Oscillations in the Winter Stratosphere: Part 1. Description

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ABSTRACT

Two patterns dominate changes of monthly mean temperature and pressure-height in the stratosphere. In the one, the middle latitudes vary oppositely to low and high latitudes, and in the other the changes at higher latitudes are out of phase with those at lower latitudes.

A shorter trend consisting of opposite changes at middle and high latitudes is superposed on the above variations which a cross-spectrum analysis shows has a preferred time scale of one to three weeks. The contrast between middle and high latitudes thus undergoes a series of corresponding fluctuations and we show that these are associated with amplitude changes in waves 1 and 2 in that the meridional contrast decreases when the amplitude of one or both waves is large, and *vice versa*.

1. Introduction

Looking through the maps of the changes of stratospheric monthly mean winter temperatures and pressure heights in the Northern Hemisphere, which appear regularly in the Meteorologische Abhandlungen of the Freie Universität in Berlin, one notes that two patterns account for most of the changes. In the one the changes in low and high latitudes are opposite; in the other the changes at middle latitudes are opposite to those at low and high latitudes. In the threee winter months of 1966–1967 in Fig. 1, a and b, for instance, the polar and tropical temperature changes are in the same sense and contrary to those in middle latitudes, whereas in 1967–1968 the changes are opposite in low and high latitudes, as illustrated in Fig. 1, c and d, by means of pressure heights.

These trends are further described below, mainly by means of temperatures, and it is also demonstrated that a shorter time variation of opposite phase in middle and polar latitudes is superposed on them and that the latter is linked with oscillations of the planetary waves. In Part 2 we shall study the connection between this shorter variation and horizontal eddy transports of heat.

Our data are partly from the daily maps analyzed at the Freie Universität in Berlin and partly from the daily analyses of the National Meteorological Center; the source is given in each figure caption.

2. Monthly changes

The maps of monthly changes of 30-mb temperature through the winters in Fig. 1 are supplemented by zonally averaged changes for the rest of the two winters in Fig. 2. The winters were at either extreme of stratospheric circulation since a protracted breakdown of the polar vortex took place from the top to the bottom of the stratosphere in 1967–1968, whereas the vortex suffered no major disturbance during the winter of 1966–1967—at least not in the lower half of the stratosphere. At the beginning of winter in 1967 (Fig. 2, A) the zonal mean temperature rose from November to December at middle latitudes while it fell at high and low latitudes. This was followed by a temperature rise north of 50°N from December to January and a simultaneous fall to the south, and by a rise in the tropics and fall at higher latitudes from January to February. At the end of the winter the zonal mean rose at all latitudes from February to March but substantially more so in middle than in high and low latitudes.

In the winter of 1966–1967 the zonal mean temperature fell at high and low latitudes during the first half of the season while it rose, or fell less, at middle latitudes. During the second half the rises were at high and low latitudes and the falls, or smaller rises, at middle latitudes.

The change from December to January in the zonally averaged 30-mb temperature is shown in Fig. 3 for the nine years available after the first year with reliable temperature analyses from the Freie Universität (see introduction to Labitzke, 1972). There were five

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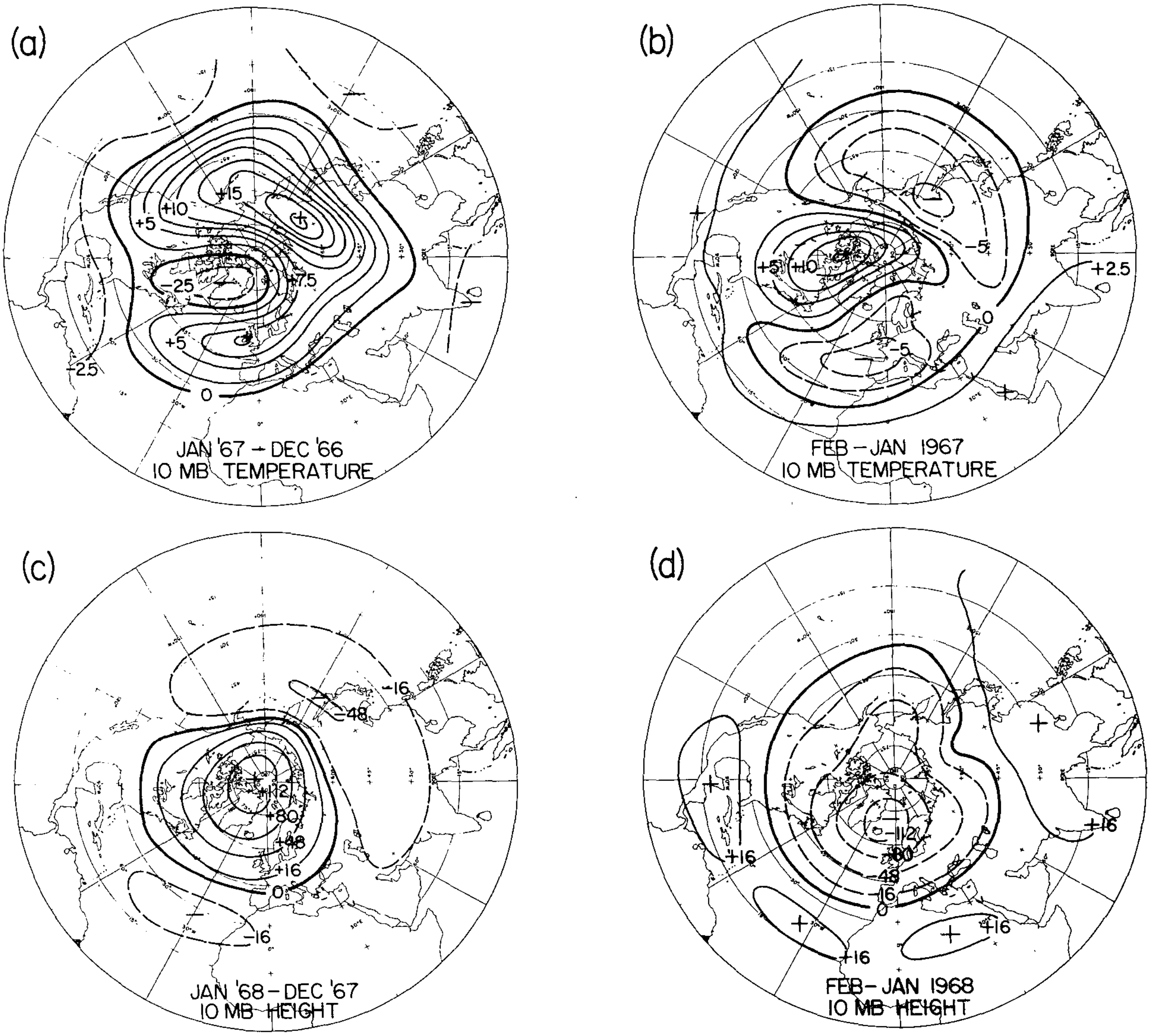


