Winds and Wave Motions to 110 km at Mid-Latitudes. V. An Analysis of Data from September 1974–April 1975

A. H. MANSON, J. B. GREGORY, C. E. MEEK AND D. G. STEPHENSON

Institute of Space and Atmospheric Studies, University of Saskatchewan, Saskatoon, Canada S7N OWO

(Manuscript received 13 July 1977, in final form 9 November 1977)

ABSTRACT

The behavior of the daily noon winds at 52°N, 107° W(Saskatoon, Canada) at altitudes from 52 km to about 110 km are studied for the interval September 1974–April 1975. These data are compared with ROCOB temperatures and winds ($\lesssim 55$ km) for Churchill (94°N, 59°W). The thermal wind equation and running cross-correlation analysis are used to demonstrate the seasonal variations of the meridional temperature gradient, and of coupling, within the stratosphere, mesosphere and thermosphere. The effects of the stratospheric warming of January 1975 are also investigated. The correlations were dominated by this event, and show that coupling occurred between the stratosphere (20–30 mb) and mesosphere/thermosphere ($\lesssim 100$ km) during the first half of January. Spectral analysis for two intervals before and after the stratwarm show that coupling was more significant during the late winter; periods near 2–3, 4–5 and $\gtrsim 20$ days were involved.

Comparisons between daily mean winds and daily noon winds show that up to 100 km the daily variations are well represented by the noon data; above 100 km the daily variations are less reliable but trends are well represented by the noon data.

1. Introduction

In Paper II of this series (Gregory and Manson, 1975a), mean zonal cross sections of winds at 52°N, 107°W (Saskatoon, Canada) at altitudes 62–116 km for the years 1969–73 were presented. During the major stratospheric warmings (Paper III, Gregory and Manson, 1975b), it was found that the winds above the stratosphere were affected to varying altitudes (80–100 km); and thermal winds indicated that associated temperature changes occurred throughout the high-latitude mesosphere (1969/70, 1972/73).

In the present paper, some results of daily measurements of the noon winds (52–118 km) are presented, for the period 8 September 1974–27 April 1975. These were obtained by the partial reflection, radio wave drifts technique. During this period a stratospheric warming occurred. These wind data are compared with ROCOB winds and temperatures ($\lesssim 55$ km) from Churchill (94°W, 59°N). Correlations, coherences and spectral analyses are applied to various groupings of these data to find the extent of the coupling between various regions of the atmosphere.

2. Data

The radio winds data comprise the medians of up to 12 profiles obtained in 1 h soundings near local noon. Detailed discussions of the assumptions and analyses made in obtaining these data have been described in Papers I and II of this series (Manson *et al.*, 1974; Gregory and Manson, 1975a). Briefly, however, a 2.2 MHz vertical incidence radiowave sounder was used; and the time variations of the echo amplitudes were monitored at three antennas placed at the vertices of an equilateral triangle of side 2λ. Echoes from 52–118 km were sampled by a digital system which has 40 m gates spaced at 3 km intervals.

Values of the drift velocity were then derived by a method of similar fades (Manson *et al.*, 1974), but with the time displacements between the fading records calculated from cross-correlation analyses [see Pfister (1971) for a comparison of analysis techniques]. Taken in pairs, these time shifts provided three estimates of the drift velocity, appropriate to a 3 min sampling of the diffraction patterns. The median of the vectors (by angle) was used in later analyses, and the angle between the three estimates (the angular dispersion) was used to edit the wind data. The maximum value acceptable for the retention of any wind estimate was 145°, but this criterion led to the rejection of little data (mean dispersion is 15–20°).

In earlier papers in this series, we have assumed that the velocity calculated was appropriate to that of the neutral gas. A short comment on this is now required. Recent work in Australia (Stubbs and Vincent, 1973; Vincent *et al.*, 1977) has shown excellent agreement between the so-called "true velocity" (Briggs *et al.*, 1950) and data from radio meteors and rockets. The velocity we calculate here

