Winds and Wave Motions to 110 km at Midlatitudes. VI. Tidal, Gravity and Planetary Waves, 1976

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ABSTRACT

The results of partial reflection radiowave wind observations (60–110 km) for four 10-day intervals in 1976 at Saskatoon, Canada (52°N, 107°W), are presented. A harmonic analysis has been applied to data for the four seasons: the means of the semi-diurnal and diurnal components are in reasonable agreement with other measurements at similar latitudes. There are large day-to-day variations in the amplitudes and phases of the tides. The seasonal variations of mean winds (Gregory and Manson, 1975a) are not appreciably altered by the removal of tidal components. Gravity waves with periods $\sim$5 h are identified and the periods are found to vary with the mean background wind. The mechanism involved is not understood. An oscillation with a 2-day period is found in August and a similar oscillation is seen in stratospheric temperatures near 20 km.

1. Introduction

In this paper, we present an assemblage of data obtained by the radiowave partial reflection drifts technique at Saskatoon (52°N, 107°W) during 1976. The wind data have been obtained at a radio frequency of 2.2 MHz by a system described in an earlier paper (Manson *et al.*, 1974). In that paper (Part I) and others in the series (Parts II–IV; Gregory and Manson, 1975a,b; Manson *et al.* 1975), emphasis was placed on the analysis of 1 h noon soundings ($\leqslant 12$ profiles) and their interpretation in terms of mean circulation, planetary waves and gravity waves (periods $\tau \lesssim 1$ h). It was argued in Parts I and II that tidal components would not significantly affect the results of such analyses. This was confirmed in Part V (Manson *et al.*, 1978) where mean daily winds were compared with the noon winds.

In this paper tidal motions will be discussed, and also gravity waves ($\tau > 1$ h) and planetary waves (1 day $< \tau <$ 10 days).

2. Winds data

During 1976, four continuous runs lasting 10 days each were performed (Table 1), using the partial reflection drift technique to obtain winds in the 60–110 km region, with sampling at 3 km intervals. Complete soundings were made every 5 min, and those which yielded useable winds were averaged to give an hourly median (January and April) or mean (August and October) value.

The January and April runs were analyzed to give an "apparent velocity" (Briggs *et al.*, 1950) using a method and an editing procedure detailed in earlier papers in this series (Manson *et al.*, 1974). The data from three adjacent heights were then averaged to one value with weighting according to the number of individual velocities contributing to each hourly median at each height. Commencing at the start of each 10-day data set (see Table 1) the data were then divided into 24 h blocks and each block was subjected to a least-squares fit to a constant and linear trend plus 24 and 12 h oscillations; the blocks were then moved by 12 h so that as many as 20 (non-independent) estimates were available at each height range. The means and standard deviations of the mean wind and of tidal amplitudes and phases for 10 (and sometimes 5) days were calculated.

It is not easy to estimate the accuracy of the amplitudes and phases obtained in this analysis. However, the standard deviation of the harmonic components can be calculated from the rms deviation of the data from the fit to the tidal oscillations (Hoel *et al.*, 1971, p. 126). Estimates of error in the phases and amplitudes can then be derived. A typical "good" value would have an error of about ±4 m s^{-1} in amplitude and ±20° in phase: these were found to be smaller than the daily variability (especially of the phase) of the 24 and 12 h harmonic components.

The August and October data were analyzed by the full correlation method (Fedor, 1967) giving a "true velocity", with special criteria built into the analysis

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program to decide on the acceptability of the wind measurements (Meek, 1977). This true velocity has been shown to be similar to winds measured by meteor radar systems (Stubbs and Vincent, 1973; Stubbs, 1973) and rockets (Vincent *et al.*, 1977). With this improved analysis method two heights (instead of three) were averaged together. Estimated errors were typically ± 3 m s^{-1} and $\pm 20°$. Comparison was made between hourly means from 6 h of data, which were treated (i) with the wind analysis and editing techniques used for the January and April data (and previous work) and (ii) by the full-correlation method. The two methods showed very similar values from 80 to 100 km with differences being typically 10–20%; above 100 km the means from (ii) were smaller by $\sim$50% (Meek *et al.*, 1978). Thus, below 100 km it is possible to compare amplitudes of daily means and tidal components from all four seasons, while above 100 km the amplitudes for January and April should be reduced by $\sim$50% before being compared with those for August and October.

3. Prevailing wind component

The mean or prevailing wind was obtained from the constant component of the harmonic analysis which was applied to the data. Day-to-day changes in the mean wind can thus be studied and these have been used elsewhere in a study of the variability of electron densities with planetary waves (Meek and Manson, 1978). There is also some discussion of such long-period waves in Section 7. Here, however, we are interested in the means and standard deviations (sd) for the 10-day intervals. As expected, these means were similar (within standard error) to the means of all the hourly values within the 24 h blocks.

Our previous measurements of mean winds had been derived from data all gathered near local noon (Gregory and Manson, 1975a). These were averaged over four years of data in order to estimate a seasonal variation. We will be interested in comparing these two sets of data.

