they can contribute to time variations in the transport.

To illustrate the role of the interaction terms, the transient component of zonal wavenumber one in the height field at 60°N, determined by the BP of ZS_1 and ZC_1, is presented in Fig. 11 for part of January 1969. Also indicated is the quasi-stationary component of the corresponding temperature wave determined by the LP of TS_1 and TC_1. Their interaction produces maximum northward transport when the transient height wave is one quarter of a cycle east of the quasi-stationary temperature wave. This occurs around 11 January, in good agreement with the relative maximum in total eddy transport indicated in Fig. 5. The January 1972 interaction between the transient component of zonal wavenumber two in the temperature with that of the quasi-stationary component of wave two in the height field can be deduced from Fig. 12. The times of relative maxima and minima in the transport correspond well with those indicated in Fig. 5 for the total transport.

Quasi-stationary and transient wave interactions can account for a considerable portion of the total fluctuations in eddy transport, since the term $(\overline{TC}_1\widetilde{ZS}_1-\overline{TS}_1\widetilde{ZC}_1)$ computed from Fig. 11 ranges from relative minima of −12.4 and −13.0 K m/s on 2 and 19 January to a maximum of 7.4 K m/s on 12 January. The range is about one-half that indicated for the corresponding fluctuations in the total zonal wave one transport shown in Fig. 5. From Fig. 12, the term $(\overline{ZS}_2\,\widetilde{TC}_2-\overline{ZC}_2\,\widetilde{TS}_2)$ ranges 60–70 K m/s from relative minima of −19.6, −29.0, and −34.2 on 1, 11, and 19 January to relative maxima of 40.3 and 38.2 on 6 and 15 January. This, too, is of the order of one-half that indicated for the corresponding fluctuations in zonal wave two as shown in Fig. 5. That there is correspondence between the total fluctuations in eddy transport and those given by the interaction terms is not completely surprising, since we have mathematically broken the transport up into components and then put some of them back together. However, what we think is important is that two of

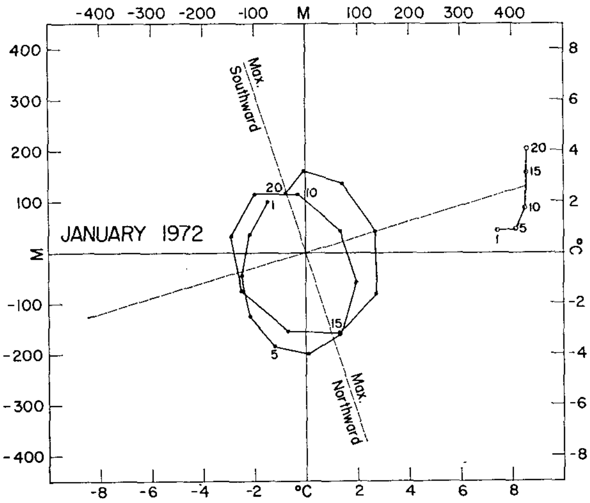


FIG. 12. Same as Fig. 11 except for the transient wave two in the temperatures and the corresponding quasi-stationary height wave. Scale for the transient temperature wave at bottom and right-hand side in °C. Counterclockwise rotation suggests eastward propagation. Scale for quasi-stationary wave at top and left-hand side in meters.

those components, namely wave one in the heights and wave two in the temperatures, exhibit regular phase propagation as implied by the cross-spectral results shown in Figs. 8 and 9, and that, alone, their interaction with the quasi-stationary waves accounts for a considerable part of the total fluctuation.

5. Discussion

Muench (1965) showed evidence of time-dependent energy propagation from troposphere to stratosphere from his analysis of zonal wavenumbers one and two in the pressure-height field. The existence of planetary-scale waves that amplify in the troposphere and propagate upward into the stratosphere has also been shown by Hirota and Sato (1969). At the same time there is a growing body of evidence indicating that transient, planetary scale waves occur regularly in the troposphere (e.g., Kubota and Iida, 1954; Deland, 1964 and 1965; Eliasen and Machenhauer, 1965 and 1969). Deland and Johnson (1968) and Deland (1973b) present evidence that transient planetary scale waves often extend from the lower troposphere to as high as 10 mb.