0022-4928/78/0592-0599$05.00

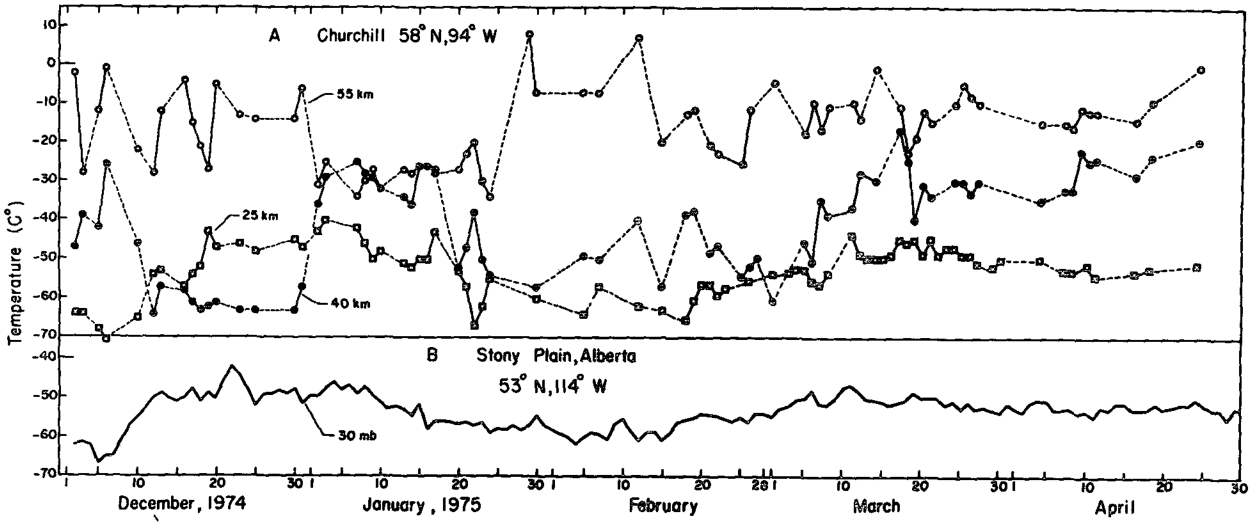

FIG. 1. Temperatures from rockets (ROCOB) for Churchill and from balloons for Stony Plain.

is effectively the "apparent" velocity of Briggs *et al.* (1950). We have therefore compared hourly mean profiles for several sets of data from 1976, using both true and apparent velocities. It was found that the ratio of these two mean velocities also depends upon the selection criterion discussed above, and a full report on analysis methods will appear elsewhere. In brief, however, it was found that up to about 100 km the 2 h mean profiles lay within the envelopes created by their respective standard errors: above this height the apparent velocities were typically $\lesssim 50\%$ greater than the velocity of the neutral gas (true velocity). Fortunately, this is not a serious factor for our purposes here. Subsequent analysis at this location will make use of the true velocity.

Temperatures and winds (ROCOB) obtained at Churchill, Manitoba (94°W, 59°N) have also been used: these provide dates for the onset of warmings at various levels in the stratosphere ($\lesssim 55$ km), as well as extending the height over which thermal winds may be calculated. Time series of ROCOB data from Primrose Lake, Alberta (110°W, 54°N) had poorer time resolution, and data comparisons were therefore not found to contribute anything significant to the overall analysis.

3. Winds and temperatures from December 1974–April 1975

The dominant features of this interval were the temperature and wind changes associated with the stratospheric warming of January 1975. A preliminary analysis of winds data from 16 December–22 January has been published elsewhere (Gregory *et al.*, 1975).

Temperatures from Churchill (ROCOB data) are shown in Fig. 1, along with 30 mb radiosonde values from Stony Plain, Alberta (53°N, 114°W), which is the closest sounding station to Saskatoon. From this it appears that temperature increases in the mid-stratosphere (~25 km) began over the Canadian prairies in mid-December, but that the most dramatic changes (increases at 40 km, decreases at 55 km) began near 1 January. The winds at Churchill (not shown), at altitudes between 30 and 40 km, began to shift from eastward through southward beginning in mid-December, and showed a reversed (westward) flow on 9 January. The remainder of the time series shows the recovery from the warming, the transition into the springtime regime, and some indications of a minor warming in March.

Winds from Saskatoon are shown in Figs. 2a and 2b: the daily values are means, for the four height intervals shown, of values from the hourly noon median profiles. The height resolution has been improved from 15 km (Gregory *et al.*, 1975) to 12 km. There were few gaps in the resulting data sequences, and these were quite evenly distributed, so that the time series shown here and used in other analyses were effectively insensitive to the interpolation methods used to complete them. In this case, gaps in the layer-means were filled by random numbers lying within the standard deviation of the curve, and three passes of a 1-2-1 filter were then applied: periods less than 5 days are then attenuated by $\geqslant 10$ dB so that longer term variations could be followed more easily. The weakening of the eastward wind, beginning about 25 December, is evident in all layers. In contrast, the meridional winds (Fig. 2b) show comparatively small systematic variations during the stratwarm: only the winds from 103 to 118 km evidenced large changes in early January that suggest a slow rotation of the wind vector. The extension of the series to 27 April shows the recovery of the eastward zonal flow below 100 km in January and February, and then the trend toward weaker flow