FIG. 1. a) 10-mb temperature (°C), January 1967 minus December 1966. b) 10-mb temperature (°C), February minus January 1967, c) 10-mb height (dam), January 1968 minus December 1967, d) 10-mb height (dam), February minus January 1968. Data from the Freie Universität, Berlin.

winters in this period when tropical and polar regions varied in the same sense but opposite to middle latitudes, and these were months without breakdowns of the polar vortex; in the four other years, when low and high latitudes were out of phase, the vortex broke down in January. Figures 1–3 illustrate well the stratosphere's limited choice of monthly change.

The pattern of change in which height and temperature at middle latitudes vary contrary to those at low and high latitudes means, of course, that the changes of the zonal wind or the thermal wind will be of opposite sign on either side of the largest height or temperature change at middle latitudes. In the other pattern of change the wind changes sign (or decreases or increases) over a major part of the hemisphere.

The temperature trends identified above are, of course, not well described by the arbitrary, although convenient, period of one month. To remedy this shortcoming, we have prepared Fig. 4 showing the course of the temperature through the colder part of the year in three different years: one with a major warming (Fig. 4, A), one with a fairly high temperature level in midwinter but without a major warming (Fig. 4, B), and one with a very low midwinter temperature level (Fig. 4, C). Note that the ordinate scale at 80°N is half that at 20°N and 50°N. The figure speaks for itself as regards the duration of the trends described in Figs. 1–3; they can be followed through the lines connecting the monthly means and last from one to three months. It is, in addition, worth noting that in the winters

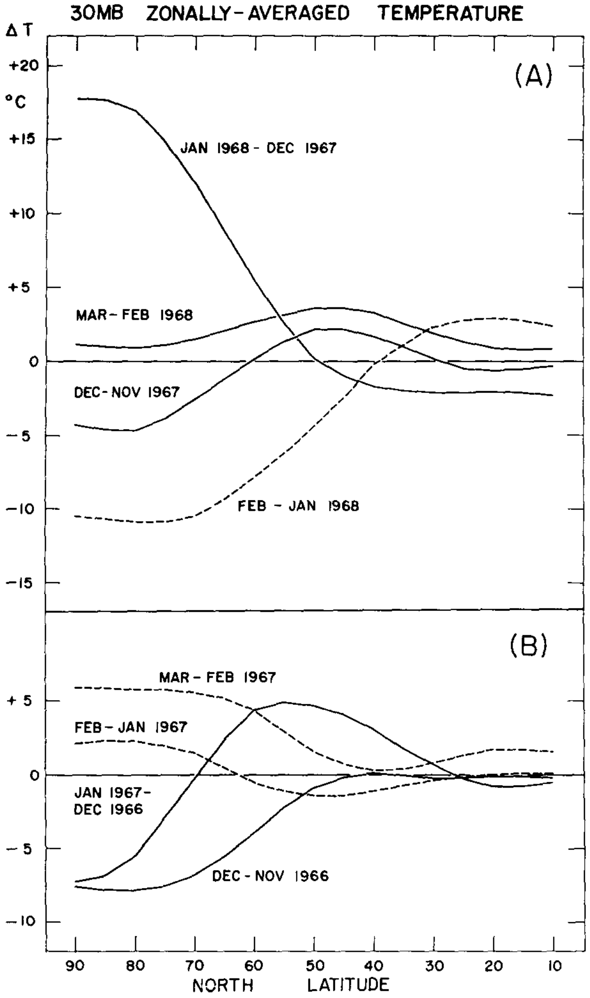


FIG. 2. Monthly changes of 30-mb zonally averaged temperature (°C) in (A) winter of 1967–1968, and (B) winter of 1966–1967. Data from the Freie Universität, Berlin.

without a major breakdown (Figs. 4, B and 4, C) the zonally averaged temperature at 50°N rose from the beginning till the end of winter, the tropical temperature dropped at the same time, and the polar temperature ran counter to the one in middle latitudes until middle or late winter. In the disturbed winter (Fig. 4, A) the rise at 50°N stopped when the warming began in mid-December and for the rest of the winter 50°N varied in the same sense as 80°N and opposite to 20°N. All of these trends indicate a substantial amount of dynamic control of the stratospheric temperature in winter

The zonally averaged temperature contrast between higher and lower latitudes changes sign during a major warming, as is well known, but this may also happen during periods when no breakdown is observed at the routinely analyzed levels. Examples of this can be seen at 50 and 80°N in late November 1968, early March 1969 and the middle of February 1972 (Fig. 4 and Fig. 7, B and C). Such a reversal of latitudinal temperature contrast implies, of course, that the zonal thermal wind changes sign and that the westerly circulation at higher levels probably weakens.