A preliminary look at tropospheric levels during the eight winters studied here also suggests that there is some coupling between the transient disturbance at 30 mb and similar disturbances in the troposphere. For example, the coherence squared estimated from a cross spectrum between the cosine coefficient of the wave one height field (ZC_1) at 60°N and 500 mb and the sine coefficient of the corresponding wave (ZS_1) at 30 mb, has a broad maximum in the 1–3 week period range. The peak value of 0.41 occurs at a longer period ($\sim$14 days) than the corresponding peak evident in Fig. 8a. The phase angles in the 1–3 week range are nearly in quadrature with ZS_1 at 30 mb leading ZC_1 at 500 mb, suggesting that the coherence is associated with westward propagating disturbances of small or only moderate slope with height. This result is not inconsistent with the findings of Deland and Johnson (1968) and Deland (1973b). In an effort to isolate the transient disturbance at 500 mb, the BP is applied to ZS_1 and ZC_1 for 60°N from that level. The resulting BP coefficients displayed on harmonic dials often indicate a regular westward propagation. However, as might be expected, the indicated regular propagation is interrupted frequently. In fact, the 500 mb transient wave determined by the BP, and corresponding to the 30 mb transient shown in Fig. 11, shows no regular phase propagation but rather a wave-amplitude vacillation (Fig. 13). In this latter respect, the amplitude variations evident in Fig. 13 are similar to those reported in the rotating annulus experiments of Pfeffer *et al.* (1974). An interesting feature is that the interaction between the transient height wave and quasi-stationary temperature wave at 500 mb is out of phase with that at 30 mb. This is due to the fact that the quasi-stationary wave one in temperature at 60°N changes phase between troposphere and stratosphere. It is clear that further diagnostic study is warranted to establish the relationship between the troposphere and the stratospheric phenomena described here.

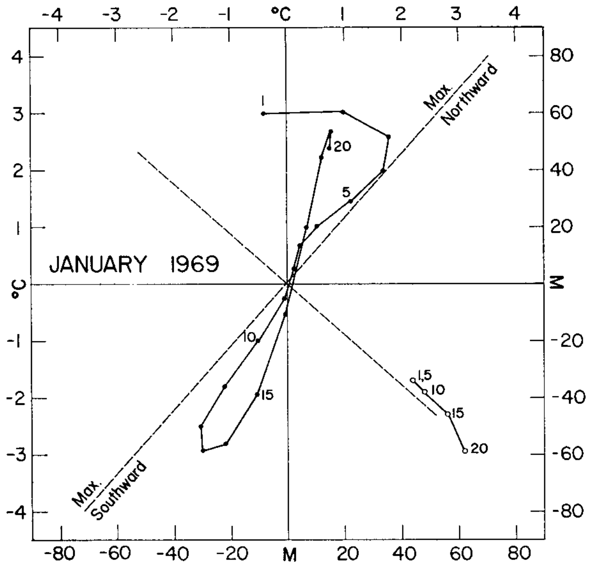


FIG. 13. Same as Fig. 11 except at 500 mb.

Of course, a basic feature of the stratospheric data described here is the 1–3 week period that is reflected in the high coherence between zonal mean temperatures, eddy heat transports and zonal mean temperatures, and sine and cosine coefficients of, primarily, wave one in the heights and wave two in the temperatures. Hirota and Sato (1969) find a periodicity of about two weeks in the polar night westerlies, in the amplitude of wave one in the pressure-heights, and in horizontal eddy momentum fluxes at 30 mb. They propose that there may be an "index cycle" of about two weeks in the stratosphere due to nonlinear wave zonal flow coupling. Further, they suggest that since theory indicates that the ability of wave energy to propagate up from the troposphere is dependent on the strength of the zonal wind, the quasi-periodic two-week variation may be a response of energy propagation to day-to-day variation of the mean zonal westerlies. In support of this suggestion, Hirota (1971a), in his numerical model, forces changes in the mean zonal wind with largest amplitude in the lower atmosphere. He finds that the stratospheric response is similar to the observations of Hirota and Sato (1969) and points out that the resulting stratospheric fluctuations can be interpreted as a superposition of a traveling wave and standing wave.