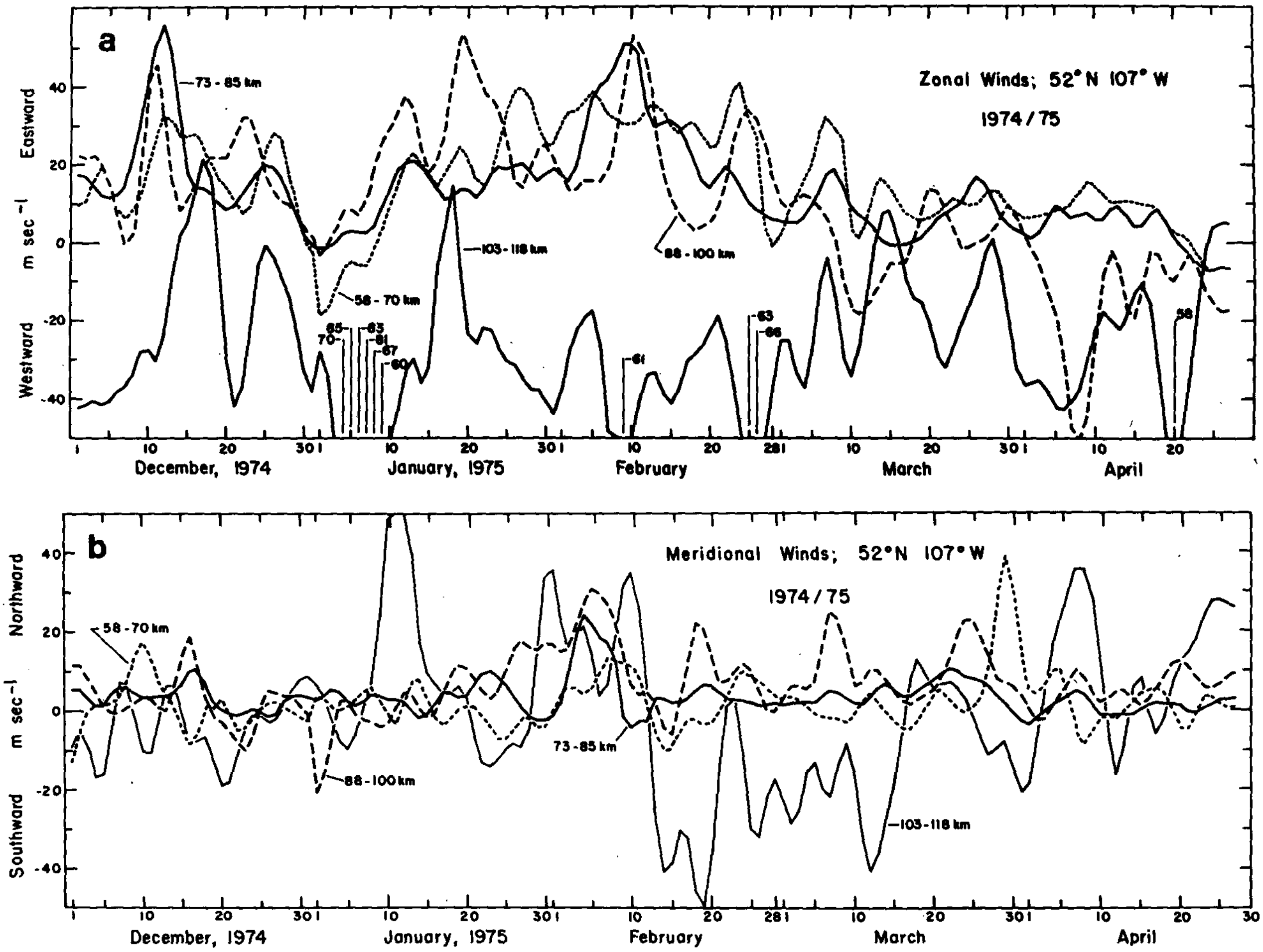

FIG. 2. Zonal (a) and meridional (b) components of the daily mean wind, for 1 h at local noon, and in four altitude ranges, at Saskatoon. Short periods (<5 days) are effectively removed (attenuated by ⩾10 db).

and eventually westward flow in March and April. This seasonal transition has been a consistent feature of other years studied (Gregory and Manson, 1975b). There was no obvious response of the zonal flow above 58 km to the minor warming in March.