3. Shorter-period changes

It is immediately apparent in Fig. 4, and particularly in Fig. 4, B, that in addition to the longer variations described above, the temperature at 50°N very often varies oppositely to that at 80°N on an average time scale of a couple of weeks and with a bigger amplitude at 80°N. Such oscillations may be similar to those of opposite phase on either side of 30–40°S which Fritz and Soules (1970) found in satellite radiances, except that in our instance the nodal latitude is farther poleward and the oscillations do not reach into the tropics.

Even though they cannot be identified as readily as in the two other winters, the opposite oscillations are present in 1971–1972 (Fig. 4, C). Figure 5, for example, shows the zonally averaged temperature difference between each day and the day before in January 1972 when, apart from a few instances (e.g., the 8th–10th), the day-to-day changes north of 55–60°N tend to be opposite to those to the south. The largest changes in the southern domain are near 40°N; in the polar region they occur at any latitude and are generally bigger than their opposite at middle latitudes. The

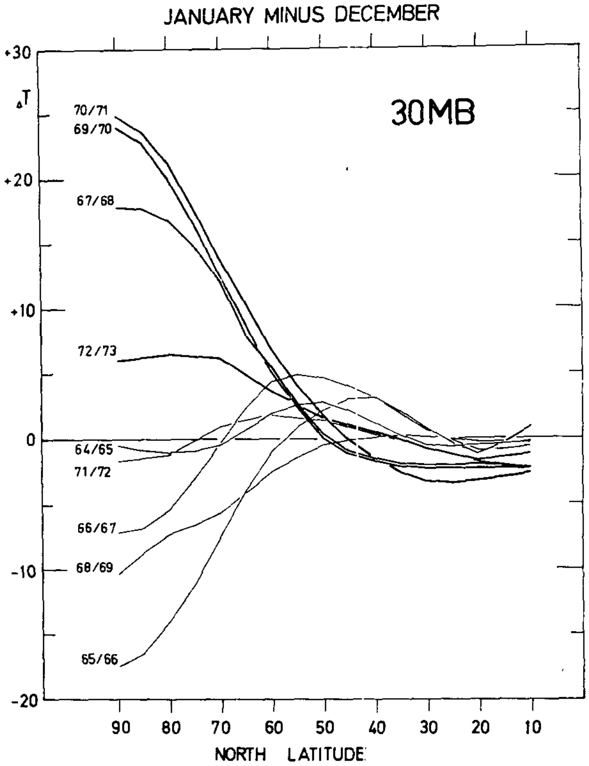
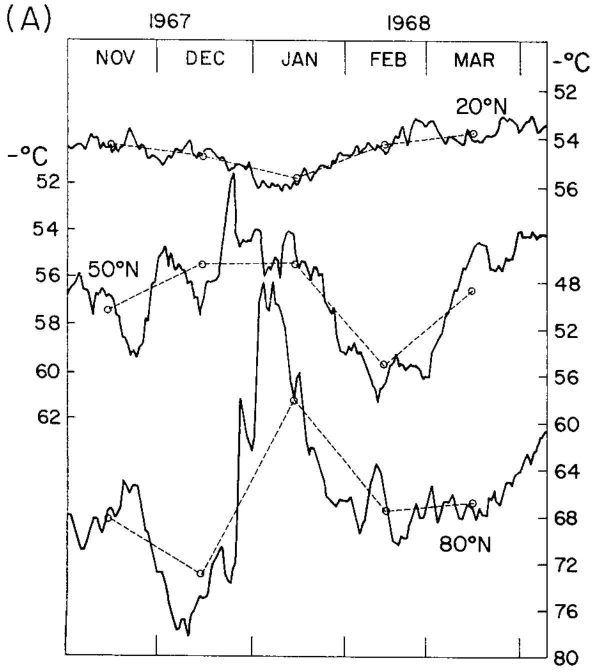


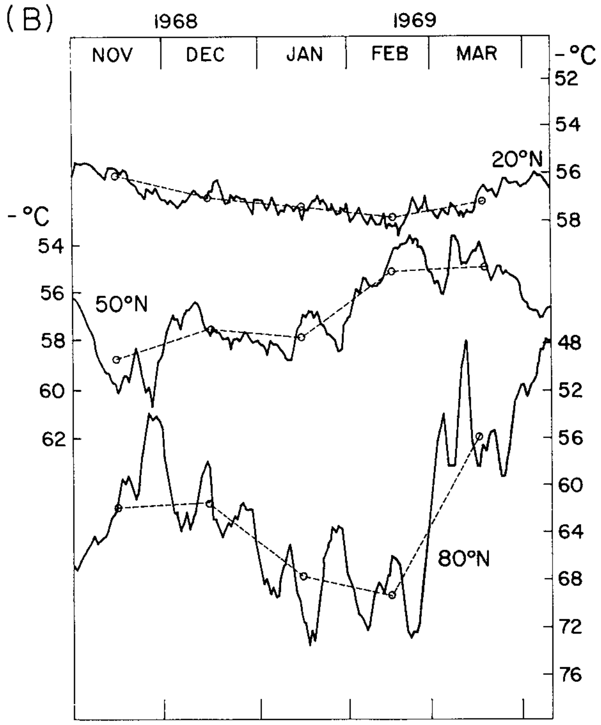
FIG. 3. Zonally averaged 30-mb temperature (°C): January minus December in nine different years. Data from the Freie Universität, Berlin.

drawing gives an impression of a standing wave with its nodal latitude near 60°N.

The opposing short-term temperature oscillations at middle and high latitudes in Figs. 4 and 5 are clearly not cyclic; that is, they have no regular period but occur over periods of less than one month. To ascertain the spectral range of the oscillations and to test if the out-of-phase character is typical of more winters than the three shown in Fig. 4, we have made a cross-spectrum analysis of the 30-mb temperatures of the eight winters 1964–1965 to 1971–1972, using the daily analyses from the National Meteorological Center.

