Seasonal and Diurnal Variations of Middle Atmosphere Winds

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Seasonal and diurnal variations of middle atmosphere winds

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Previously published meridional cross sections of monthly mean W–E and S–N wind components from 60 to 130 km are reviewed in the light of wind data obtained by ground-based radio methods over various timescales including that of the solar cycle. A mean meridional circulation in the winter hemisphere is implied in which a dominant mesospheric cell between low and high latitudes is confined to lower heights at higher latitudes: a second meridional circulation is tentatively located above the former in the lower thermosphere extending downwards to lower heights at higher latitudes and introducing the possibility of polar and equatorial air mixing at mid-latitudes at heights close to 90 km. Meridional circulation is discussed in relation to the winter anomaly in D-region radio-wave absorption.

Diurnal and semidiurnal wind oscillations at heights between 25 and 60 km are presented which are the results of a comprehensive analysis of data from short series of rocket launchings held at various Western Hemisphere sites between 1965 and 1974. Phase and amplitude profiles at different times and locations rarely show similarities, but at latitudes greater than about 30°, S–N components are consistently in quadrature with and similar to the W–E components. An interpretation of the oscillations at these latitudes in terms of a superposition of tidal modes indicates the presence of quasi-steady high-order modes excited at tropospheric heights by sources of limited ($\sim 10^3$ km) extent. At latitudes less than about 30°, steady or quasi-steady diurnal and semi-diurnal components are not necessarily the dominant components of daily variation. At high latitudes diurnal phases generally show little change with height in comparison with observations at lower latitudes in accord with the latitudinal properties of positive and negative diurnal modes.

1. Introduction

Since the early 1950s, and particularly during the 1960s, rocket techniques have provided a major source of new information on upper atmosphere structure. The role of the rocket in this type of experimentation has usually been that of a vehicle of transport from which to eject one or more types of experimental package in flight. Data have been acquired for different height regions by means of parachutes or similar forms of decelerating device (often with a temperature sensing package) as well as chaff, falling spheres, grenades and chemical releases. Atmospheric temperatures, pressures and densities have been investigated by these techniques, but the parameter most frequently measured over different height intervals extending into the thermosphere has been the wind velocity.

At heights close to 90 km, ground-based radio techniques have also been available for wind determination. Although their observational height range is of limited extent compared with that of rocket techniques, they are particularly suitable for the study of time dependences which, in upper atmosphere winds, are traditionally classified in terms of a prevailing component, being that part of the wind velocity that does not change in the course of a day, tidal motions, turbulence and gravity waves of a few hours periodicity or less. Seasonal and

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longer-term effects contribute to the prevailing component but in addition day-to-day variations (of about 4 days periodicity) have also been found to contribute significant energy peaks to the spectra of meteor wind data (Teptin 1972).

In the first part of this paper (§§ 2–6), seasonal wind variations at heights above 60 km are reviewed, particular attention being given to S–N components and meridional circulation. The second part of the paper deals with diurnal wind variations as investigated by short series of rocket launchings extending over 1–3 days at heights of 25–60 km (or to 90 km on a few occasions). On 19–20 March 1974, 70 rockets were launched at eight Western Hemisphere sites; the results from these launchings are presented and discussed in §§ 7–13 in conjunction with those of earlier launchings.
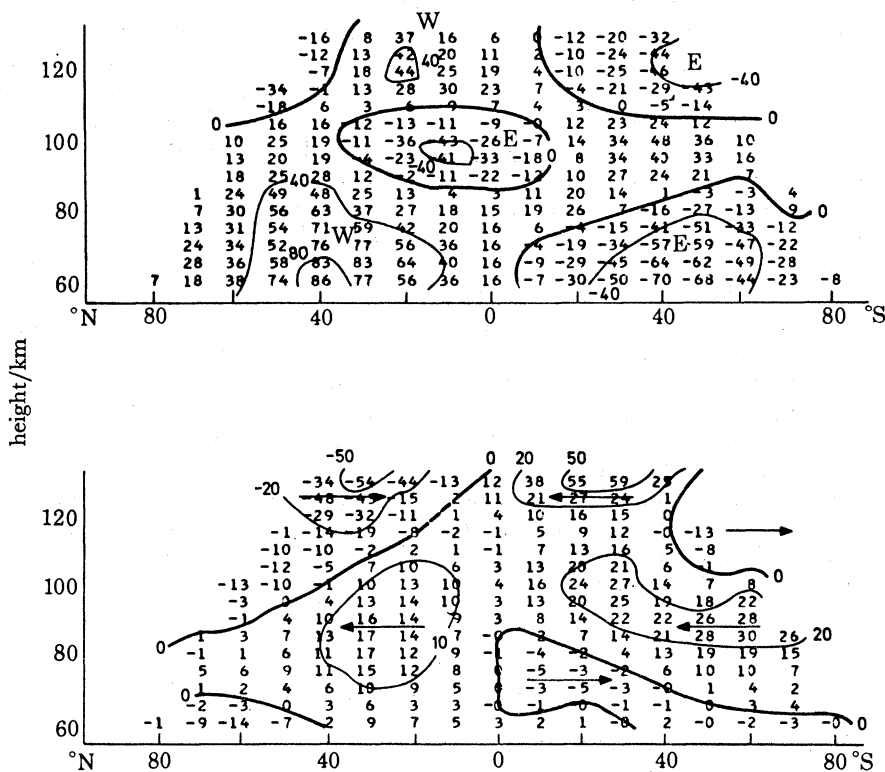

FIGURE 1. Meridional cross sections of W–E winds (above) and S–N winds (below) in m/s for 1 January. E denotes winds from the east (Groves 1969).

2. MERIDIONAL CROSS SECTIONS OF W–E AND S–N WINDS, 60–130 km

The smaller types of meteorological rocket that are in regular use with, for example, the U.S. Meteorological Rocket Network, rarely contribute wind data above 60–70 km altitude and it is therefore upon the relatively fewer launchings of medium-sized vehicles that data acquisition at these heights has depended. In relation to the complex nature of wind variations in space and time, coverage has been extremely sparse. Nevertheless, it has been possible by combining rocket data (and gun-probe data at certain sites) with radio wind data to construct meridional cross sections of mean W–E and S–N wind components at monthly intervals (Groves 1969). The rocket and gun-probe data available at that time were from grenade experiments at Woomera, Wallops Island and Fort Churchill and chemical releases at Bardados,

Eglin, Woomera and other mid-latitude sites. Data were provided by ground-based radio techniques sited in Europe and the Southern Hemisphere at Adelaide and at Mawson.

Figure 1 shows the models for 1 January. In constructing these cross sections seasonal symmetry was assumed between Northern and Southern Hemispheres in an attempt to overcome the shortage of data, i.e. Southern Hemisphere data were combined with Northern Hemisphere data after a 6-month change of date and a change of sign of S–N components. On account of the poor longitudinal distribution of data and unknown magnitude of standing waves, the extent to which the models represented zonal mean values was uncertain; values of 20 m/s for S–N wind components at 90 km being considered to be unlikely to be globally representative. As cross sections of observed averages, however, the models provided a convenient reference against which to compare other individual measurements that might become available. The W–E wind model in a slightly revised form was included in *C.I.R.A.* (1972, part 2).
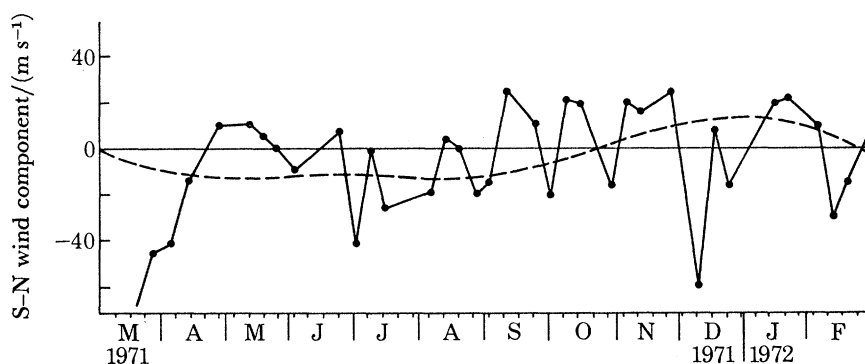

FIGURE 2. The 24 h averages of S–N wind components taken at weekly intervals by the Jamaica meteor-radar technique. The dashed curve is the 1969 S–N wind model for 15° N (Scholefield & Alleyne 1975).