To assess the related changes in meridional temperature gradient, the thermal winds for the mean weekly profiles (⩽7 per week) were calculated for Saskatoon (radio winds) and Churchill (ROCOB). Data from 8 September to 30 December were also included; although these did not include any interesting short-term variations, they allowed the seasonal trends to be assessed. The winds data were smoothed with a 1-2-1 filter before the vertical wind gradient was calculated, to minimize the effects of gaps in the data and small-scale waves; the sign of the corresponding north-south temperature gradients are shown in Fig. 3. A positive gradient implies that the atmosphere is warmer to the north and vice versa. Although Churchill is ~1000 km northeast of Saskatoon, general similarity of variations in circulation and planetary waves can be expected (e.g., Muller and Kingsley, 1974), so data from the two locations are included on the same figure for convenience. A displacement of approximately 1 week would bring the two sets of data into better agreement. It is evident that at the time of the warming in the upper stratosphere (the last week in December) the gradient was consistent with a mesosphere which was warmer to the north, up to about 75 km, but in the following week the gradient reversed throughout the mesosphere (65–88 km). Also, as the warming spread downward during January, there was a negative north-south gradient in the upper stratosphere and lower mesosphere ($\lesssim$65 km). This latter behavior is similar to other years studied (1969/70, 1972/73; Gregory and Manson, 1975b). Above this height layers with alternately positive and negative gradients existed. This is also similar to earlier warmings (e.g., Labitzke, 1972), although the regions of positive gradient between 65–90 km that occurred just after the warming event, were much smaller than in 1969/70 or 1972/73.

These differences are also apparent when the sea-

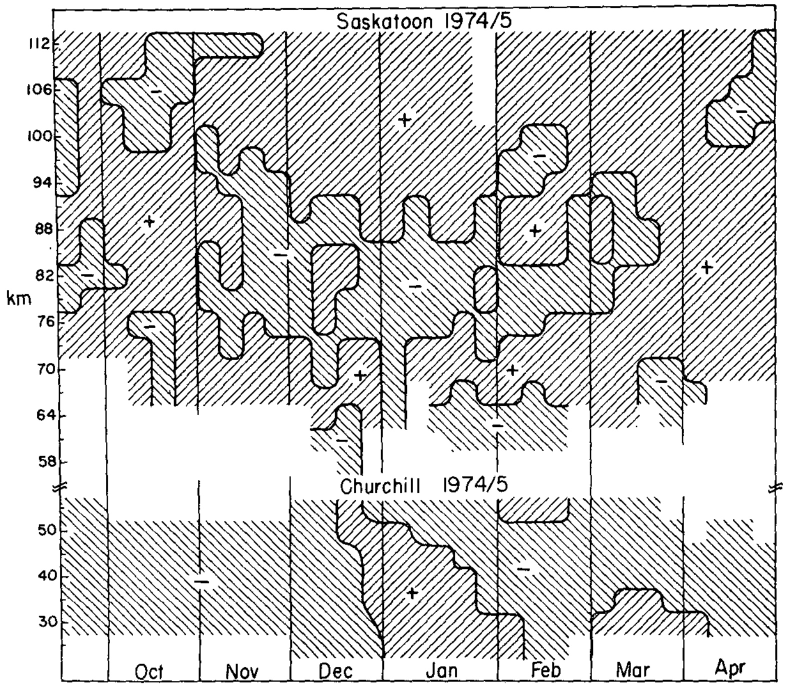

FIG. 3. North-south temperature gradients. Positive values imply that the atmosphere is warmer to the north and vice versa.

sonal variations in the temperature gradient are considered. There was a negative north-south gradient in the high mesosphere and lower thermosphere (73–90 km) from November to early March. The extent of this was much greater in height and time than in 1969/70 or 1972/73. It is also useful to compare these results with the *mean* gradients (1969–73) shown by Gregory and Manson (1975a). There it was shown that the mean gradients below ~90 km were alternating or uncertain in sign during winter, probably due to the effect of stratwarms occurring at varying times during December and January in several years (Gregory and Manson, 1975b). It now appears that the *extent* of the relative northward cooling may