The method of estimating the spectra was that suggested by Bingham *et al.* (1967). The sample mean of an N-member series is removed. Ten percent of the first and last members of the series is tapered by multiplication by a cosine curve so that both ends of the series are zero. The fast Fourier transform then determines $N/2+1$, raw, harmonic coefficients. Spectrum estimators can be computed by averaging the squared amplitudes of L adjacent, raw, harmonic coefficients over a frequency interval, a technique we shall refer to as frequency averaging. A second way to proceed is to break up the time series into q segments, determine the raw, harmonic coefficients of each segment and then average the squared amplitude at a given frequency over all q segments. We use here both frequency averaging and segment averaging to produce smoothed spectral estimates. Since each Fourier component has two degrees of freedom (dof), the combined frequency-segment averaging results in a total of





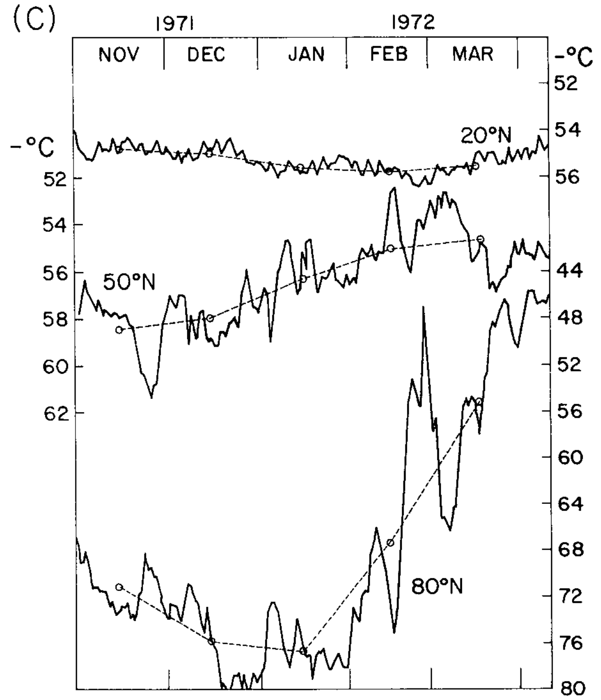


Fig. 4. The march of zonally averaged 30-mb temperature (°C) at 20, 50 and 80°N in the winters of (A) 1967–1968, (B) 1968–1969, and (C) 1971–1972. The circles are the monthly means. Data from the National Meteorological Center.

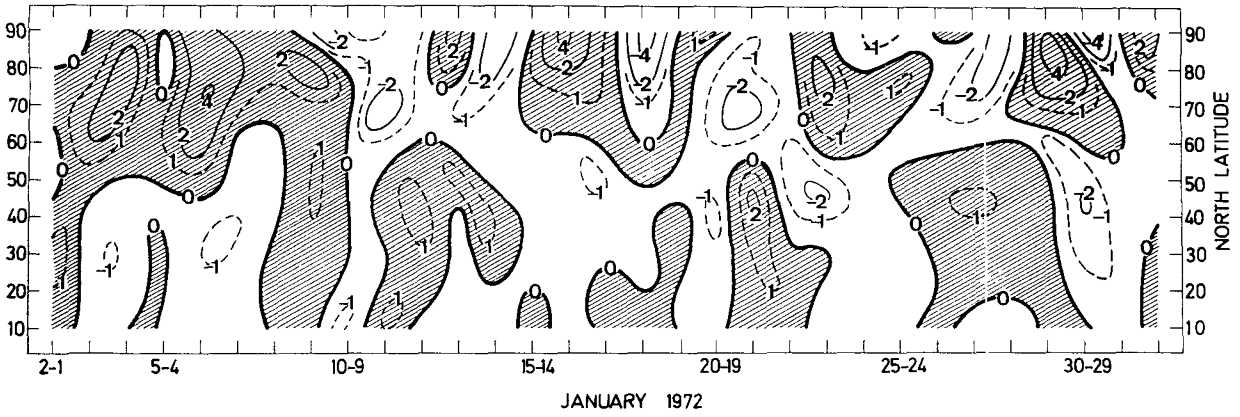


FIG. 5. Difference between one day and the previous one of 30-mb zonally averaged temperature (°C) in January 1972. The times when the temperature fell from one day to the next are shaded. Data from the Freie Universität, Berlin.