3. COMPARISONS OF RECENT RADIO WIND DATA WITH S–N AND W–E MODELS

In recent years a number of comparisons have been made between radio wind observations and the S–N and W–E models of §2. Many of these observations are from longitudes where data were not previously available, notably in the Western Hemisphere, and offer the opportunity of checking the main features of the models and their seasonal trends for a range of heights centred close to 90 km.

The first measurements by partial radio-wave reflexions at Saskatoon (52° N, 107° W) (Gregory & Rees 1971) showed satisfactory agreement with the 1969 models, but more extensive comparisons up to 110 km (Gregory & Mason 1975) have shown satisfactory agreement to 85 km only and differences in the annual variation of zonal flow above 100 km.

Mean meteor winds measured at Durham, New Hampshire (43° N, 71° W) from May to December 1970 were in general agreement with the models, the meridional winds showing flow of 10 m/s towards the equator during summer and a similar flow towards the poles in winter (Clark 1975). A similar magnitude of *ca.* 10 m/s towards the equator in summer (9 August–4 September 1974) was found for 90–100 km at Atlanta (34° N, 84° W) (Roper 1975).

In 1970, meteor wind data were obtained for the first time in Jamaica (18° N, 77° W) and results from March 1971–February 1972 (Scholefield & Alleyne 1975) showed a seasonal variation in good agreement with the 1969 models. The general trend of the S–N component (figure 2) was towards the equator in summer and towards the pole in winter, although data

points deviated appreciably from the model at times: the particularly large deviation in March–April 1971 corresponded to replacement of easterly by northerly flow.

Meridional flow from November 1970 to November 1971 in the meteor region at Christchurch, New Zealand (43° S, 72° E) was towards the equator in local summer and towards the pole in local winter, being not in conflict with the pattern of flow suggested by figure 1 (Wilkinson & Baggaley 1975).
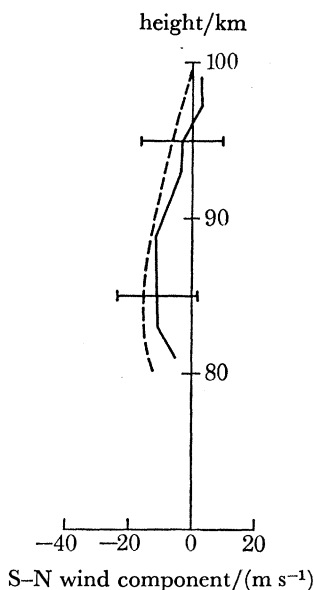

FIGURE 3. S–N prevailing wind components at Adelaide, S. Australia. Key: ——, observed ionospheric drift by partial reflexion technique 15–21 June 1973; –––, the 1969 S–N wind model for the same latitude and time of year (Vincent & Stubbs 1977).

Monthly mean ionospheric drifts from 80 to 100 km for 1972 have been obtained at Adelaide (35° S, 139° E) by the partial reflexion technique and compared with the 1969 models (Stubbs 1976). Overall, the models provided a better picture of the 1972 winter than the 1972 summer for which they fairly consistently exceeded observed S–N drift velocities and underestimated W–E magnitudes. For 15–21 June 1973 prevailing components have been derived with estimates of error, and S–N components compare well with model values as shown in figure 3 (Vincent & Stubbs 1977).

4. Day-to-day and long-term wind components

The spread of data points in figure 2 is evidence of the presence of variations on timescales of greater than one day and less than a few weeks. Such variations are now recognized as a general feature of radio wind observations with various possible dominating periodicities according to location, altitude and time of year. Spectral analysis of meteor radar winds at Obninsk (55° N, 36° E) and LF radio drift measurements between Kühlungsborn (54° N, 12° E) and Collm (51° N, 13° E) during the period November 1972 to March 1973 show peak intensities at periods of 10–16 days for the zonal, 16–20 days for the meridional component and of 2.5–6 days in both components (Lysenko et al. 1975). The results of other investigators tend to fall in the same ranges. Periods between 2 and 5 days, and amplitudes between 10 and 20 m/s were found by Muller & Kingsley (1974) at Sheffield (53° N, 1° W), the absence of

a marked seasonal effect being taken to indicate an indirect process of coupling with tropospheric variations of similar periodicities and not direct planetary wave propagation. Simultaneous wind variations at Garchy (47° N, 3° E) and Obninsk have been identified as a planetary wave of a 2-day period and longitudinal wavenumber around 3 (Glass *et al.* 1975). At Adelaide (35° S, 139° E) the variation is again found at all times of the year and is comparable in magnitude to that of the mean flow, being quasi-periodic with *ca.* 10–15 day periods (Elford 1976). Long-period waves also appear in spectral analyses of data from Durham, New Hampshire (Clark 1975) and Saskatoon (Belmont *et al.* 1977). The quasi-periodic character of the variations is well illustrated by figure 4, which shows the S–N prevailing wind for winter 1972–3 at Obninsk, the results having been subjected to harmonic analysis with a sliding 24 h interval shifted in steps of 1 h, and at Kühlungsborn–Collm, where values refer to midnight (Lysenko *et al.* 1975).
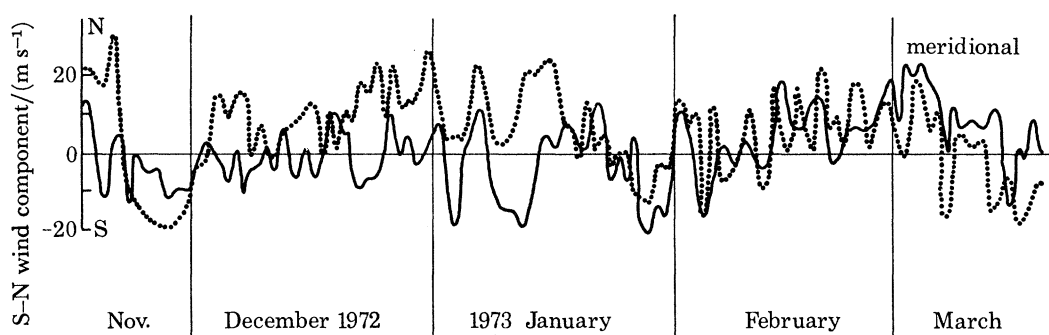

FIGURE 4. S–N prevailing wind components for winter 1972–3 at 95 km. Key: ——, Obninsk; ....,
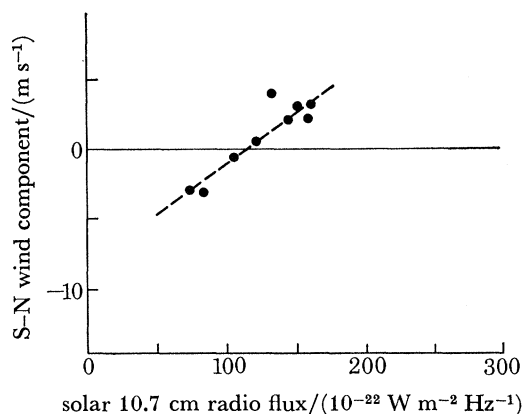Kühlungsborn/Collm (Lysenko *et al.* 1975).

FIGURE 5. Prevailing S–N wind components at 95 km for the winter months November–February plotted against solar 10.7 cm radio flux. Data are from Kühlungsborn/Collm (1957/58–1974/75) and Obninsk (1964/65–1972/73) (Portnyagin *et al.* 1977).

Long term variations can be studied at only a few sites which have an adequate time record. During the years 1966–72, meteor winds at Adelaide showed a sudden change in early 1969 of the vertical gradient of the meridional component at 90 km, from slightly positive (*ca.* $+1\ \mathrm{m\,s^{-1}\,km^{-1}}$) to slightly negative (*ca.* $-1\ \mathrm{m\,s^{-1}\,km^{-1}}$), without evidence of any substantial complementary change in the zonal flow (Elford 1976). From the 1956–73 run of ionospheric drift

measurements at Kühlungsborn–Collm, an oscillation of about 22-month period in the zonal prevailing wind has been reported (Sprenger *et al.* 1975). A dependence on solar activity of the prevailing wintertime (November to February) winds was shown some years ago for both W–E and S–N components by the Kühlungsborn–Collm observations (Sprenger & Schminder 1969). This dependence has been confirmed by subsequent data up to 1975 and by the radar meteor wind measurements at Obninsk, as shown for the S–N components in figure 5 (Portnyagin *et al.* 1977). No well defined correlation between wind speeds and solar activity has been found for summer months.
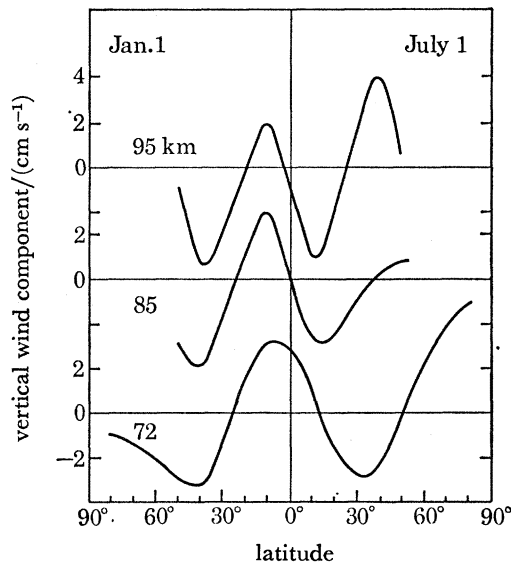

FIGURE 6. Variation with latitude of the mean velocity component normal to the isobaric surfaces at heights of about 72, 85 and 95 km in the N hemisphere for January 1 and July 1. Positive values represent upward motion (Ebel 1974).