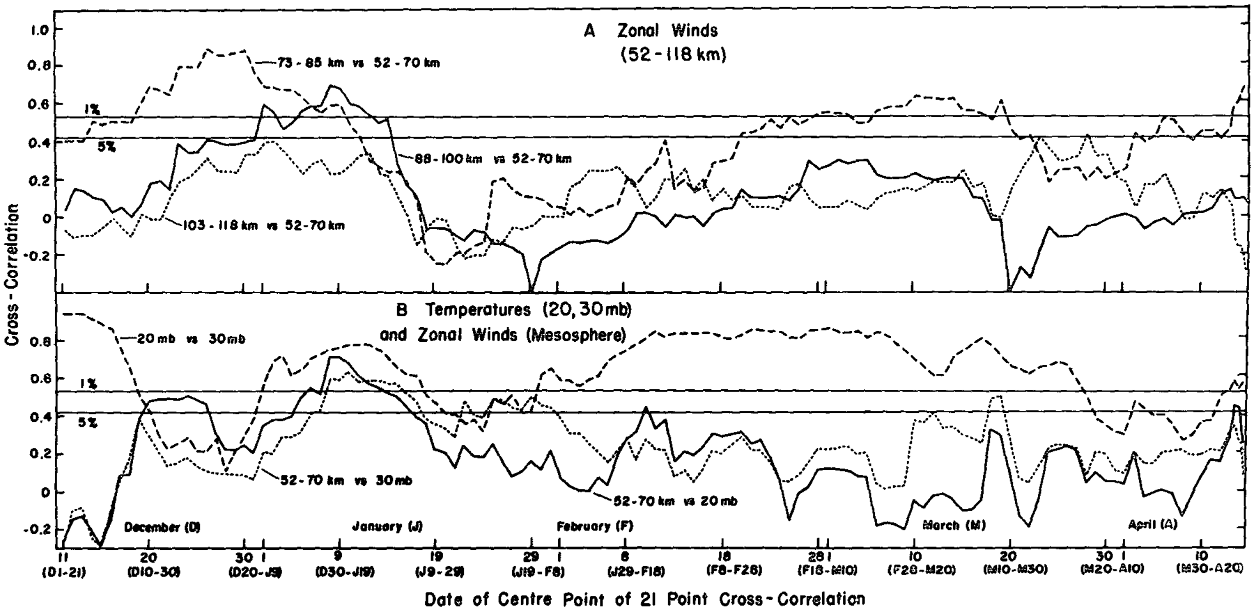

FIG. 4. Cross-correlation coefficients of zonal components of winds at Saskatoon, between four altitude ranges, and stratospheric temperatures and (zonal) mesospheric winds.

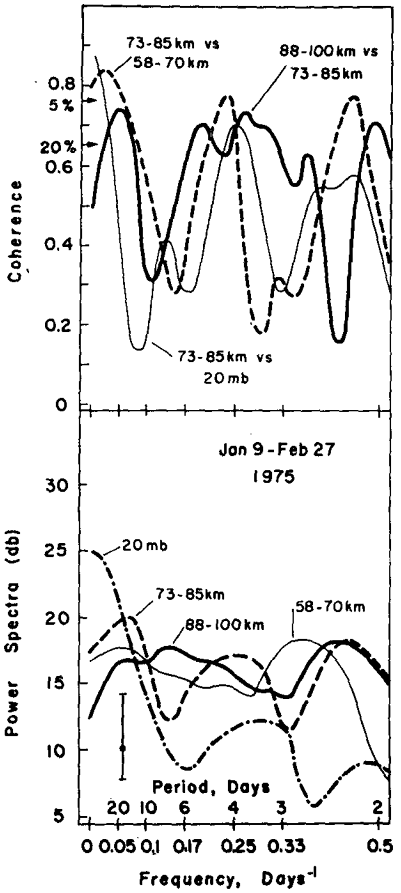

FIG. 5. Variance spectral densities (power spectra) and coherences for meridional winds (58–100 km) from Saskatoon and stratospheric temperatures (20 mb) from Stony Plain. The 20% confidence limits on the power spectra are +4, −2.5 dB; 5 and 20% confidence limits on the coherences are marked.

also vary significantly from year to year. Above 90 km, the gradient was positive for winter months, both in the mean cross-section (1969–73) and for 1974/75.

Two other observations should be made. First, the effect of the minor warming in the stratosphere during March appears to be limited to the lower stratosphere (Fig. 3). And second, the nature of the meridional temperature gradients shown here is essentially a limited, regional view of what is a hemispheric phenomena. Certainly, as thermal distributions are often not symmetrical about the pole, any inferences about poleward heating must be restricted to the location north of the station.

4. Correlations and coherences for various intervals

a. Correlations, December–April

The wind data discussed above are unusual in that they represent an almost continuous set of about 230 days. Various types of statistical analysis were therefore attempted.

The most useful involved the use of 21-point running cross correlations: the unfiltered winds data from 1 December to 27 April were used for Fig. 4a, and stratospheric temperatures (20–30 mb) from Stony Plain, Alberta (53°N, 114°W) were used in conjunction with the winds for Fig. 4b. The correlations between temperatures and winds were significant to better than 5% up to 70 km, in the first half of January, at the peak of the stratospheric warming. (The correlations were also significant at this time to 100 km, but for only a few days). Within the mesosphere and thermosphere (Fig. 4a), there were correlations at the 5% level between wind layers from 52 to 100 km, from mid-December until mid-January. Analyses were also completed using data from which low frequencies ($\geqslant 8$ day period) had been removed, and then repeated eliminating high frequencies. This showed that low frequencies were an essential part of the coupling between stratosphere and mesosphere, but that high and low frequencies were involved (i.e., both gave significant correlations) within the region from 52–100 km.