We look first at the *zonal* (positive eastward) mean winds whose altitude profiles are shown in Fig. 1. It should be noted that the heights shown are virtual heights. Corrections have not been made for group retardation above 100 km, so that heights shown from 100–118 km will likely refer to 100–110 km. The January results show remarkable consistency from day to day. In particular, all days show an increase in the magnitude of the westward wind above 100 km, typical of winter circulation (Gregory and Manson, 1975a). In contrast, the April data clearly fall into two groups: 6–10 April in which the wind is increasing westward at the higher altitudes (similar to the January winter circulation) and 11–15 April in which there is a westward increase at lower altitudes. These changes may be associated with planetary waves or more probably with the seasonal transition of the zonal flow (Gregory and Manson, 1975a,b) which usually occurs in this month. The August results in some ways appear like a mirror image of the January structure, with an eastward wind maximum between 100 and 110 km. These results, taken from the first half of the month of August, contrast with the finding of a mean westward wind in August above 100 km by Gregory and Manson (1975a). However, the time of change from the summer eastward regime to the winter westward winds does vary from year to year, giving rise to eastward *or* westward winds in individual years (Gregory and Manson, 1975b). Here it appears that August is part of the summer circulation. In October we see strong

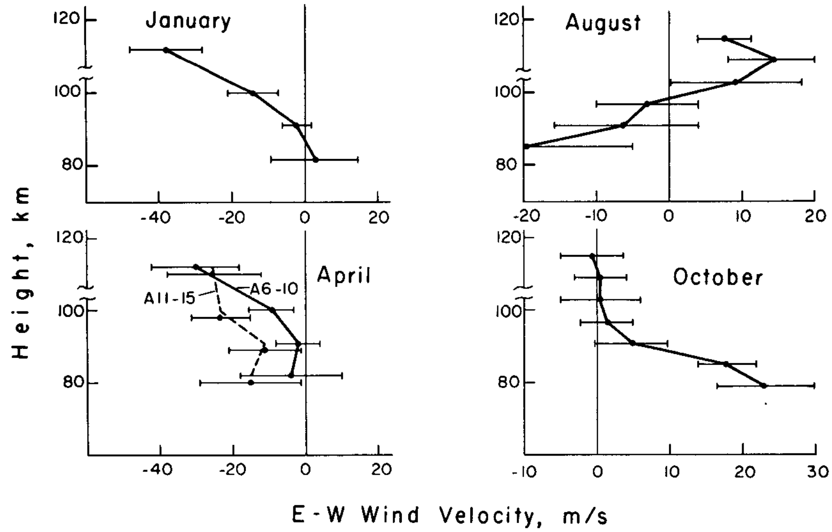

Fig. 1. Height variation of east-west (positive eastward) mean winds and standard deviations. The month is indicated for each curve, and the dates of each 10-day set are given in Table 1.

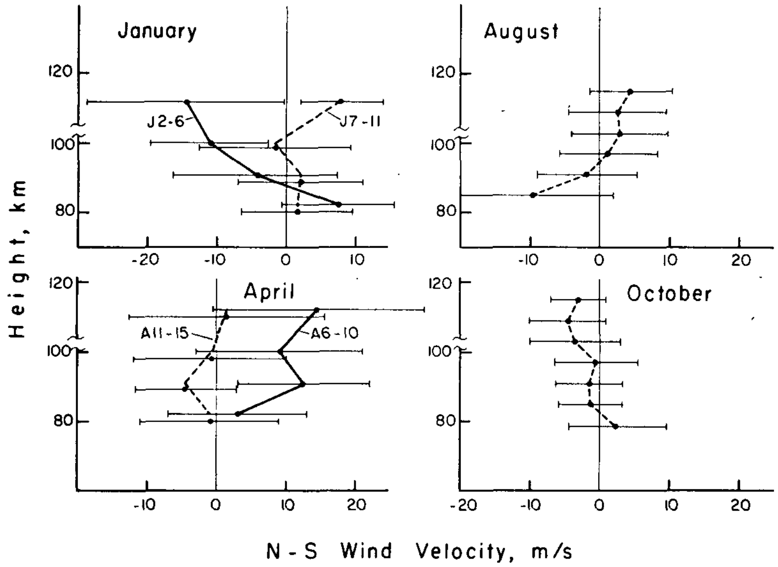

FIG. 2. Height variation of north-south (positive northward) mean wind and standard deviations.

eastward winds below 100 km, then smaller amplitudes above 100 km, the average near 110 km being slightly westward. Overall, the winds are consistent with the means of four years (Gregory and Manson, 1975a) or individual years (Gregory and Manson, 1975b).

Turning our attention to the *meridional* (positive northward) winds shown in Fig. 2, the January and April results are interesting in that they each demonstrate two groups of days which show similar structure. These trends will be associated with planetary waves and/or seasonal changes. Treating August as a summer month again, the winds in Fig. 2 fit the four-year pattern shown by Gregory and Manson very closely; however, it should be noted that because of the large sd and small means there is no unique direction for the meridional winds in the months studied. Also, in both north–south and east–west profiles, there are systematic day-to-day changes (evident through the height ranges) with periods τ of 2–10 days which are present in all months and whose amplitudes are given approximately by the sd: these and particularly the August event are discussed in Section 7.

4. Semidiurnal tide

a. General

It has become customary to try to identify which tidal mode is present by measuring the vertical wavelength of the tide. This can most conveniently be done by plotting the phase of the tide as a function of altitude. One expects to find an upward propagating tide as evidenced by phase increasing with height (i.e., time of maximum decreasing). Such behavior can be found in our results, consistent with modes of short wavelength ($\lambda \approx 30$ km) and very long wavelength ($\lambda \approx 100$ km) and corresponding to such modes as the S_4^2, S_6^2 and S_2^2. However, other more irregular behavior is found just as often (cf. Bernard, 1974). Sudden changes in phase with height are seen as well as cases of phase *decreasing* with altitude. These irregularities can be seen over several adjacent (in space and time) estimates of amplitude and phase, and in time series of the wind amplitudes, so the effect is only partly due to data unreliability. [The incorporation of a linear trend in the harmonic analysis reduced the variability of values only occasionally and appears not to be an essential part of the analysis, given the relatively small amplitudes of the longer period (planetary) waves.] These more complex behaviors may be due to 1) changes of composition in the source regions, 2) the presence of more than one tidal mode, leading to interference (Fellous *et al.*, 1975), 3) reflections leading to standing waves (Fellous *et al.*, 1975), and 4) coupling of energy from one mode into another or into the background flow (Lindzen and Hong, 1974). It is very difficult to decide which of the above causes is operating in a particular case. One general remark that can be made is that the north–south winds exhibit, on the average, a more regular phase progression than the east–west winds. This is true in all months. Fellous

TABLE 1. Observation periods 1976.