5. AN INFERRED MERIDIONAL CIRCULATION

Thermally driven circulations between summer and winter hemispheres were depicted in the two dimensional theoretical 20–80 km models of Leovy (1964), with meridional winds increasing to 1.8 m/s at 70 km. This pattern of interhemispheric flow differs from that shown in figure 1 where maximum velocities reach much higher values of 10–20 (or more) m/s close to 95 km, and the latitudinal dependence is not that of a simple interhemispheric circulation cell. Subsequent radio wind measurements (§ 3) have provided further evidence of the higher values of S–N velocities shown by the model in the region of 90 km at the solstices; and, since many of these observations are at new longitudes, model values now appear unlikely to be greatly in excess of zonally averaged means. If such is the case, a mean meridional circulation may be derived on the basis of the S–N and W–E monthly wind models.

The problem has already been investigated at heights between 70 and 100 km by Ebel (1974) who used the steady state equations and the 1969 models to calculate the corresponding mean vertical motion (along with the required heat and momentum sources). The results obtained for equinox and solstice conditions show that the strength and direction of the circulation cells undergo a marked annual change. During the equinoxes the circulation is predominantly symmetric with respect to the equator, having four cells pole-to-pole. At the solstices it is strongly asymmetric with five cells pole-to-pole (reducing to three at the lower

heights considered) and this circulation appears to be superimposed on a single-cell pole-to-pole circulation of the type proposed by Kellogg (1961). For winter the calculations depict upward motion between 5° and 20° latitude at all heights considered (figure 6): downward motion is obtained between 30° and a higher latitude which is about 50° for the upper half of the 70–100 km altitude range increasing to close to 90° latitude at 70 km. In other words, the mesospheric circulation cell over the winter hemisphere involves air rising at low latitudes, merging with a small interhemispheric flow and descending as it moves towards the winter pole.

The flow towards the equator at 60–65 km in the S–N model of figure 1 is indicative of a closed or nearly closed circulation in which descending polar air turns equatorwards. The upper boundary of this circulation cell is the zero S–N velocity line in figure 1, which passes through 80 km altitude at 80° latitude and slopes upwards to 111 km at 20° latitude: the gradient of the line is about 1:200. On its upper side the flow reverses, reaching high velocities in the direction of the equator at 120 km (figure 1). No calculations of vertical motion are available at these heights and nothing definite can be said about the lower thermosphere circulation, but it may be noted that the flow towards the equator in the model would be consistent with a circulation in which air descends over the winter polar region and ascends at low latitudes. A tentative picture that may therefore be presented of the winter hemisphere meridional circulation is that of two separate but likewise rotating circulations, one in the mesosphere and one in the lower thermosphere. Their common boundary on average is represented by the sloping zero S–N line of figure 1, which is the dividing line between two contrary moving air streams, one originating at high latitudes and one at low latitudes. At 90–95 km altitude and nearer the equator than mid-latitudes, the circulation is within the uppermost part of the mesospheric cell, whereas, nearer the pole than mid-latitudes at these heights, the circulation is within the lowermost part of the thermospheric cell.

The proximity of two contrary flow regions invites consideration of the extent to which they mix and of possible aeronomic consequences. While these matters lie beyond the scope of this paper, attention is drawn to the possible contribution of horizontal as well as vertical turbulent mixing. The presence of small-scale turbulent motions is well established for the 85–105 km region, but the day-to-day variations, such as those apparent in figure 4, would effect horizontal transport of air with path lengths of the order of 1000 km, and may be responsible for large scale eddy mixing. On such timescales, horizontal displacements across a zero S–N velocity line in figure 1 are of course possible since figure 1 represents the monthly mean situation.

6. MERIDIONAL CIRCULATION AND THE WINTER ANOMALY

The striking correlations that have been observed between the winter anomaly in D-region radio-wave absorption and meteorological parameters such as stratospheric temperatures point to atmospheric circulation as being relevant to the ionospheric phenomenon. As the latter in its most conspicuous form consists of days or groups of days of excessive absorption any relationship with meteorological parameters would more reasonably be strongest with departures from the average than with the average itself. A number of physical processes are likely to be involved in establishing the internal atmospheric conditions appropriate to anomalous absorption and here we consider only the meridional circulation as a contributing effect. In this case absorption would be expected to correlate significantly with S–N wind components in any set of observational data.

The winter observations at Arenosillo (37° N, 7° W) of 1969–70 showed that absorption increased with increasing winds from southern directions at 85 km and with increasing winds from northern directions between 90 and 93 km (Rose *et al.* 1972 *a*). Considered in conjunction with figure 1, these results would indicate an increase in mass flow above and below the zero S–N velocity line at times of greater absorption, with the upper cell extending downwards to possibly 10 km below its normal position.

The absence of the winter anomaly south of about 30° latitude directs attention to the latitudinal form of the meridional circulation at the altitude of the anomalous absorption, which is typically close to 84–85 km (Laštovička 1972). On moving from mid to low latitudes in the winter hemisphere a number of changes in the meridional circulation occur: S–N wind velocities decrease and the zero S–N velocity line (figure 1) continues to increase in altitude and becomes ill defined. Ebel (1974) sees the 30° latitude limit as coinciding with the reversal from downward motion at mid-latitudes to upward motion at low latitudes, as shown in figure 6.

Although no definite conclusions can be reached at the present stage about the role of the meridional circulation in contributing to the internal atmospheric conditions appropriate to anomalous absorption, it appears worthy of consideration in future investigations.

TABLE 1. DIURNAL LAUNCH SERIES 1965–74

site	latitude	longitude W	date	number of successful launchings
Thule	76° 33′ N	68° 49′	24–26 Oct. 1968	14
Fort Churchill	58° 44′	93° 49′	6–8 Sept. 1966	10
			8–9 Sept. 1966	10
			4–5 Jan. 1968	12
			23–25 Oct. 1968	18
			19–20 Mar. 1974	8
Wallops Island	37° 50′	75° 29′	19–20 Mar. 1974	13
Arenosillo	37° 06′	06° 44′	24–28 Feb. 1970	27
White Sands	32° 23′	106° 29′	30 June–2 July 1965	17
			9–11 Oct. 1965	16
Cape Kennedy	28° 27′	80° 32′	13–15 Dec. 1967	25†
			23–25 Oct. 1968	17
Antigua	17° 09′	61° 47′	19–20 Mar. 1974	8
Fort Sherman	09° 20′	79° 59′	19–20 Mar. 1974	8
Kourou	05° 08′	52° 37′	19–22 Sept. 1971	13
			19–20 Mar. 1974	10
Natal	05° 55′ S	35° 10′	1966–68	24
			19–20 Mar. 1974	8
Ascension Island	07° 59′	14° 25′	11–12 Apr. 1966	13
			12–13 Apr. 1966	13
			24–26 Oct. 1968	14
			19–20 Mar. 1974	8
Mar Chiquita	37° 45′	57° 25′	19–20 Mar. 1974	7

† Also analysed as 13–14 Dec. 1967 (12 launchings) and 14–15 Dec. 1967 (14 launchings).