In general, the correlations between the layers and temperatures were low for the remainder of the winter and spring, apart for correlations between 52–70 km and 73–85 km winds, which recovered to near 5% in March. However, as there was insignificant coupling between stratosphere and mesosphere at this time, the mesospheric coupling was probably not related to the minor warming in the stratosphere (cf. Fig. 3).

b. Spectral analysis

The interval from 9 January to 27 February was one of two intervals chosen for analysis, as it lay between the times of the stratwarm and onset of the spring zonal wind reversal (Fig. 2); conditions are therefore reasonably stationary. Spectral estimates and associated confidence limits were calculated by the method given by Jenkins and Watts (1968, Chap. 6) and trends were removed: significances for the coherences were found by using flat spectrum random numbers, as well as using analytical estimates (Julian, 1975; Panofsky and Brier, 1958). The spectral densities of the spectra were smoothed with three passes of a Hanning filter to improve the clarity of the plots. Unsmoothed daily mean winds for three layers 58–100 km could be analyzed, without introducing excessive uncertainty in the spectra due to gaps in the series, and the resulting power spectra and coherences for meridional components (north-south) and 20 mb temperatures are shown in Fig. 5.

There is a tendency for peaks to occur in the power spectra and coherences near 2.5, 4 and $\geqslant 20$ days, although the former are not highly significant ($\sim 20\%$). However, the coherences are significant to almost 5% within the mesosphere, and are significant to $\sim 10\%$ between stratosphere and mesosphere at about 4 days.

Spectra for the zonal winds gave similar results (2.5, ~5, ~30 days). In most cases, the phase for the coherence was stable for the peaks, and was of the order of ±1 day between layers, including the 20 mb vs 73–85 km case. The consistency of these results, for zonal and meridional winds and both types of spectra, suggest that variations with these periods existed within the stratosphere, mesosphere and thermosphere, despite the absence of highly significant features in the power spectra.

The periods found above have been reported by other workers, e.g., Muller and Kingsley (1974), found periods near 2 days, and Fraser and Thorpe (1976) found periods near 6 and 15–20 days for mesospheric data. Two-day oscillations have also been found in time series obtained during a 10-day observation in August 1976 at Saskatoon. There is little theoretical discussion of 2-day waves in the literature, but a 5-day wave has been discussed in some detail (e.g., Geisler and Dickinson, 1976). Finally, we should note that aliasing of higher frequencies, including the diurnal and semi-diurnal tides (1, 0.5 day^{-1}), could affect the spectra shown here. However, most of this energy would be shown near the low frequencies (0.05 day^{-1}) of the figure and should not lead to the peaks evident in Fig. 5. Also, the analysis in Section 5 below suggest that the tidal effects should be small.

A second interval was chosen from 8 September to 31 December, as it lay between the time of the establishment of the winter eastward zonal flow in early September and the stratwarm event. Unfortunately, the power spectra of winds above 50 km revealed no significant peaks, and the significances of peaks in the coherences were usually poorer than 20%. The only consistency evident in the analysis was that these latter peaks usually had periods near 2–3, 3–4, ~5 and 8 days.

In conclusion, it would appear that there were not, in general, well-defined cyclical variations in the mesospheric and thermospheric winds during the interval 8 September to 31 December 1974: some regularity existed from 9 January to 27 February. A similar analysis upon some of these data has been completed by A. D. Belmont (private communication), who found spectral peaks near 2 days and about 5 days with a 5% significance level, and occasional spectral peaks at longer periods (~15 days) which were less significant (≥5%).

5. Short-term variations in the wind: 11–14 February

In the above analysis and in treatment of earlier stratwarms (Gregory and Manson, 1975a,b) it has been assumed that the noon wind profile (mean of ≤12 profiles taken in 1 h) was a useful indicator of the daily mean wind, despite the presence of tidal winds.

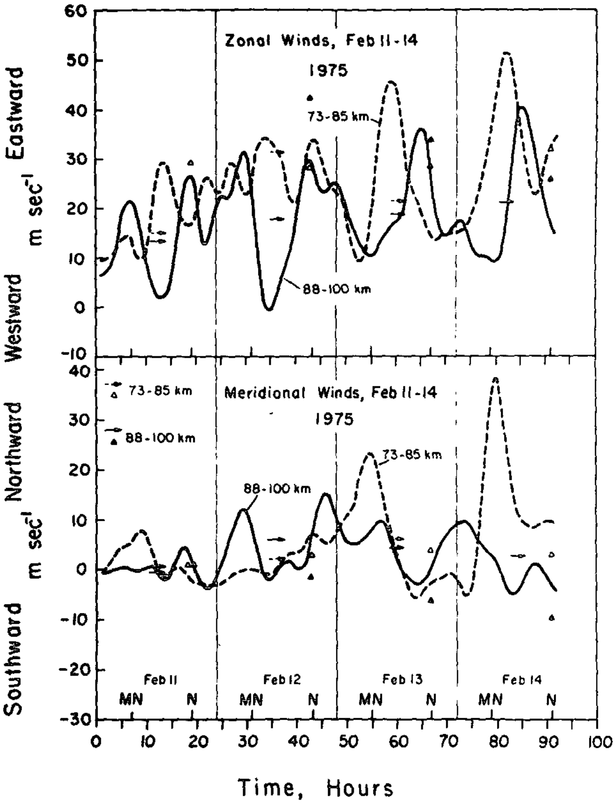

FIG. 6. Hourly mean winds for a 4-day interval: periods less than 8 h have removed from the four series. The daily mean values are shown by arrows. The daily noon values (N) taken from Figs. 2a and 2b are shown by triangles.