Month	Starting time (GMT)	(CST)	Starting day	Last day
January	1800	1200	2 January	11 January
April	0000	1800	5 (GMT) April	15 April
August	1400	0800	5 August	13 August
October	1800	1200	12 October	21 October

et al. (1975) have reached similar conclusions about the day-to-day variations of the semi-diurnal tide at Garchy (47°N); and they give experimental evidence for the superposition of S_2^2 and S_6^2 modes, and the reflection of the S_2^2 mode on individual days and groups of days.

In order to demonstrate these possibilities the variations of phase and amplitude with height of various mode mixtures are plotted in Fig. 3, and will be compared with measured (mean) phase and amplitude profiles in Figs. 4 and 5. For practical reasons the individual modes used in Fig. 3 have a constant amplitude with height, as the measured (mean) amplitudes do not evidence a strong amplitude gradient, and the actual heights of the sources or reflections of the modes are not known with any certainty. However, the results do give a qualitative indication of the types of effect that may occur. When two modes of different vertical wavelengths are mixed together a beating pattern is formed with a discontinuity in the phase progression near the height of minimum amplitude. If a wave is partially reflected there is also a large phase change in the region of the amplitude minimum—the larger the reflection coefficient the more rapid this change in phase (Fig. 3d and 3e). It is possible to find individual (daily) amplitude and phase profiles from each of the four 10-day sets of data which are similar to each of these. However, it is clear that even these data selections are too small to indicate which are the dominant interactive processes. Hence such an assessment will await the analysis of continuous, daily tidal data which are now (April 1978) becoming available (Gregory, 1978; Gregory *et al.*, 1978). It is sufficient to note here the danger in assigning a particular tidal-mode description to data solely on the basis of a simple estimate of phase progression with height, especially if the data are available over a narrow height range.

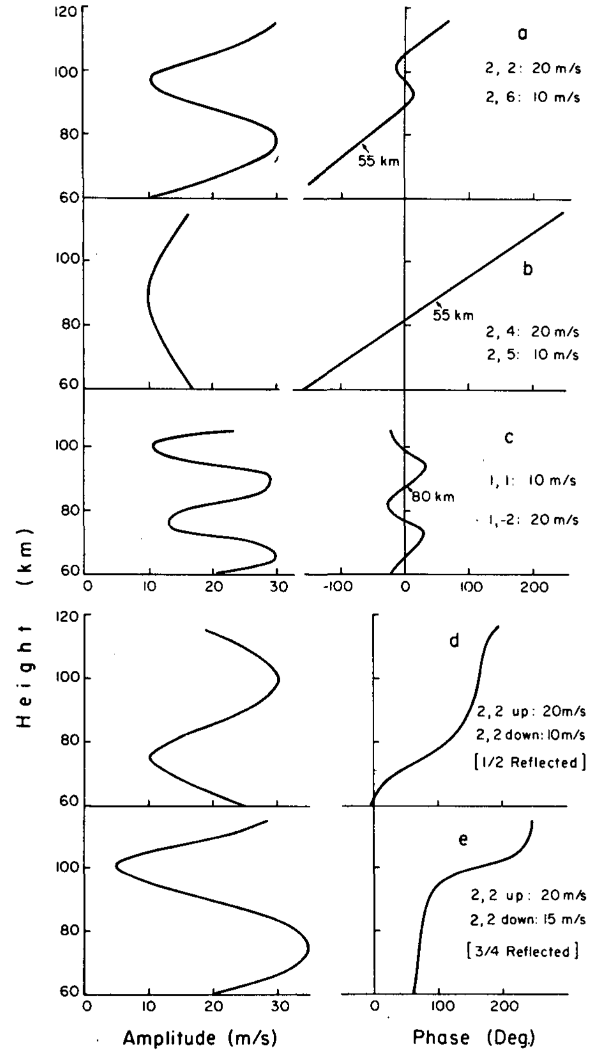

FIG. 3. Combinations of simulated tides, showing phase and amplitude variation with height. For the reflected waves (d,e), the amplitude and phase are appropriate to reflection of the mode at a node above 118 km.

b. Seasonal averages

The means and sd of the amplitudes and phases of the semi-diurnal tide for each of the 10-day runs are shown in Figs. 4 and 5. If consistent and significant changes or trends occurred, values for 5-day sequences are shown. We also applied the harmonic analysis to entire 5- or 10-day blocks and found excellent agreement between the phases of these fits and the means shown in the figures: the amplitudes from 5–10 day fits did not agree with the means as well, and the east–west/north–south amplitudes were also seldom equal, especially when the sd of the phases were large. Hence, the means of the 24 h blocks are preferred, as the sd give an indication of the daily variability and the north-south/east–west amplitudes are more nearly equal. Finally, we remind the reader that in January and April the amplitudes should be reduced by ~50% above 100 km (Section 3).