In the eight winters studied here we find no strong tendency for a 2-week periodicity in the polar night westerlies. In fact, averaged winter spectra of the mean zonal wind at 60°N at several levels show no marked tendency for increased variance in the 1–3 week range (Fig. 14). Because of this we can offer no observational

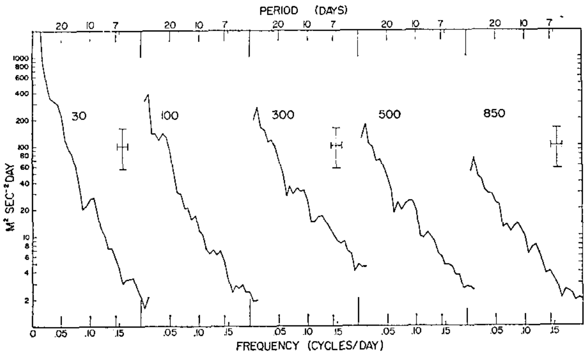


FIG. 14. Winter season variance spectra of the geostrophic zonal mean wind at 60°N at pressure levels indicated. The 99% confidence limits and bandwidth for the analyses are indicated by the cross.

evidence to support a *unique* variation in the zonal wind on this time scale that might excite the stratospheric disturbances. On the other hand, Hirota (1971a, b) discusses a "maximum response period" that is a function of the mean zonal wind and the Rossby wave speed. It is possible that the "varying mean zonal" winds whose spectra are that of red noise are capable of preferentially exciting disturbances with time scales near such a maximum response period. A similar "natural bandpass selectivity of the atmosphere" combined with red-noise forcing is proposed by Holton (1973) to account for the observed Kelvin waves in the tropical atmosphere. It is important, then, to see if the transients described here can be identified with theoretically predicted wave modes. If they can, their expected intrinsic phase speeds coupled with the zonal flow may explain the approximate 1–3 week periodicity.

Although this paper has not dealt directly with the major warmings, some speculation concerning their possible relation to the observations reported seems in order. The importance of large northward heat transports, accompanying an upward propagating planetary wave in its early stages, in inducing mean zonal vertical and meridional motions has been stressed by Matsuno (1971). He proposed that the fundamental mechanism of the warmings is the interaction between the mean zonal flow and the upward propagating waves through Coriolis torques acting on the induced meridional motions. Matsuno points out that though this mechanism may operate regularly, it is the anomalously intense planetary waves that occasionally propagate upward that are capable of initiating the warming response. Clark (1972, 1974) and Geisler (1974) study this mechanism further and demonstrate in their models that the fluctuating transports accompanying vertically propagating planetary waves arise from the superposition of the forced wave and free modes. Although the feature that distinguishes a typical fluctuation from one capable of initiating a warming differs in these two studies [resonant forcing occurring when the initial flow is such that one of the free modes is stationary in Clark's (1974), whereas the amplitude of the oscillating transport is decisive in Geisler's (1974)], the possible importance of transient and standing-wave mode interactions in understanding the sudden warmings is indicated. Indeed, Quiroz (1975) provides evidence based on satellite data that the merging of a transient and standing wave preceded four major warmings that occurred between 1969 and 1974. In this regard, it is important to study the vertical variations of the fluctuating heat transport discussed here, and, in addition, possible accompanying eddy momentum convergence, to better assess what role the interaction of transient and standing waves may play in the major warmings.

6. Conclusions

Although there is variability from year to year and month to month, evidence of the following features survives an eight-year averaging. Out-of-phase temperature oscillations on either side of 60°N occur regularly in the winter stratosphere. Based on cross spectrum analysis of eight winter seasons the typical time scale of these oscillations is 1–3 weeks. At this time scale, fluctuating horizontal eddy heat transports across 60°N, which add heat to high latitudes at the expense of middle latitudes, are apparently a dominant mechanism controlling zonal mean temperature. A considerable portion of these fluctuations in eddy heat transport can be accounted for by the interaction between forced quasi-stationary waves and planetary-scale, transient waves whose local periods are on the order of 1–3 weeks. Specifically, we have demonstrated how transient disturbances in the pressure-height field of horizontal scale zonal wave one and those in the temperature field of horizontal scale zonal wave two can interact with the corresponding quasi-stationary waves in temperature and pressure-height.

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