Technical developments and computer availability (the NCAR facility) have now made detailed tidal analysis possible. Fortunately, the first of these runs involved 4 days in February of 1975: the resulting data set provided time series of hourly means (≤12 h^{-1}) for 2 days from 73–85 and 88–100 km. The number of gaps in the series approached 20%, and satisfactory analysis was possible after interpolation.

Tidal winds (12 and 24 h periods) of varying phases are evident in the time series shown in Fig. 6; six passes of a Hanning filter have been applied so that periods less than 8 have been effectively suppressed. Harmonic analysis of the unsmoothed data gave amplitudes of 5 to 15 m s^{-1}, as suggested earlier (Manson *et al.*, 1974), and phases which changed daily by several hours. The daily *mean* values, obtained from harmonic analyses, may be compared (Fig. 6) with the appropriate daily *noon* values which have been taken from the time series, 1 December–27 April (Fig. 2).

These results are quite consistent with similar comparisons made for four 10-day runs in 1976, the full tidal results of which will appear elsewhere. We show here (Fig. 7) a comparison between zonal daily means and noon values for 5–14 April 1976: these results

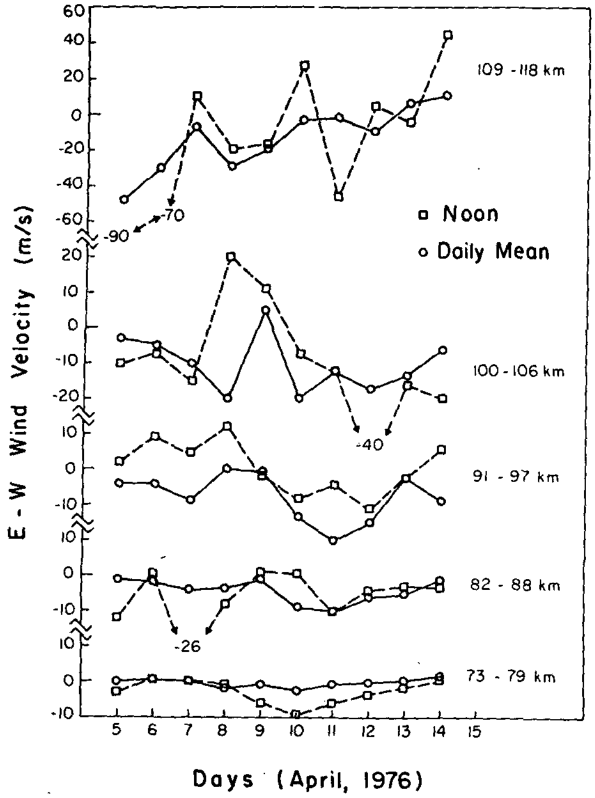

FIG. 7. Zonal components of the daily mean wind and daily noon wind for 5–14 April 1976 from Saskatoon.

are quite typical. Summarizing, we can say that below ~100 km, the daily variations are well reproduced in the noon values, with differences which are typically 5–10 m s^{-1} but may exceed 20 m s^{-1} on individual days. Above 100 km, the daily variations are not always reliably reproduced in the noon values, but the trend (positive to negative flow) is consistent.

The results of comparisons of this type are very important for the interpretation of data in this paper. For example, the six time series of Figs. 2a and 2b for heights below 100 km most likely reveal fluctuations (>5 day period) in the mean daily wind (and not fluctuation in tidal phase): the trend of the time series above 100 km should also reflect changes in the mean (daily) wind. It is also considered that the spectral peaks of Fig. 5, which all refer to heights up to 100 km, will be appropriate to the mean wind and not to tidal variability. Finally, although further study of interactions between tidal winds and mean flow are desirable, it would seem that the conclusions reached regarding variations in the weekly and daily noon winds in this and earlier papers (Gregory and Manson, 1975a,b) were quite justified.

6. Conclusions and summary

The data shown here represent the most complete study of mesospheric and thermospheric winds during an extended winter period which includes a stratwarm event. Running correlations (21 point) indicate that there was significant coupling within and between the stratosphere, mesosphere and thermosphere during the stratwarm event (mid-December 1974–mid-January 1975). The correlations were low for much of the remaining interval (early and late winter).