In January, the phase of the north–south component was quite consistent, but the east–west underwent a dramatic ~180° change between 2–6 and 7–11 January, and the sense of rotation changed from counterclockwise to clockwise. At this time the north-south mean wind also changed from southward to northward. No significant change in amplitude occurred in this time. The gradient was ~8 m s^{-1} (10 km)$^{-1}$. The phase gradient of the north–south and east–west (2–6 January) profile between ~80 and ~110 km is 7.0° km^{-1}, which is equivalent to an average wavelength of ~55 km. This is consistent with a S_3^2 mode, although a superposition of S_2^2 and S_6^2 modes or S_4^2 and S_5^2 modes (Figs. 3a and 3b) is possible as the amplitude variation with height is somewhat irregular. The April (spring, Fig. 4) data again evidenced a significant change in the interval, for both the amplitudes and phases of the components (although the north–south phase and

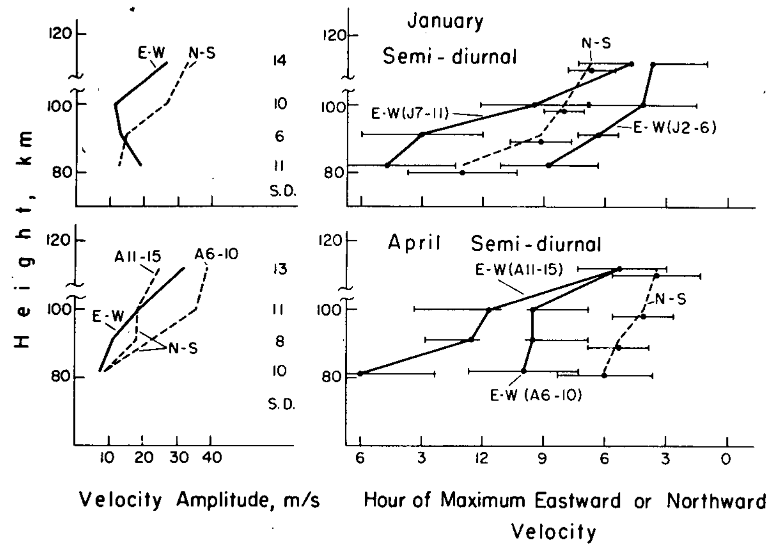

FIG. 4. Height variations of amplitude and phase of the semi-diurnal tidal components. Means and standard deviation for 5 or 10 days are shown for January and April 1976. (The amplitude sd is an average of both components.)

east–west amplitudes were consistent); at this time the mean winds were also changing direction (Figs. 1 and 2), which is suggestive of a tidal and mean wind interaction (e.g., Lindzen and Hong, 1974). The amplitude gradient is ~7 m s^{-1} (10 $km)^{-1}$, and the phase gradient of the north–south and east–west components (6–10 April) is ~3.5° km^{-1} ($\lambda \approx 100$ km). This is consistent with the S_2^2 mode, perhaps modified by reflection (Figs. 3d and 3e). The sense of rotation is clockwise.

The amplitudes and phases in August (summer) and October (autumn) are relatively regular for the 10-day intervals (Fig. 5), as might be expected from the regular mean winds (Figs. 1 and 2): the sense of rotation is clockwise with ~3 h between maximum northward and eastward amplitudes. In general the amplitudes do not increase with height, and the phase gradients from ~90–110 km are ~5.5° km^{-1} ($\lambda \approx 65$ km) in August and ~3.0° km^{-1} ($\lambda \approx 120$ km) in October. It seems unlikely that a single mode was present here, but they could be examples of superposition (e.g., Figs. 3a and 3b) or reflection (e.g., Figs. 3d and 3e) of modes. This would be similar to the conclusions reached by Fellous *et al.* (1975) that although the "tide is generally dominated" by the S_2^2 mode, "higher-order modes prevail in winter, and spring and autumn averages cannot be described by a single 'equinoctial' model".

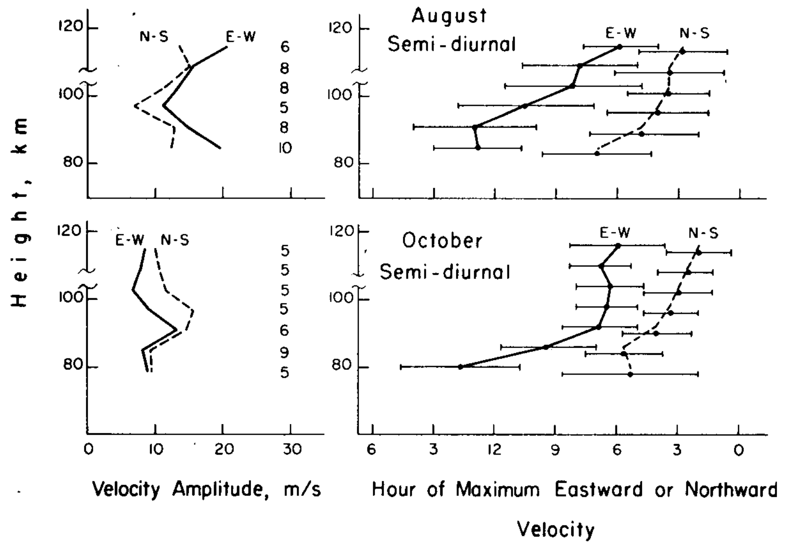

FIG. 5. As in Fig. 4 except for August and October 1976.

c. Comparison with other measurements, and theoretical estimates

Unfortunately, different groups gathering tidal data in the upper atmosphere analyze their data in different ways and this makes comparisons difficult. For example, Roper (1977) fits his data to the model of Groves (1959) and in addition, has to average together several days (>5) of data. Nevertheless, we include some data obtained by Roper at Atlanta (34°N) (Table 2) *during the same time interval in 1976 as our data*, for comparison. The mean Saskatoon values from Figs. 4 and 5 are shown. The phases at Atlanta are similar to Saskatoon in January and October but not in April. Fellous *et al.* (1975) report 90 km phases at Garchy (47°N) which are, except for April, consistently leading ours. For comparison purposes a value for the east–west tidal phase can be found by adding 3 h to the more regular north–south phase. The match with our 100 km values is better. However, their average vertical wavelengths (~27 km in summer and >100 km in winter) are different. Data given by Stubbs (1976) for 1972 shows a significant overlap of phases and a similar seasonal trend. The semi-diurnal tide in temperature near 115 km has been measured at St. Santin (45°N) and Millstone Hill (42.6°N) by Salah and Wand (1974). The results summarized by Lindzen (1976) are also included in Table 2. The temperature should have its maximum 3 h later than the northward wind, and the temperature results are therefore in excellent agreement with the Saskatoon east–west wind results except in January.