7. DIURNAL LAUNCH SERIES 1965–74

Table 1 summarizes the sets of data from short series of rocket launchings at different sites whose analysis for diurnal and semidiurnal wind components is presented here. On 19–20 March 1974, 70 rockets equipped with standard Datasonde instrumentation were launched

at eight Western Hemisphere sites by N.A.S.A. Wallops Flight Center in cooperation with other agencies, to study atmospheric tides and their latitudinal variation (Schmidlin *et al.* 1975). The locations of the eight sites are shown in figure 7. Most of the other series of launchings shown in table 1 were carried out within the U.S. Meteorological Rocket Network during the years 1965–8, the height range of investigation being approximately 25–60 km. The 23–25 October 1968 launchings took place simultaneously at Ascension Island, Cape Kennedy, Fort Churchill and Thule, whereas other launchings were conducted on different dates at various
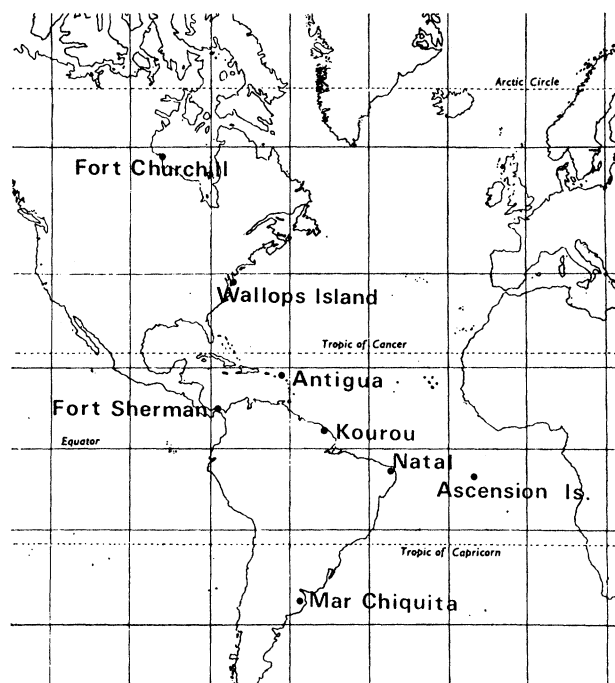

FIGURE 7. The eight sites from which diurnal series of rockets were launched on 19–20 March 1974.

low, mid and high latitude sites. The 24–28 February 1970 launchings were of Skua II rockets carrying a very lightweight chaff to measure winds from about 75 to 95 km altitude over Arenosillo (Rose *et al.* 1972 *b*). The acoustic-grenade technique provided results to 90 km over Kourou on 19–22 September 1971 (Smith *et al.* 1974) and the same technique provided results from 24 launchings at Natal in 1966–8 (Smith *et al.* 1968, 1969, 1970). Where no specific reference is quoted in the text, the data source has been the Meteorology Data Reports of World Data Center A.

8. METHOD OF HARMONIC ANALYSIS OF DATA

It has been assumed that a wind component, v, may be represented as a sum of mean, diurnal and semidiurnal components by

$$v = v_0 + A_1 \cos \tfrac{1}{12}\pi t + B_1 \sin \tfrac{1}{12}\pi t + A_2 \cos \tfrac{1}{6}\pi t + B_2 \sin \tfrac{1}{6}\pi t, \tag{1}$$

where t is local mean time in hours, departures from apparent local solar time being neglected. The symbols v_0, A_1, B_1, A_2, B_2 are five unknowns which may be determined, together with estimates of their standard deviations, by the method of least squares from, in principle, six or

more observations. The analysis has been previously described (Groves 1967) and does not require equal time intervals between observations. All observed wind values have been given an equal weight, although the analysis permits the introduction of different weights.

Results are presented below in terms of the amplitudes and phases of the harmonic components, which may be readily calculated from the values determined for the As and Bs in equation (1): phase is expressed by the local time at which an oscillation maximizes. The horizontal lines in figures 8–18 are centred on the least-squares calculated value of a quantity and are equal in length to two standard deviations. At heights where amplitudes are small, phases become indeterminate as indicated by very large error bars or a data point in brackets. Attention has been given to the removal of a background trend in v by replacing v_0 in (1) by a polynomial in time. When the total observing time exceeded 2 days, a cubic was adopted. Many series of launchings extend over only 1 day and in most cases the analysis of these has been performed with v_0 expressed linearly in time: when there were no more than eight launchings in a series, the background trend was ignored.
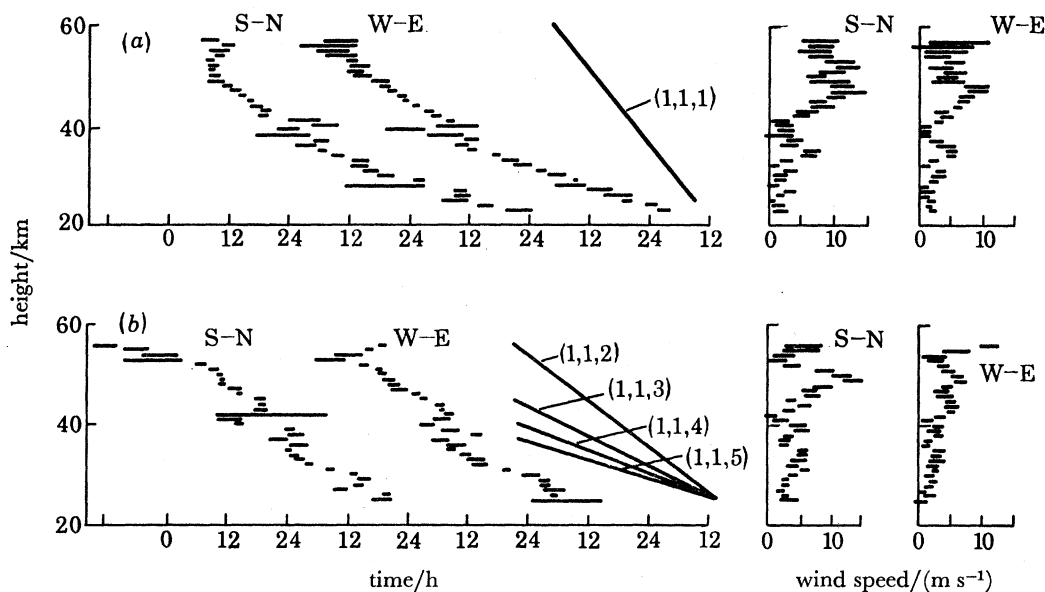

FIGURE 8. Diurnal wind components at Cape Kennedy. The straight lines indicate the approximate theoretical slopes of the phase profiles of the first five positive migrating modes. (a) 23–25 October 1968, 17 launchings in 48 h, (b) 13–15 December 1967, 25 launchings in 48 h.

9. DIURNAL WINDS AT MID-LATITUDES

The diurnal wind oscillations derived for 23–25 October 1968 and 13–15 December 1967 at Cape Kennedy have previously been compared and discussed (Groves 1976). The results are shown here in figure 8 in comparison with the theoretical phase profiles (the straight lines) for the migrating Hough modes (1, 1, 1) to (1, 1, 5): observed phases are seen to correspond most nearly with modes of a higher order than the leading (1, 1, 1) mode. Phase profiles for 23–25 October 1968 show about 2.25 rotations of the wind vector between 25 and 55 km and are similar to that of the (1, 1, 3) mode. For 13–15 December 1967 the average gradient of the phase profiles corresponds more closely with that of the (1, 1, 2) mode.

A notable property of the Cape Kennedy results of 23–25 October 1968 (figure 8) is that the profiles of S–N and W–E amplitudes show no significant differences and that W–E phases at all heights are later than S–N phases by close to 6 h: in other words, the diurnal wind vector at any given height rotated clockwise with no change of magnitude within the limits of accuracy of the data. If the oscillation may be regarded as a superposition of positive ($n > 0$) Hough modes $(1, s, n)$, then the above property implies approximate equality of W–E and S–N Hough wind functions for each mode that is significantly present. By examination of numerical evaluations of Hough wind functions for various s and n (not demonstrated here) it is found that this apparently stringent condition holds (to within about 20 %) at latitudes between 20° and 40° latitude, provided that eastward travelling modes are generally small compared with westward travelling modes.
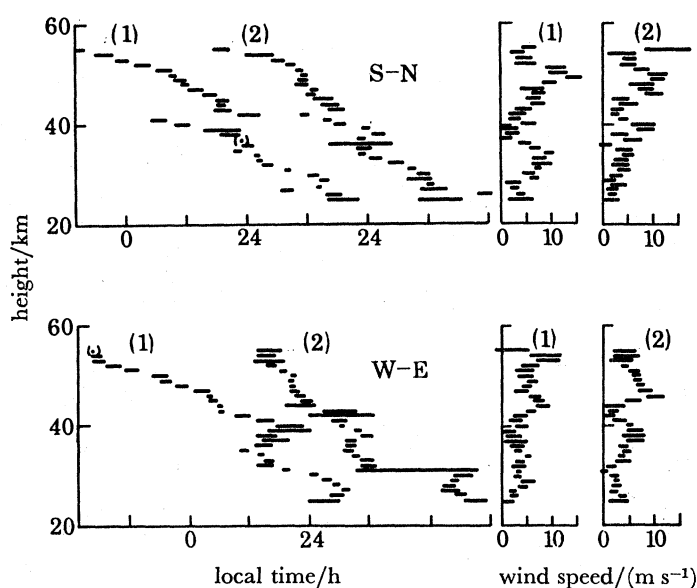

FIGURE 9. Diurnal wind components on two consecutive days at Cape Kennedy. (1) 13–14 December 1967; (2) 14–15 December 1967.