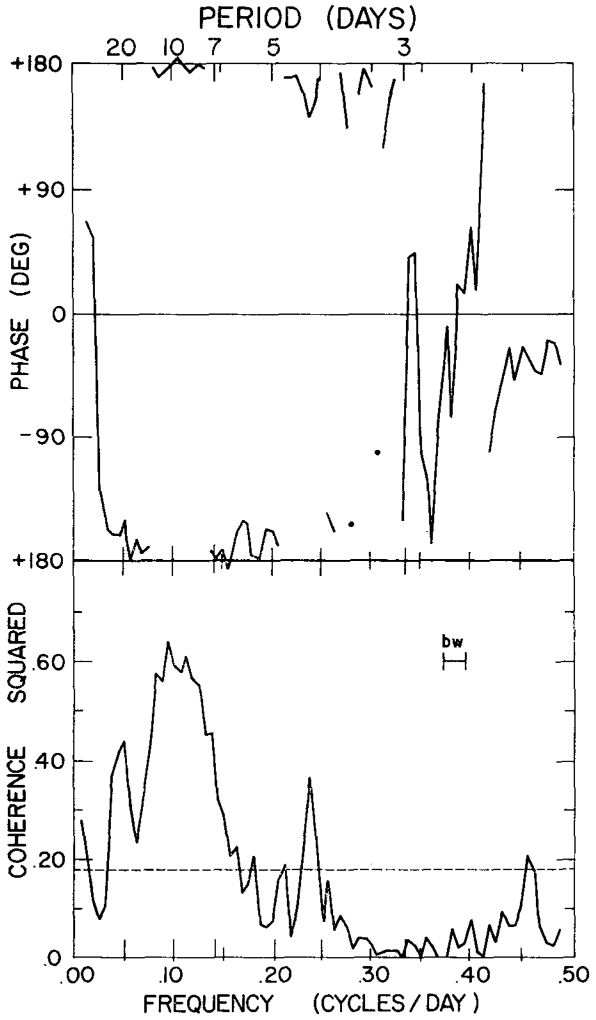


FIG. 6. Coherence squared bottom, phase top, between the zonally averaged 30-mb temperature for the latitude bands 40–50°N and 70–80°N. Positive phase means that 40–50°N band leads 70–80°N band. The dotted line is the 99% confidence limit. Data from the National Meteorological Center.

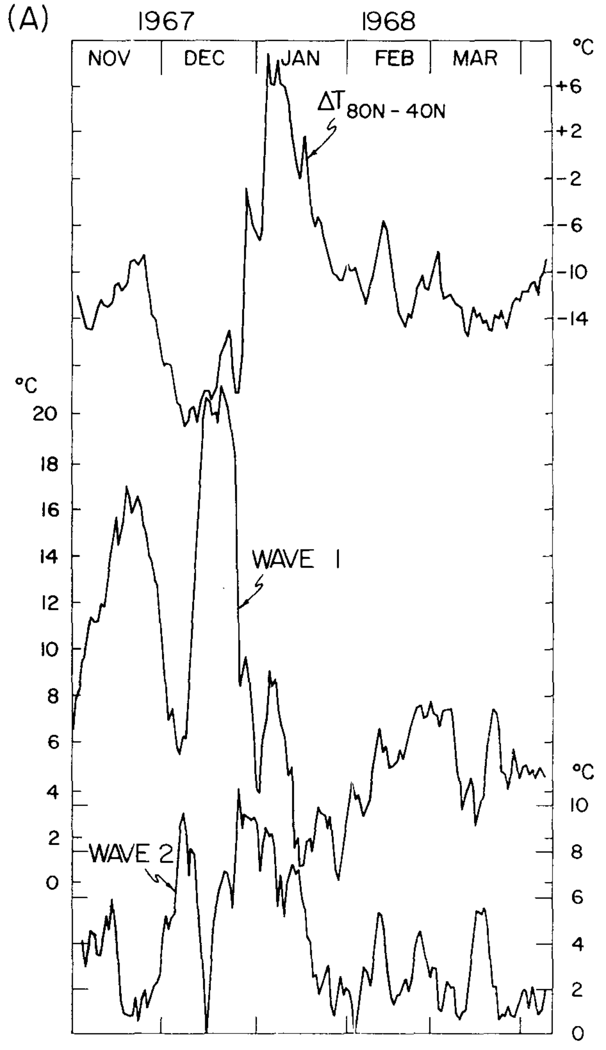


FIG. 7a.

approximately $2Lq$ dof.[3]

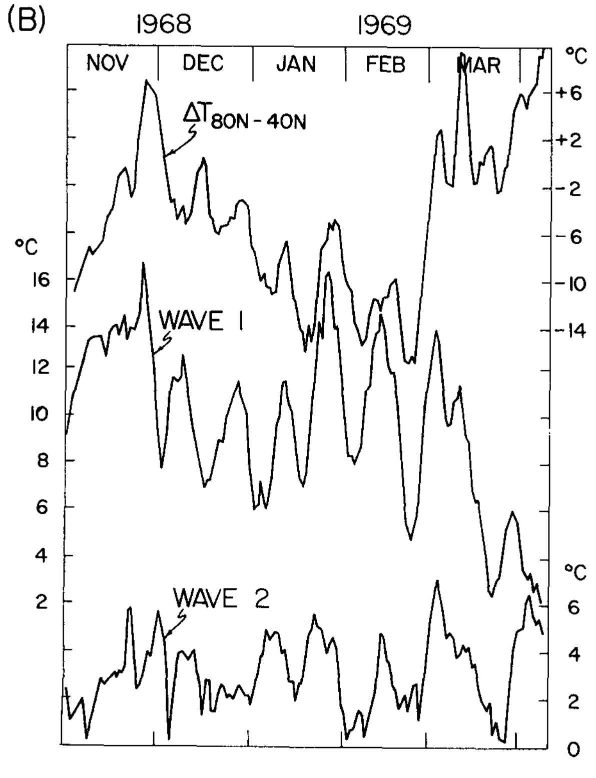
Initially, zonal-mean 30-mb temperatures determined from NMC analyses were studied for the eight winters. Each winter was treated as a separate segment of the time series. Twelve GMT data from 160 days, beginning 1 November and ending in early April, comprised each winter segment. One time series, $x(t)$, was taken to be the zonal mean temperature for the latitude band of 40–50°N and a second time series, $y(t)$, was taken as the zonal mean temperature for 70–80°N. The smoothed spectral estimates, φ_x and φ_y, were then determined for the individual series x and y by the combined frequency-segment averaging. Frequency averaging was accomplished by a 3-point running average ($L=3$) passed over the squared amplitudes of the raw harmonic coefficients of each segment. For the segment averaging, we had eight winter segments so $q=8$ and the dof are approximately $2\cdot3\cdot8=48$.