TABLE 2. Seasonal variations of semi-diurnal tide phases (hour of maximum). Temperatures (°C) at latitude 42–45° are from Millstone Hill and St. Santin (Lindzen, 1976). Atlanta data are from Roper (private communication, 1977), Garchy from Fellous *et al.* (1975) and Adelaide from Stubbs (1976).

	January	April	August	October
	Top height (~110 km)			
Saskatoon NS	~7	~3.5	3–4	2–3
Saskatoon EW	~4	~5.5	6–8	6–7
Temperature	6	6.7	7	6.7
	Near 100 km			
Saskatoon NS	~8	~4	3–4	3–4
Saskatoon EW	—	—	8–10	6–7
Atlanta NS	6.5	0.5	—	3
	Near 90 km			
Saskatoon NS	~9	~5.5	5–7	4–6
Saskatoon EW	—	—	12–01	7–9
Adelaide NS	10–11	4–6	7–10	2–5
Garchy EW	9.5	8.5	7	5.5

In conclusion the mean semi-diurnal tidal phases from Saskatoon (53°N) show considerable internal consistency and generally compare well with data from other locations. The agreement with the theoretical phase variations of Lindzen and Hong (1974), which include the effects of realistic models of seasonal distributions of wind and temperature, are also remarkably good for winter (east–west, 2–6 January) and summer (east–west, August). This comparison is usefully made from Fellous *et al.* (1975) who compare their own data with the appropriate theoretical curves. The Saskatoon amplitudes also compare well in magnitude and general altitude gradient—even a minimum in summer near 90 km is evident in the August data.

5. Diurnal tide

a. Seasonal averages

The diurnal tide also evidences irregular behavior. We show the mean and sd of the amplitudes and phases in Figs. 6 and 7. In all seasons there is no systematic

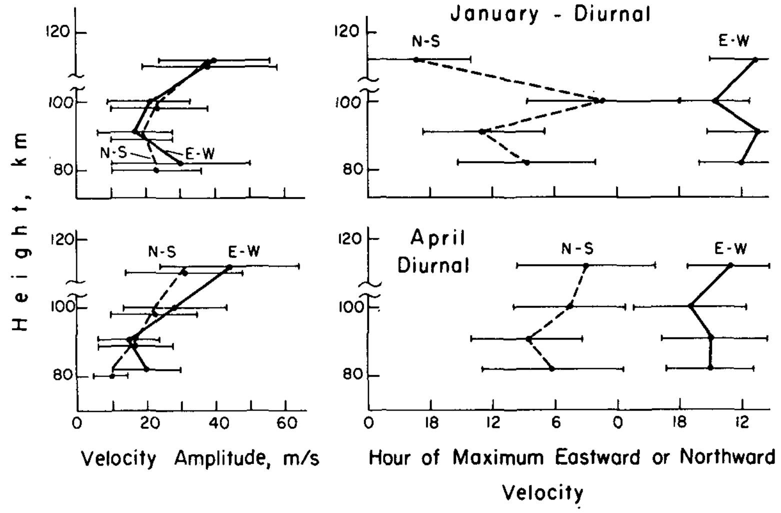

FIG. 6. Height variation of amplitude and phase of the diurnal tide. Means and sd for 10 days are shown for January and April 1976.

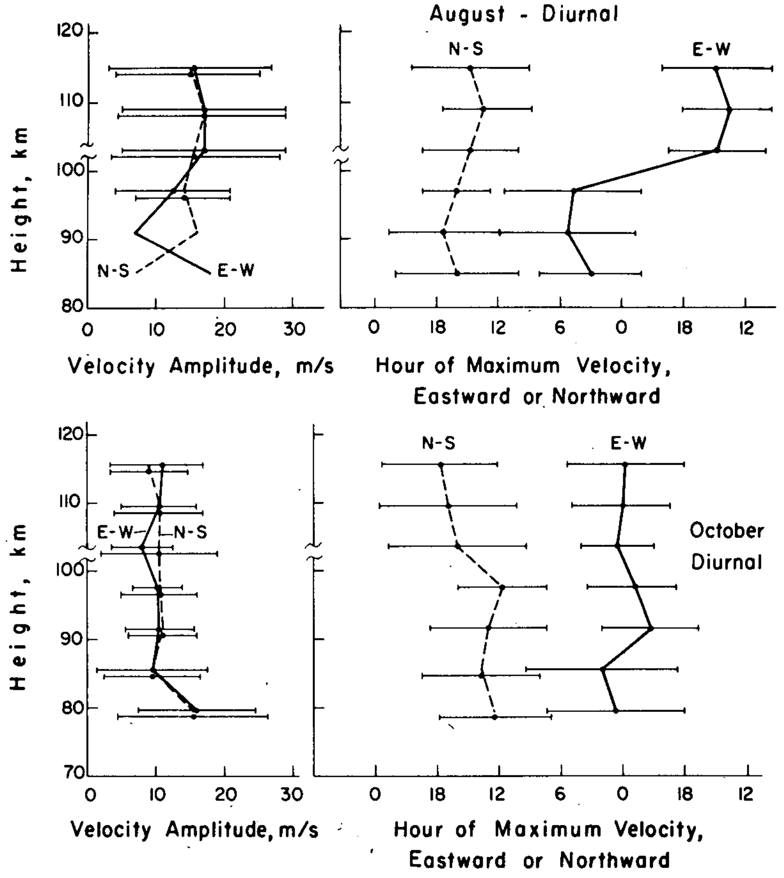

FIG. 7. As in Fig. 6 except for August and October 1976.

phase progression with height and in only January and April does the amplitude increase with height above 90 km. Generally there is ~6 h phase difference between northward and eastward components with the northward leading, although the January and August phases show some irregularity. It seems likely that the main evanescent modes S^1_{-1}, S^1_{-2} are involved here, perhaps in conjunction with the S^1_1 mode (cf. Fig. 3c simulation). We should note that *individual* phase profiles, especially those from October when the height resolution is best, demonstrate rapid changes near 80–90 km which are consistent with $\lambda \approx 20$ km (S^1_1 mode). Typically, above these heights the phase progression is less as would be expected of evanescent modes.