For the 13–15 December 1967 data, a clockwise rotating wind vector of constant magnitude is found at less than half the heights analysed, S–N and W–E amplitudes in particular showing significant differences (figure 8). Further analysis of these results in figure 9 shows that, whereas the S–N oscillation is steady over the 2-day interval, that of the W–E component is not: some disturbance would appear to be affecting the W–E tidal oscillation. Although little can be said about the nature of such a disturbance, the direction of slope of the phase profiles (to earlier times with increasing height) points to a source of excitation, that is at lower heights and probably in the troposphere.

Data have now been analysed for diurnal winds at slightly higher latitudes than Cape Kennedy and the results (figures 10 and 11) are found to be generally consistent with the diurnal rotation of a wind vector of approximately constant magnitude at any given height. The number of launchings in each series is shown in table 1, but data from all launchings may not be available at every height. Reference lines at 12 h and 18 h have been added to the plots of S–N and W–E phases respectively for Northern Hemisphere sites to aid comparisons. The

S–N phase profiles at White Sands are quite well reproduced with a 6 h delay by the W–E phase profiles. So also is that for Arenosillo (figure 11). For the Southern Hemisphere site of Mar Chiquita, observed phases are consistent with an anticlockwise rotation of the wind vector in accord with tidal theory. Mar Chiquita phase profiles have approximately the same average slope as those taken at the same time at Wallops Island, which is at the same latitude (within 0.1°) in the opposite hemisphere. A 12 h shift between S–N phases at the two sites therefore indicates a tidal excitation that is predominantly symmetric with respect to the equator; but amplitude profiles differ between the two sites to an extent that suggests that non-migrating modes, i.e. modes that have both local-time and longitudinal dependences, may be significant even for a separation of only 18.1° in longitude.

Results of the White Sands launchings of 30 June–2 July 1965 have previously been reported in some detail by Beyers et al. (1966).
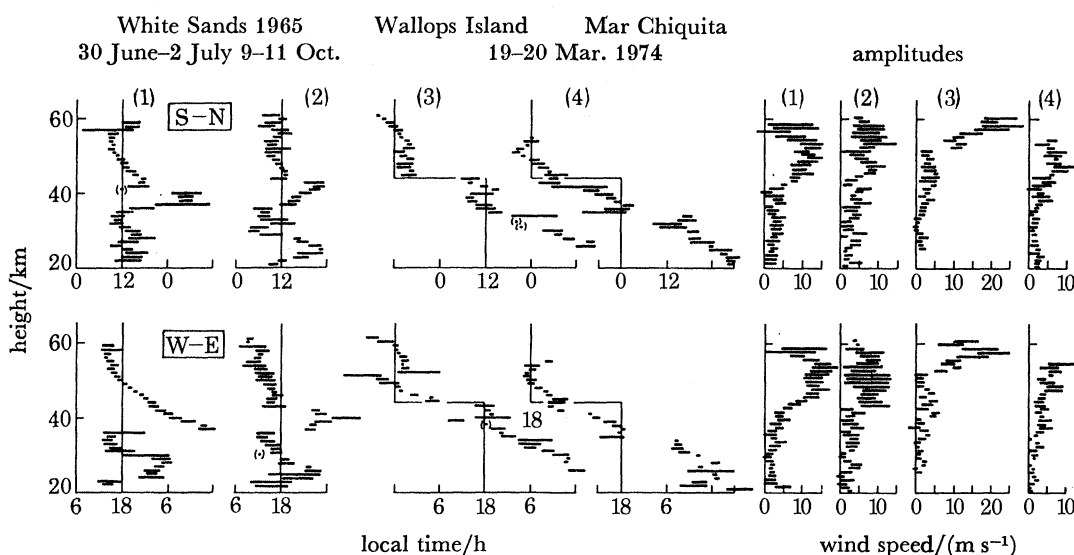

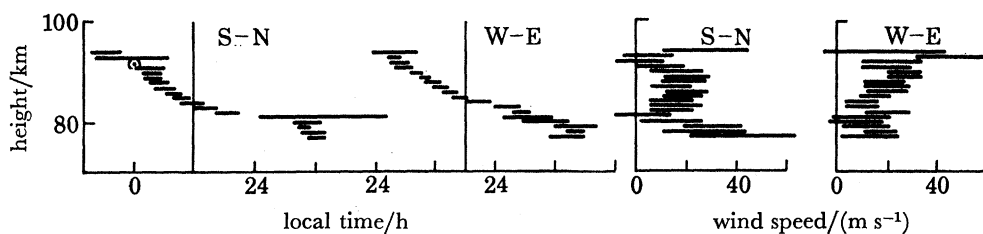FIGURE 10. Diurnal wind components at White Sands, Wallops Island and Mar Chiquita.

Figure 11. Diurnal wind components at Arenosillo, 24–28 February 1970.

10. DIURNAL WINDS AT LOW LATITUDE

S–N and W–E Hough wind functions for positive diurnal modes (not presented here) are found by inspection to become increasingly different in form at latitudes of less than about 15°; and hence at low latitude sites S–N and W–E amplitude and phase profiles would be expected to differ appreciably: the observational results (figures 12–15) confirm this expectation.

The results for Antigua show that W–E phases are later than S–N phases by 6 h at most heights except for the interval from 36 to 51 km (figure 12): short wavelengths appear to be propagating in the W–E component below 36 km and in the S–N component below 51 km changing to longer wavelengths above these heights.

Four sets of results for Ascension Island are compared in figure 13. The two sets showing greatest similarity are those for April 1966 which are based on the first 13 and the last 13 launchings of a series of 24 over a 2-day interval. A detailed analysis of the April 1966 data
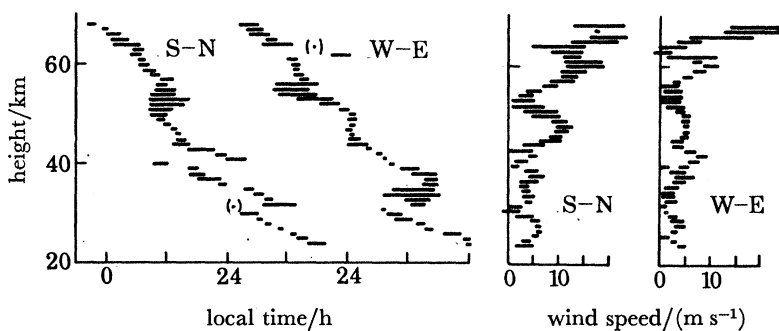

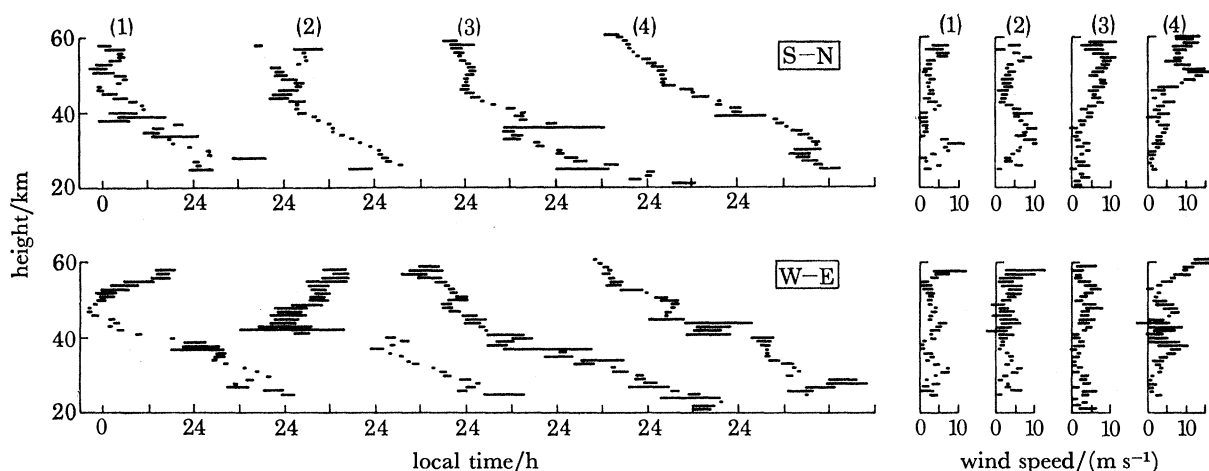FIGURE 12. Diurnal wind components at Antigua, 19–20 March 1974.