The coherence-squared statistic is determined by

$$\mathrm{coh}^2=\frac{\varphi_{xy}{}^2+\varphi_{xy}{}^{*2}}{\varphi_x\varphi_y}$$

where φ_{xy} and $\varphi_{xy}{}^*$ are the real (co-spectrum) and imaginary (quadrature spectrum) parts of the cross spectrum determined by the same frequency-segment averaging. The tangent of the phase angle between the two series is given by the ratio $\varphi_{xy}{}^*/\varphi_{xy}$.

The two individual, averaged spectra (i.e., that for the 40–50°N band and that for the 70–80 band) showed no marked peak in the range of less than one month; however, the average coherence squared (Fig. 6) does have a strong maximum from about 0.14 to 0.05 cycles day^{-1} (1–3 weeks) which is above zero at a level greater than the 99% confidence limit. The 99% limit determined from the tables of Amos and Koopmans (1963) is about 0.18 assuming 48 dof. The phase angles indicate that temperature oscillations in this frequency range tend to be out of phase between middle and high latitudes. This demonstrates that although this frequency range is not necessarily a preferred one for



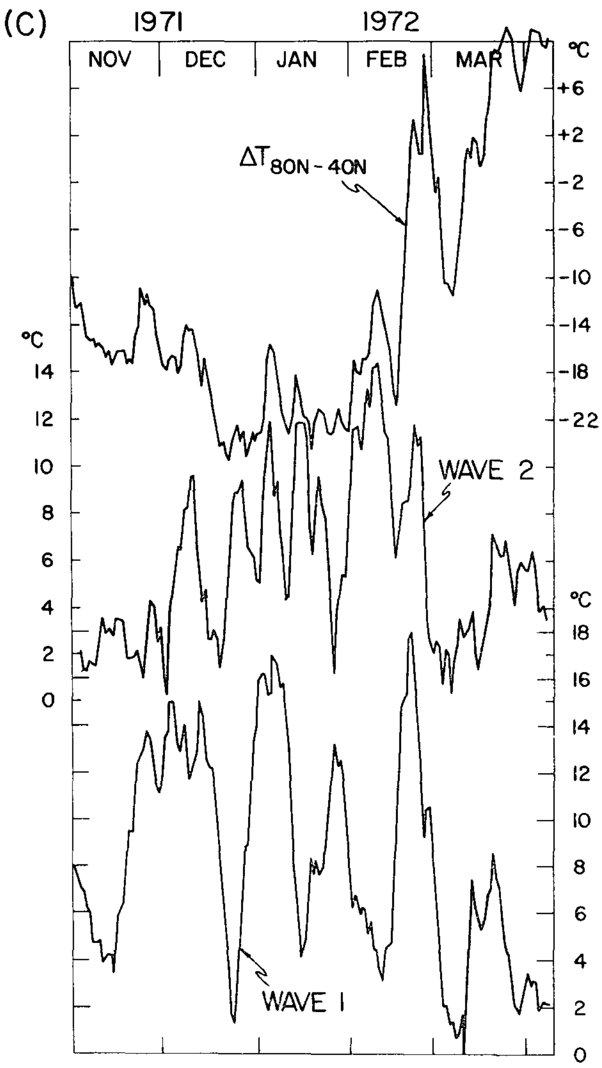


Fig. 7. Daily values of the zonally averaged 30-mb temperature difference (°C) 80°N minus 40°N, and of the amplitudes (°C) of the zonal harmonic temperature waves 1 and 2 in the winters of (A) 1967–1968, (B) 1968–1969, and (C) 1971–1972. Data from the National Meteorological Center.

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[3] The tapering procedure results in fewer than N dof in the original data and hence actual dof of the spectral estimates is somewhat less than $2\ Lq$. The reduction is on the order of 10% (Julian, 1971).

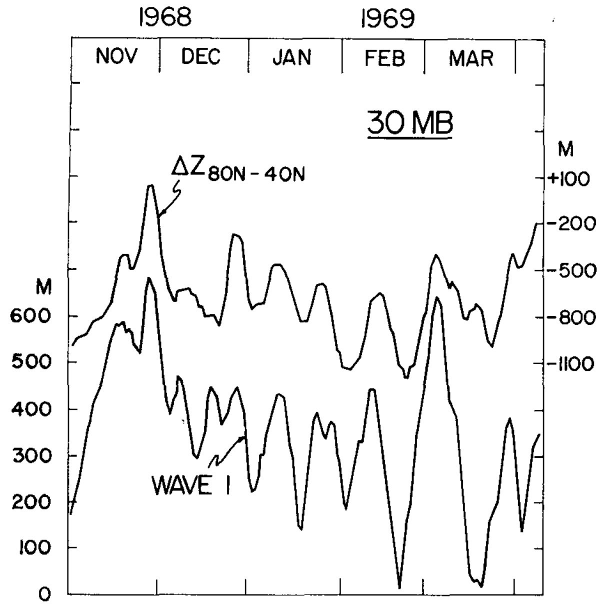

FIG. 8. Daily values in the winter of 1968–1969 of the zonally averaged 30-mb height difference (m) 80°N minus 40°N, and of the amplitude (m) of the zonal harmonic pressure-height wave 1. Data from the National Meteorological Center.

temperature variations in either the middle or high latitude band, it is preferred for coherent, out-of-phase temperature variations *between* the two bands.

The relative minimum in the coherence squared near 0.025 cycles per day probably reflects the presence of the two patterns that are evident in the monthly changes discussed at the outset. At these longer time scales middle and high latitudes sometimes vary in phase and sometimes out of phase.

Cross spectra were computed separately for four years with a major stratospheric warming and for four years without. In both instances, the resulting coherence squares had relative maxima exceeding 0.50 in the range 0.14 to 0.05 cycles per day. We therefore conclude that the out-of-phase seesaw in zonal mean 30-mb temperature across 60°N is a frequently occurring feature in all eight winters and that its typical time scale is one to three weeks.