TABLE 3. Seasonal variations of diurnal tide phases (hours of maximum).

	January	April	August	October
	Top height (~110 km)			
Saskatoon NS	—	~3	13–15	17–18
Saskatoon EW	~10	~13	14–15	23–24
	Near 100 km			
Saskatoon NS	—	~5	14–16	12–16
Saskatoon EW	~14	~17	—	23–01
Atlanta EW	18	—	—	12
	Near 90 km			
Saskatoon NS	—	~9	16–17	13–14
Adelaide NS	21	17	14	3
Saskatoon EW	10	~15	3–5	22–02
Adelaide EW	13	10	9	12
Atlanta EW	—	9	—	1
Garchy EW	10	12	11.5	8.5

Similar irregularities in phase progression have been noted by Fellous *et al.* (1975), who also suggested that the features could not be represented by one mode. They suggested that nonlinear interactions with the prevailing wind, with other tidal oscillations and gravity waves (Spizzichino, 1969) could lead to energy transfer to other components. Again, it is felt that a considerably greater volume of data is needed to systematize such possible irregular tidal features, so further discussion will not be given here.

b. Comparisons with other measurements and theoretical estimates

The mean diurnal phases at several heights are given in Table 3. Although comparisons are difficult on account of the large variability, some generalizations can be made. Adelaide results for 1972 from Stubbs (1976) are seen to be frequently out of phase with those at Saskatoon, even when allowance is made for the sense of rotation in the two hemispheres. Some results from Atlanta, selected at heights where the phase is not varying very fast with altitude, and for common days, are also included in the table (Roper, 1977). The phases are quite similar in this case. Finally, phases at Garchy (Fellous *et al.*, 1975) agree fairly well in January and April, but not in August and October. Better agreement is not expected as their average vertical wavelengths are different. Forbes and Garrett (1976) give maximum northward wind theoretically at 0000 GMT at our top height. This is similar to phases from our most regular data (April and October), where east–west and north–south phase progressions are systematic. The comparisons in the table are quite good, considering the local variability and that referred to by other authors.

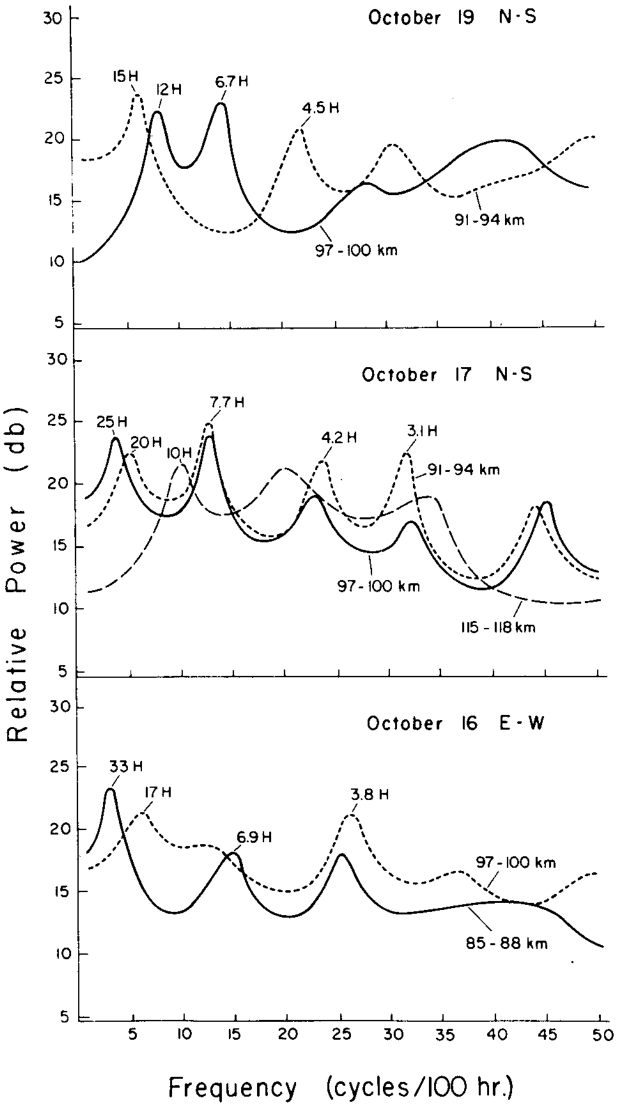

FIG. 8. Maximum entropy spectra of winds.