FIGURE 13. Diurnal wind components at Ascension Island. (1) 11–12 April 1966; (2) 12–13 April 1966; (3) 24–26 October 1968; (4) 19–20 March 1974.

has been given by Beyers & Miers (1968), who noted considerable variation in both S–N and W–E components between the two days and concluded that the diurnal variation may have been masked or distorted by some other short term disturbance. On close comparison of the two sets of April 1966 results in figure 13, it is found that 40% of the phases on the second day differ significantly from those on the first. The situation is similar to that reported above for 13–15 December 1967 at Cape Kennedy: a steady or quasi-steady tidal oscillation appears to be replaced or dominated by variations that arise from a non-tidal source, i.e. one that does not correlate with the hour angle of the Sun over several days. For other low latitude analyses reported here (figures 14 and 15) it is not possible, with the number and distribution of available launchings, to compare consecutive cycles and no indication can therefore be given of the presence or otherwise of non-tidal effects.

A comparison between the results for Fort Sherman in figure 14 and those taken on the same date (19–20 March 1974) at Ascension Island is of interest as the two sites are at nearly the same latitude in opposite hemispheres. A similar comparison in § 9 for Wallops Island and Mar Chiquita indicated a predominantly symmetric excitation with respect to the equator, but from figures 13 and 14 the Fort Sherman and Ascension Island oscillations are seen to differ markedly in phase and amplitude. These differences may be attributed to the presence of non-tidal effects as discussed above or to the presence of non-migrating modes as referred to in § 9 in conjunction with the 65.6° change of longitude between the two sites. The 19–20 March 1974 results (figure 15) for Kourou and Natal, which are also sites at approximately equal latitudes in opposite hemispheres, again show very dissimilar phase and amplitude profiles.
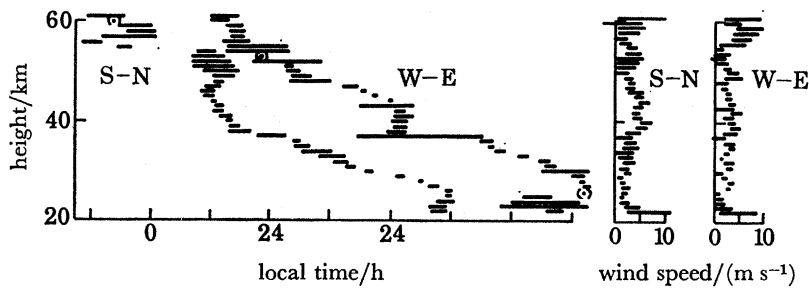

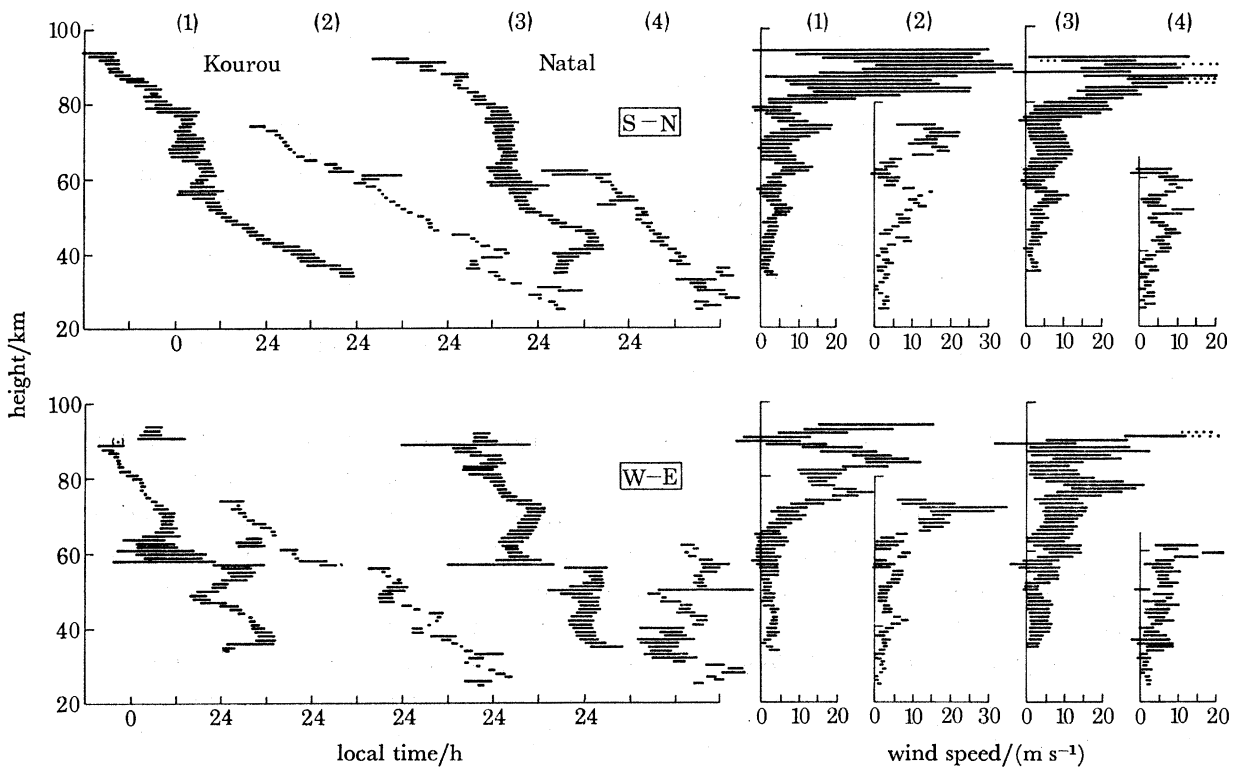FIGURE 14. Diurnal wind components at Fort Sherman, 19–20 March 1974.

FIGURE 15. Diurnal wind components at Kourou and Natal. (1) Kourou, 19–22 September 1971; (2) Kourou, 19–20 March 1974; (3) Natal, 1966–68; (4) Natal, 19–20 March 1974.

Also shown in figure 15 are results obtained by the acoustic-grenade technique at Natal (Groves 1974) and Kourou (Groves 1975 a). The Natal launchings differ from the other launch series on account of their distribution over an interval of 22 months; consequently the results from them would be expected to reveal a component of oscillation that is steady for much of the year. The Kourou acoustic-grenade phase profiles (figure 15) match those for Natal of 1966–8 to a remarkable extent except at the lower heights. As reported previously, however (Groves 1975 a), the Kourou temperature oscillation showed significant differences from that for Natal, indicating some variation in the source of excitation for which the atmosphere response was of observational significance in temperature and not in winds. Further evidence of variation in the source of excitation between different dates is provided by the 19–20 March 1974 wind results at Natal and Kourou which differ significantly from the acoustic-grenade results at the corresponding sites (figure 15).
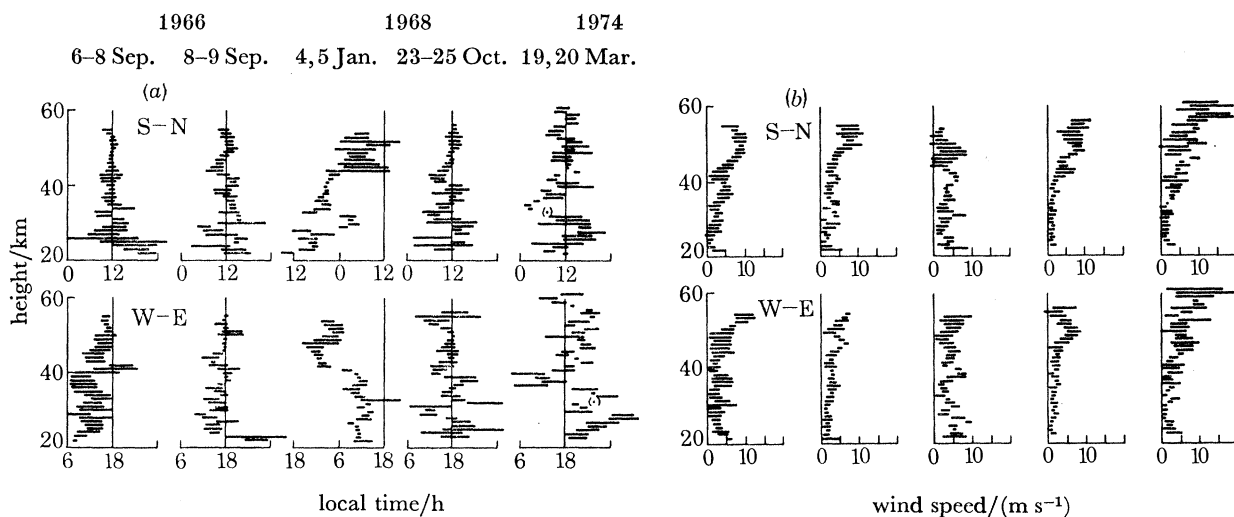

FIGURE 16. Diurnal wind components at Fort Churchill. (a) Phases, (b) amplitudes.