The thermal winds from October 1974 to April 1975 show in superb detail the changes in meridional temperature gradient appropriate to the mid-Canadian sector. In general there was a negative temperature gradient (consistent with cooler air to the north) in the upper mesosphere and lower thermosphere (73–90 km) from November to early March which was more extensive than during 1969/70 or 1972/73. A positive gradient existed above 90 km, which has been a feature of all of the years studied. There was again evidence of stratification, especially after the stratwarm. At the time of the stratwarm, the gradient was positive throughout the stratosphere and up to about 75 km in the mesosphere.

Spectral analyses of time series from two intervals, before and after the stratwarm, showed that cyclical variations and coupling between layers was much more significant during the late winter interval: periods near 2–3, 4–5 and $\gtrsim$20 days were then dominant. Harmonic analysis of 4 days of hourly soundings (92 points) allowed the resolution of 12 and 24 h tidal winds and the daily mean winds. This initial comparison, and another 10-day comparison, showed that the changing phase of the tides can lead to important differences between *noon* winds and the daily *mean* winds. However, below 100 km the daily variations were well represented by the noon values; and above 100 km the trends were evident from the noon values. More study of these differences is called for, however, as it is likely that the tidal variations may themselves be due planetary wave effects in the source regions in the stratosphere.

Acknowledgments. The work described above has been supported by the National Research Council of Canada, by the Atmospheric Environment Service, Environment Canada, and by the University of Saskatchewan through the Institute of Space and Atmospheric Studies. The use of the computing facility at the National Center for Atmospheric Research is gratefully acknowledged. NCAR is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation.

REFERENCES

Briggs, B. H., G. J. Phillips and D. H. Shinn, 1950: The analysis of observations on spaced receivers of the fading of radio signals. *Proc. Phys. Soc. London*, **B63**, 106–121.

Fraser, G. J., and M. R. Thorpe, 1976: Experimental investigations of ionospheric/stratospheric coupling in southern mid-latitudes—1. Spectra and cross-spectra of stratospheric temperatures and the ionospheric *f*-min parameter. *J. Atmos. Terr. Phys.*, **38**, 1003–1011.

Geisler, J. E., and R. E. Dickinson, 1976: The five-day wave on a sphere with realistic zonal winds. *J. Atmos. Sci.*, **33**, 632–641.

Gregory, J. B., and A. H. Manson, 1975a: Winds and wave motions to 110 km at mid-latitudes. II. Mean winds at 52°N, 1969–73. *J. Atmos. Sci.*, **32**, 1667–1675.

——, and ——, 1975b: Winds and wave motions to 110 km at mid-latitudes. III. Response of mesospheric and thermospheric winds to major stratospheric warmings. *J. Atmos. Sci.*, **32**, 1676–1681.

——, ——, D. G. Stephenson, J. S. Belrose, M. J. Burke and T. N. R. Coyne, 1975: Mesospheric and lower thermospheric wind changes over Canada during the January 1975 stratospheric warming. *Nature*, **258**, 62–64.

Jenkins, G. M., and D. G. Watts, 1968: *Spectral Analysis and Its Applications*. Holden-Day, 525 pp.

Julian, P. R., 1975: Comments on the determination of significant levels of the coherence. *J. Atmos. Sci.*, **32**, 836–837.

Labitzke, K., 1972: Temperature changes in the mesosphere and stratosphere connected with circulation changes in winter. *J. Atmos. Sci.*, **29**, 756–766.

Manson, A. H., J. B. Gregory and D. G. Stephenson, 1974: Winds and wave motions to 110 km at mid-latitudes. I. Partial reflection radiowave soundings, 1972–1973. *J. Atmos. Sci.*, **31**, 2207–2215.

Muller, H. G., and S. P. Kingsley, 1974: On the scale sizes of wind systems in the meteor zone. *J. Atmos. Terr. Phys.*, **36**, 1851–1861.

Panofsky, G., and B. Brier, 1958: *Some Applications of Statistics to Meteorology.* The Pennsylvania State University Press, 224 pp.

Pfister, W., 1971: The wave-like nature of inhomogeneities in the E-region. *J. Atmos. Terr. Phys.*, **33**, 999–1025.

Stubbs, T. J., and R. A. Vincent, 1973: Studies of D-region drifts during the winters of 1970–72. *Aust. J. Phys.*, **26**, 645–660.

Vincent, R. A., T. J. Stubbs, P. H. O. Pearson, K. H. Lloyd and C. H. Low, 1977: A comparison of partial reflection drifts with winds determined by rocket techniques—I. *J. Atmos. Terr. Phys.*, **39**, 813–821.