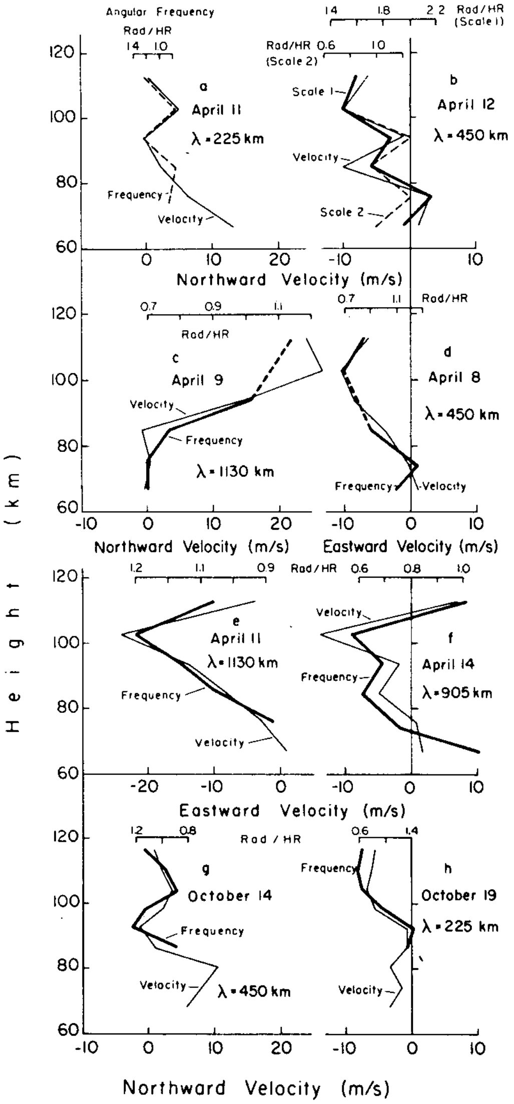

FIG. 9. Height variation of angular frequency (rad h^{-1}) of spectral components derived from MEM analysis of winds plotted alongside mean wind variation of same component (north–south or east–west). Calculated horizontal wavelengths are given.

6. Spectral analyses

a. Gravity waves

Individual day's data were subjected to a spectral analysis using the maximum entropy method MEM (Ulrych and Bishop, 1975). When resolved, the periods of peaks, supposedly appropriate to semi-diurnal and diurnal tides, were rather variable, typically varying from 10–15 h and 17–30 h (e.g., Fig. 8). This variability was also reported by Spizzichino (1969). The daily variability of tidal amplitudes and phases reported by ourselves and others referenced above, is consistent

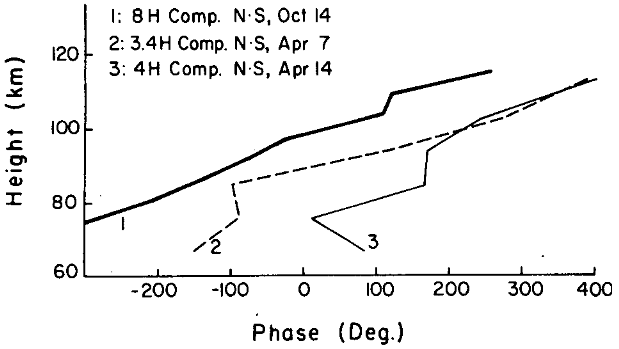

FIG. 10. Height variation of phase of some selected shorter period waves.

with the nature of these spectra. If several modes of the 12 and 24 h tides are excited, and these suffer differential interactions with background temperature and winds, broadening of the frequency spectrum is certainly to be expected.

The spectra usually provided prominent peaks of several hours period (2–10 h): peaks of similar period could often be located throughout the altitude range 80–110 km and in both components. A relationship did emerge, however, between the small variations in period τ (and angular frequency ω) with respect to height and the mean background wind v for the 24 h interval. A study of time series for each case showed that particular waves were present throughout much of the 24 h interval—hence the effect of tidal oscillations, which *are* part of the background wind for a short-period wave, were minimized or averaged out. Some spectra are shown in Fig. 8, and a selection of comparisons between daily mean wind profiles and wave frequencies ω are in Fig. 9. Such matchings are not infrequent and are available from data for all four months discussed in the paper. Further, we do not believe that this is an artifice of the analysis, e.g., the position of the peaks in the spectra are virtually independent of the order of the autoregressive process assumed and were also not shifted when the data were first filtered to remove low-frequency trends and tidal components.

A relationship of this type was reported by Rastogi and Bowhill (1976) who suggested that Doppler shifting of gravity waves with periods near 15 min had occurred. They also calculated a horizontal wavelength assuming $k_{x,y}=2\pi/\lambda_{x,y}=\Delta\omega/\Delta v_{x,y}$. Both of these are curious results, as "traditional" linear gravity wave theory states that a ground-based observer should *not* see a change in frequency with height, even if the background wind *is* changing with height, and irrespective of whether the source is in the frame of reference of the observer or moving with respect to the observer (e.g., in the troposphere). In the latter case, of course, the observed constant frequency will be Doppler-shifted with respect to the natural frequency of the source. The fact that we do see changes in ω suggests that the background flow is accelerating (Jones, 1969) or that nonlinear effects are significant (Weinstock, 1976; Weinstock and Hyde, 1976), or that critical levels have been established for the waves (Hines, 1968; Geller *et al.* 1975). Under such conditions, a non-accelerating observer (e.g., at the ground) might expect to record a frequency shift (Hines, 1974, p. 300) due to the nonlinear interaction. It is possible that it is this frequency change that is being seen. It is also clear that a wavepacket rather than a monochromatic wave is involved, and that despite the nonlinear interaction, wave energy continues to propagate through to at least 110 km.

A reviewer has proposed an alternate explanation of the data in Fig. 9: it was suggested that a gravity wave near its critical level should begin to resemble an inertial oscillation, whose observed frequency at the ground would be the sum of the Coriolis frequency and the advection frequency $k_{x,y}v_{x,y}$. However, this implies that the frequencies at $v_{x,y}=0$ in Fig. 9 should be identical and equal to the local inertial (or Coriolis) frequency ($\sim$0.4 rad h^{-1}): this is not the case.