4. Zonal harmonic temperature waves and meridional temperature contrasts

The opposite fluctuations of the temperature at middle and high latitudes mean, of course, that the temperature contrast between the two regions undergoes similar fluctuations in time, and the following shows that the changes in the temperature contrast are linked with the zonal harmonic waves, as suggested by Matsuno (1971).

The daily temperature difference between 40°N and 80°N and the daily amplitude of waves 1 and 2 at 60°N, obtained from a harmonic analysis of the temperature field along the parallel, are shown together in Fig. 7 for the same three winters used in Fig. 4. In the mean, these two waves reach their peak at 60–70°N in the stratosphere and together account for most of the total variance (van Loon *et al.*, 1973). It is plain from Fig. 7 that the oscillations in the latitudinal temperature contrast are associated with fluctuations in wave amplitudes: Sometimes the fluctuations in the temperature contrast are matched, on both the time scale de-

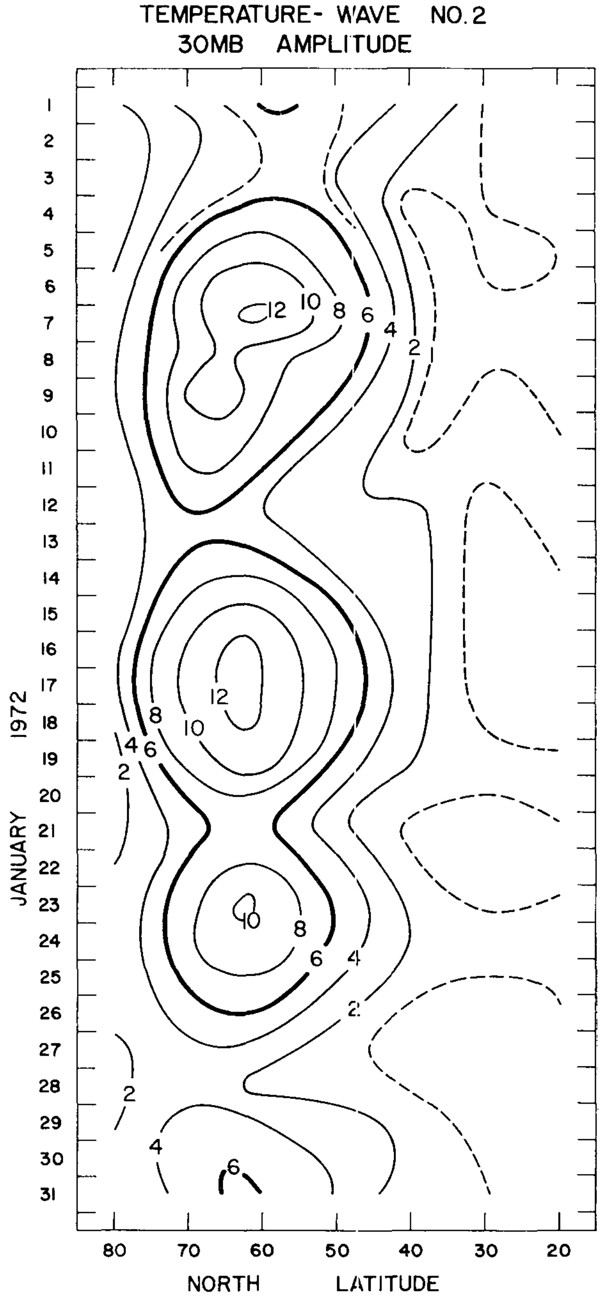

FIG. 9. Daily values (°C) of zonal harmonic temperature wave 2 in January 1972. Data from the National Meteorological Center.