11. DIURNAL WINDS AT FORT CHURCHILL

It is a well known property of diurnal Hough functions (Chapman & Lindzen 1970; Groves 1975 b) that positive modes are confined to low and mid latitudes, whereas negative modes attain their greatest values at high latitudes. At Fort Churchill tidal oscillations can therefore be expected to be composed of negative modes. Another property of negative modes is that, in contrast to the vertically propagating and oscillatory nature of positive modes, they show no rotation in height and have amplitudes that decay in either vertical direction away from the level of excitation, such that stratospheric oscillations would be excited by stratospheric (ozone) heating. The height independence of phase at high latitude was confirmed by the analysis of Reed et al. (1969) of summer data between 30 and 60 km from the combined stations of Fort Churchill and Fort Greely for the diurnal S–N wind oscillation: observed S–N wind phases were very close to 12 noon, the value which accords theoretically with an expected 12 noon phase for the ozone heating rate.

Figure 16 shows S–N and W–E diurnal winds for Fort Churchill obtained from series of launchings conducted on the dates shown. The results are independent of those of Reed et al.
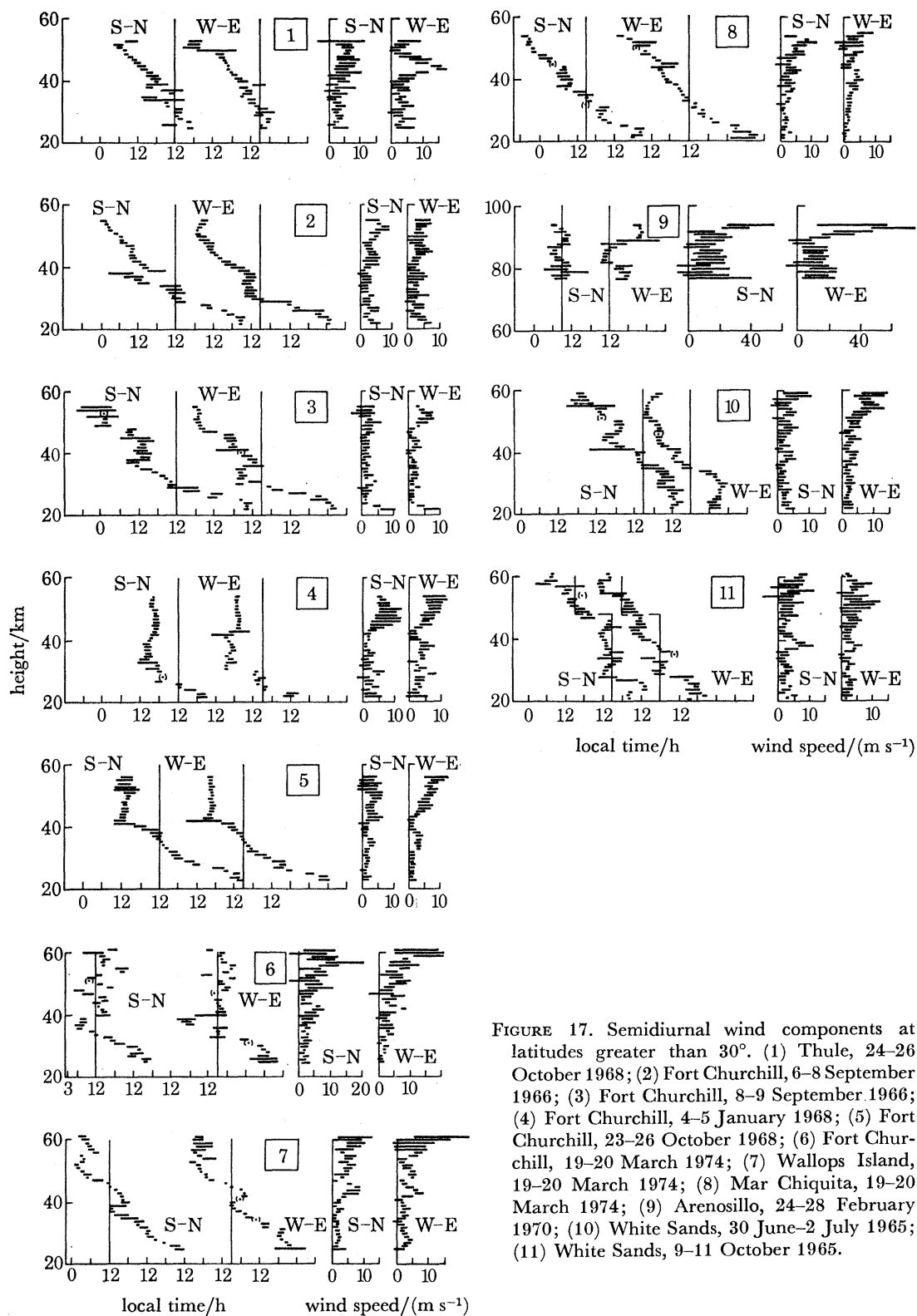
FIGURE 17. Semidiurnal wind components at latitudes greater than 30°. (1) Thule, 24–26 October 1968; (2) Fort Churchill, 6–8 September 1966; (3) Fort Churchill, 8–9 September 1966; (4) Fort Churchill, 4–5 January 1968; (5) Fort Churchill, 23–26 October 1968; (6) Fort Churchill, 19–20 March 1974; (7) Wallops Island, 19–20 March 1974; (8) Mar Chiquita, 19–20 March 1974; (9) Arenosillo, 24–28 February 1970; (10) White Sands, 30 June–2 July 1965; (11) White Sands, 9–11 October 1965.

(1969) which were derived from data widely distributed in time over the summer months of several years up to and including 1966. S–N phases at or close to 12 noon are common in figure 16 with the notable exceptions, to be discussed in the next paragraph, of 4–5 January 1968 and certain heights below 45 km. For the W–E wind oscillation the corresponding theoretical phase is 1800 h, the rotation of the wind vector being clockwise. With the same exceptions this value is fairly well supported observationally. The two launch series in September 1966 comprise the first ten and the last ten launchings respectively of a series of 19 launchings at 4 h intervals over 3 days. The general form of the phase profiles in figure 16 clearly differs in character from that at other latitudes (figures 8–15) where positive modes are able to propagate.

Below 40 km ozone lifetimes increase sufficiently for atmospheric motion to become an effective transport mechanism and longitudinal asymmetries in ozone distribution arise (Heath *et al.* 1973; Krueger *et al.* 1973; Dütsch 1974). Maximum heating rates may then be displaced in longitude from the subsolar longitude, and phases of the S–N wind below about 45 km would not necessarily be at 12 noon. In the absence of information on ozone distributions such relations cannot, however, be examined. The unusual phase profiles of 4–5 January 1968 also direct attention to the possibility of a disturbed ozone distribution, in this case up to 55 km, and considering the time of year this might arise from a stratospheric warming and its effect on temperature-dependent photochemistry (Barnett *et al.* 1975). On examining M.N.R. synoptic charts of North America, it is found that this series of launchings coincided with a major warming which started in December 1967 and persisted into the beginning of 1968: by the end of December, the temperature gradient between polar and mid latitudes had reversed throughout the entire middle and upper stratosphere making the event the earliest major warming ever to be recorded (E.S.S.A. 1970; N.O.A.A. 1971). Of the other above Fort Churchill launchings, none took place at the time of a stratospheric warming.

12. Semidiurnal winds at latitudes greater than 30°

Figure 17 shows semidiurnal wind phases and amplitudes at six different sites, data being available at Fort Churchill for four different dates. The 19 launchings of 6–9 September 1966 at Fort Churchill have been divided into two groups consisting of the first ten and the last ten launchings respectively: each group extends over three consecutive cycles and the results of the first group are quite well reproduced by the second group indicating the presence of quite a steady oscillation over this 3-day interval. Comparisons between other sets of results are, in contrast, notable for conspicuous differences in phase and amplitude profiles.