Estimates of $\lambda_{x,y}$ from $k_{x,y}=\Delta\omega/\Delta v_{x,y}$ are shown in Fig. 9, and lie in the gravity wave spectrum; it is not clear that this equation is appropriate, but the number obtained is at least a spatial scale factor. These data are very interesting and no existing theory gives an immediate and unambiguous explanation. Further study of this phenomena, which bears on many problems of wave interactions, is called for.

b. *Vertical wavelength of gravity waves*

Due to the Doppler shifting phenomenon discussed above, it is not easy to follow the progress of a gravity wave up through the atmosphere and derive a vertical wavelength. However, a few examples are presented in Fig. 10. The phases were derived by performing a harmonic analysis of the day's data at the period indicated. The vertical wavelengths obtained are mostly around 20 km, in agreement with the finding of Spizzichino (1969). Amplitudes are of the order of 10 m s^{-1}.

7. Planetary waves

Reference was made earlier to the existence of an oscillation in the mean winds for August. This 2-day period oscillation can clearly be seen in the north–south mean wind at all height intervals from 91–94 km to 115–118 km. The winds are plotted at two heights over the 9-day period in Fig. 11. The east–west winds also exhibit the 2-day periodicity. Also plotted is the surface pressure, tropopause temperature and 50 mb level temperature at Edmonton, Stony Plain, Alberta (53°N, 114°W). The 2-day oscillation is not visible in the surface pressure variation, there is a slight hint of it at the tropopause (near 12 km altitude) and it is clearly present at the 50 mb level (near 21 km) where a minimum in the temperature curve (plotted on an inverse scale for comparison) coincides with a maximum in the northward wind in the lower thermosphere: the coincidence persists for $3\frac{1}{2}$ cycles of the wave. The large difference in scales for the tropopause and 50 mb temperatures should be noted; we chose to amplify the latter, as the temperature oscillation is small but has a clear 2-day period. Stratospheric data from other Canadian stations do not show such a good correlation, though the 10 mb level temperatures at The Pas (54°N, 101°W) corresponds fairly well. The 2-day period is consistent with the 51 h wave found by Muller and Kingsley (1974) at 97 km altitude and it occurs in the same summer season. Actually Muller (private communication, 1976), after examining several years of data, finds this wave occurs only in July and August. However, we differ from Muller and Kingsley in finding a correlation with a stratospheric parameter rather than with surface pressure. This may have some implications regarding the source of this wave.

In other months mean wind changes of longer period (several days) can be seen but 10 days of data is inadequate to determine the period.

8. Conclusions

1) The partial reflection drifts technique has been shown to be capable of yielding information on tides, gravity waves and planetary waves in the upper atmosphere. In comparison with the meteor radar method it covers a larger height range but does not give as good height resolution as some such systems.

2) The seasonal variation of mean winds, previously reported by Gregory and Manson (1975a), is not appreciably altered after removal of tidal components.

3) There is evidence for considerable day-to-day variability in the amplitudes and phases of diurnal and semi-diurnal tides: this suggests interference between tidal modes, coupling from one mode into another or with the background flow, and changes in the source regions.

4) The mean and sd of semi-diurnal tidal amplitudes and phases for 5–10 day intervals were internally consistent, although the winter phases were different from other seasons. The mean vertical wavelengths were 55–120 km, and amplitudes increased with heights in January and April only $[7\text{–}8 \text{ m s}^{-1} (10 \text{ km})^{-1}]$. The winter and summer data are similar to theoretical profiles from Lindzen and Hong (1974).

5) The diurnal tide showed no systematic phase progression with height, and only in January and April did the amplitudes increase with height. It is likely evanescent modes were dominant.

6) Waves with periods near 3–5 h have frequencies which were found to vary with the mean background wind; the mechanism for this relationship is not understood.

7) An oscillation with a 2-day period was found in the August winds data and a similar oscillation was seen in the stratospheric temperature near 20 km.

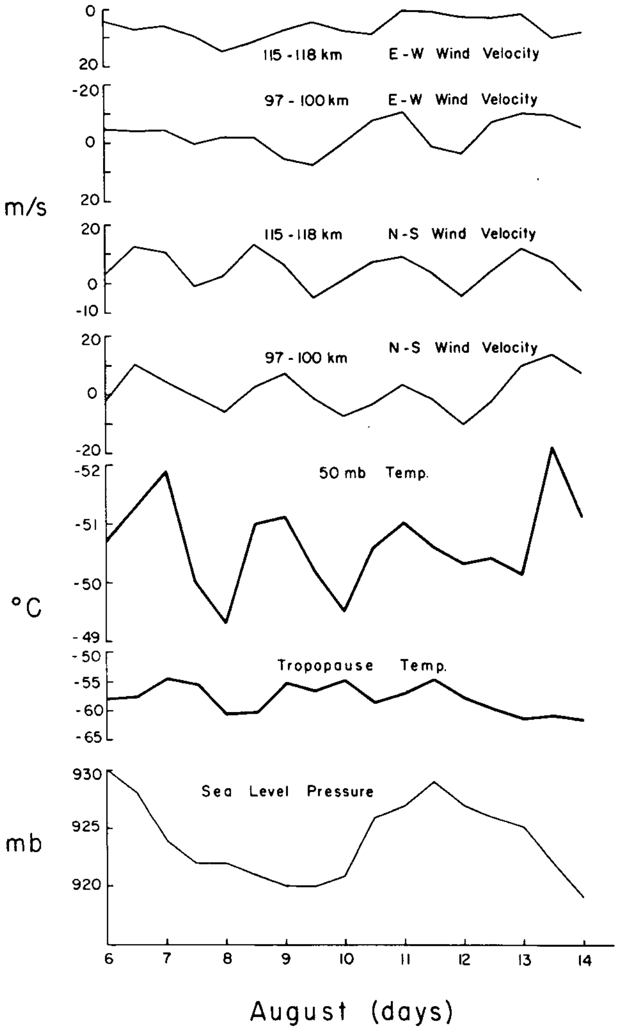

FIG. 11. Time variations of mean wind amplitudes and of other lower atmospheric parameters during nine days in August 1976 illustrating the 2-day oscillation.

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