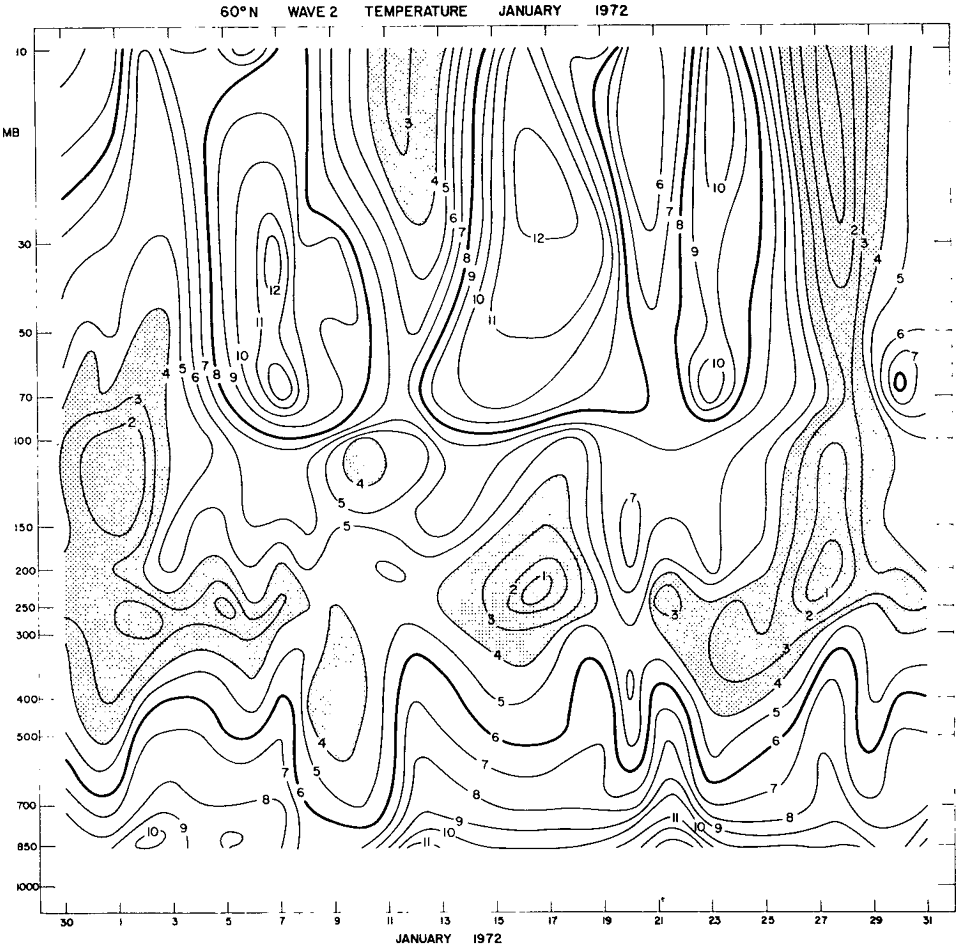

Fig. 10. Vertical section for January 1972 of the amplitude (°C) of zonal harmonic temperature wave 2 at 60°N. Data from the National Meteorological Center.

scribed in Section 3 and on longer time scales, by fluctuations in wave 1 alone (most of Fig. 7, A); sometimes by both waves (most of Fig. 7, B), and sometimes by wave 2 alone (most of Fig. 7, C). The relation between wave amplitude and latitudinal temperature contrast is in the sense that amplitude peaks in one or both waves are accompanied by decreases or reversals of the temperature difference, and conversely; and this pattern suggests that there is a corresponding inverse relation between eddy available potential energy and zonal available potential energy. The relationship between wave amplitude and temperature contrast is least obvious in the year with the major warming, 1967–1968. Even the spring reversal of the temperature contrast toward the end of February (Figs. 7, B and 7, C) must contain a large dynamic component as it takes place in several surges, each accompanied by a peak in one or both waves.

The oscillations in the zonally averaged latitudinal contrast of pressure heights in the stratosphere are likewise linked to oscillations in the wave amplitudes. An example of this is Fig. 8 where the close connection between the growth and decay of pressure wave 1 and the increase and decrease of latitudinal pressure-height contrast in the winter of 1968–1969 is plain to see. Zonal thermal wind and zonal geostrophic wind variations in the stratosphere on the one-to-three week scale are therefore closely linked to pulsations of the large-scale waves.

It should be noted that Hirota and Sato (1969) showed a negative correlation between the zonal wind at 65°N and the amplitude of wave 1 at 60°N, and that Finger *et al.* (1966) found a 10–15 day oscillation in the central height of the north polar low in the winter of 1964–1965, both of which observations are most likely part of the oscillation which we describe.

5. Vertical extent of the zonal harmonic waves

The daily zonal waves observed in the winter stratosphere are generally accepted as being associated with the waves in the troposphere. Muench (1965), for instance, found "good evidence for the existence of long waves which amplify near the earth's surface and propagate this amplification upwards". His analysis was of pressure-height waves, but since we are dealing with temperatures we have made an analysis of the temperature waves. From Fig. 7, C, we chose January 1972 as a period when the relationship between wave 2 at 60°N and the temperature contrast between 40°N and 80°N was good. During this month the peak of temperature wave 2 at 30 mb stayed at 60–65°N (Fig. 9), and the wave had three maxima to each of which corresponded a minimum in the meridional temperature difference (Fig. 7, C), and four minima, each accompanied by a peak in the temperature difference.

The vertical time section of temperature wave 2 at 60°N in January 1972 in Fig. 10 is based on daily NMC data at the standard pressure levels listed on the ordinate. The wave is biggest at the bottom of the troposphere; it decreases upward to a minimum at the tropopause and increases again in the stratosphere. The three peaks discernible at 30 mb in Fig. 9 are continuous in the part of the stratosphere we are observing and reach their highest values below the top of the diagram; the four minima are similarly continuous. Despite the more complex pattern in the troposphere, it seems that for each minimum in the stratosphere there is a minimum in the troposphere three to five days earlier, and likewise for each maximum. The maxima and minima do not slope upward with time but occur on the same day in all of the troposphere or in all of the stratosphere. These variations in temperature wave 2 suggest a transient wave 2 which changes phase near the tropopause and moves through a standing wave 2. The delay between an extreme in the troposphere and the corresponding extreme in the stratosphere would depend on the amount by which the standing wave slopes from the vertical or by which the moving wave changes phase near the tropopause, or both.

Qualitatively, then, this indicates that the growth and decay of the zonal temperature waves in the winter stratosphere are linked to the growth and decay of the corresponding waves in the troposphere (although not all oscillations of a given wave in the troposphere penetrate into the stratosphere). As indicated in Figs. 7 and 8, the fluctuations in the latitudinal differences of height and temperature, and thus of the geostrophic wind, are to a large extent connected with fluctuations in the amplitude of the zonal waves. We may therefore presume that the oscillations of one to three weeks in middle and high latitudes in the stratosphere are linked to events in the troposphere through the large-scale waves.

6. Conclusions

1) During the winter the month-to-month changes of temperature and pressure height in the part of the stratosphere we have investigated take place mainly in two patterns. The one consists of changes in middle latitudes which are opposite to those in high and low latitudes, and the other of changes which are opposite in low and high latitudes.

2) Superposed on the variations of longer period are short-term oscillations which are out of phase between middle and high latitudes. A cross-spectrum analysis of temperature series from the two latitude regions shows that the out-of-phase variations are a significant feature in the eight winters investigated and their typical time scale is one to three weeks.

3) During these shorter-term opposing temperature fluctuations in temperate and polar regions, the meridional temperature contrast, of course, undergoes corresponding fluctuations. A comparison between the daily temperature contrast across 60°N and the daily amplitudes of waves 1 and 2 at 60°N demonstrates that the meridional temperature contrast decreases when the amplitude of one or both waves is large, and conversely. This strongly suggests that horizontal eddy transport of heat plays a part in the oscillations, and this will be studied in Part 2.

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