One feature that stands out in figure 17 is that S–N and W–E profiles show similarities of phase and, to a lesser extent, of amplitude, W–E phases being later than S–N phases by close to 3 h, corresponding to a clockwise rotation of the wind vector. For the Southern Hemisphere site of Mar Chiquita an anticlockwise rotation is indicated.

Another feature of the phase profiles in figure 17 is their failure to comply with previous theoretical results for semidiurnal oscillations, which present a mainly constant phase arising from the assumed predominance of the (2, 2, 2) mode. In the classical treatment (Chapman & Lindzen 1970) a rapid phase reversal is obtained just below 30 km between adjacent regions of almost constant phase extending up to the mesopause and down to the surface. In the more recent calculations of Lindzen & Hong (1974) with a more realistic atmosphere, the chief modification is to the level at which the reversal occurs.
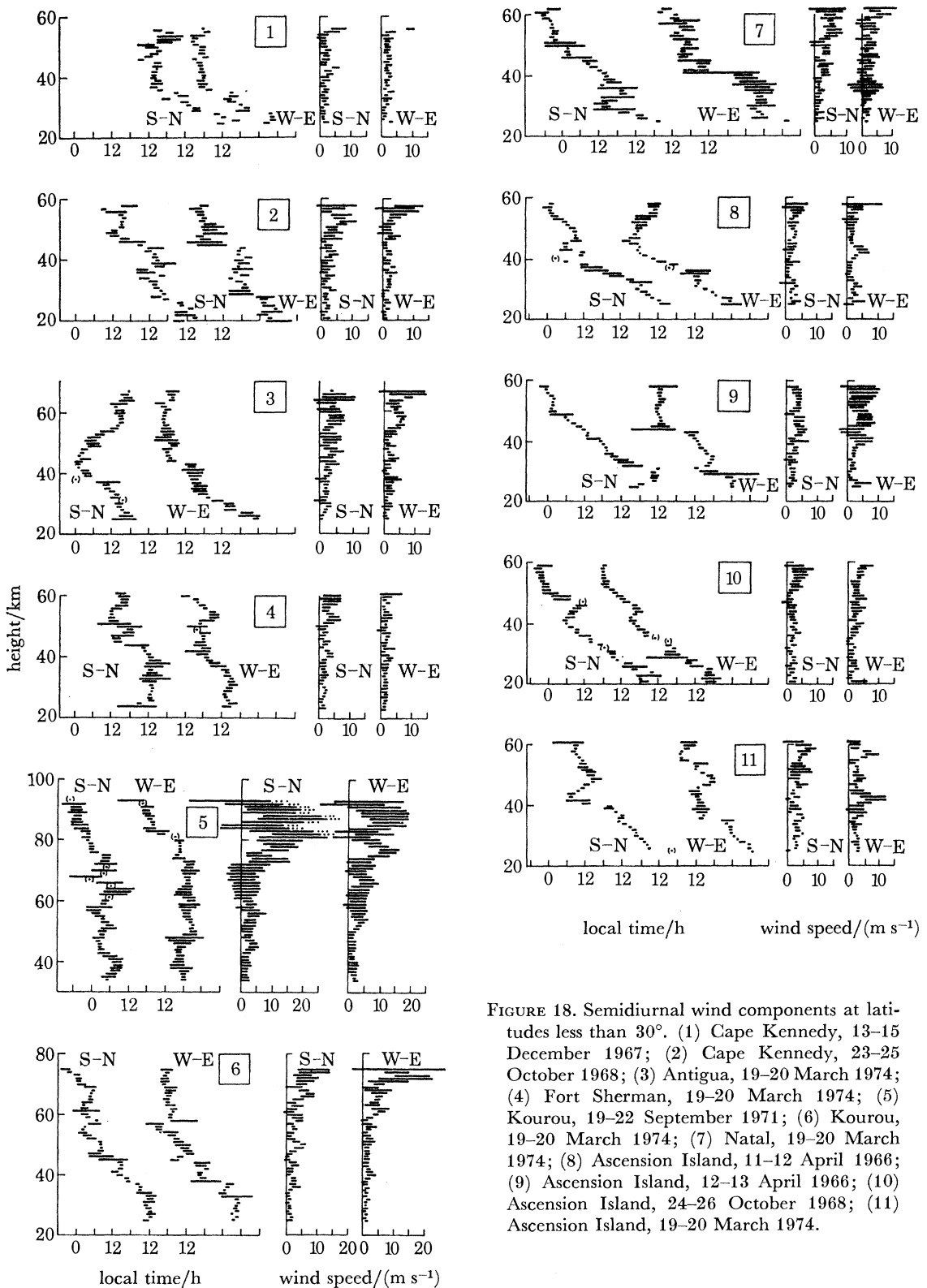
FIGURE 18. Semidiurnal wind components at latitudes less than 30°. (1) Cape Kennedy, 13–15 December 1967; (2) Cape Kennedy, 23–25 October 1968; (3) Antigua, 19–20 March 1974; (4) Fort Sherman, 19–20 March 1974; (5) Kourou, 19–22 September 1971; (6) Kourou, 19–20 March 1974; (7) Natal, 19–20 March 1974; (8) Ascension Island, 11–12 April 1966; (9) Ascension Island, 12–13 April 1966; (10) Ascension Island, 24–26 October 1968; (11) Ascension Island, 19–20 March 1974.

Interpretation of the results in figure 17 in terms of tidal Hough modes requires the introduction of significant contributions from higher-order semidiurnal modes. Some guide to the order of modes present is provided by the phase profiles which, for particular height ranges, complete one rotation (i.e. 12 h change of phase) within 14 km or less of vertical distance. Among the migrating semidiurnal modes, those having such oscillatory structures would be $(2, 2, n)$ where $n \gtrsim 14$. As with the diurnal components (§ 9) the direction of slope of the phase profiles (to earlier times with increasing height) points to a source of excitation at lower heights, most probably in the troposphere, where a common identity would be expected with the source of excitation of the diurnal components.

The above account of the properties of the semidiurnal oscillations closely follows that previously given (Groves 1976) on the basis of the Fort Churchill results of 6–9 September 1966 and 23–25 October 1968 and the Wallops Island and Mar Chiquita results of 19–20 March 1974. The further observations that have since been analysed and now appear in figure 17 support the previous account. The similarity between S–N and W–E semidiurnal profiles at mid and high latitudes, and the clockwise rotation of the wind vector at northern latitudes and anticlockwise rotation at southern latitudes, are in accord with the properties of Hough wind functions as previously discussed (Groves 1976). These properties were previously examined for migrating modes $(2, 2, n)$ and further calculations (not presented here) show that they also hold for both eastward and westward travelling non-migrating modes $(2, s, n)$, $s \neq 2$.

13. Semidiurnal winds at latitudes less than 30°

Figure 18 shows sets of results of semidiurnal oscillations derived at sites of less than 30° latitude. The two sets of results for Cape Kennedy at 28.5° N are consistent with a clockwise rotating wind vector at most observation heights within the limits of error and could be grouped with the results in figure 17. For Antigua at 17° N and also at still lower latitudes, S–N and W–E Hough wind functions become appreciably dissimilar and corresponding dissimilarities are to be expected between S–N and W–E semidiurnal wind components. The observational results for Antigua, Fort Sherman and most other launch sites in figure 18 show conspicuous differences between S–N and W–E components, which would appear to confirm this expectation.

The analyses for Ascension Island on 11–12 and 12–13 April 1966 (figure 18) show that both S–N and W–E semidiurnal components change radically between the two days. As with the diurnal components at low latitude (§ 10), a non-tidal variation would appear at times to replace or dominate a steady or quasi-steady tidal oscillation. Insufficient data are available to examine the frequency of such occurrences.

14. Discussion

14.1. *Seasonal wind variations*

Meridional cross sections of S–N and W–E wind components from 60 to 130 km at monthly intervals were prepared in 1969 and similar W–E wind models appear in *C.I.R.A.* (1972). These cross sections were prepared by averaging and smoothing observed wind components and have provided reference models against which to compared newly acquired data. Recent wind measurements by radio techniques, 80–100 km, tend to confirm the main features of the

models and their seasonal trends. Although many of the recent observations are from new longitudes, data coverage is still inadequate to allow reliable zonal mean motions to be obtained. With the new data, however, zonal means would not appear unlikely to differ greatly from model values and in particular from the high (*ca.* 10 m/s) S–N model velocities at heights close to 90 km.

Consideration has been given in § 5 to the mean meridional circulation that may be inferred from the wind models by reference to the 1974 calculations of Ebel for vertical wind velocities and by interpretation of the sloping zero S–N velocity line in the winter hemisphere of figure 1 as a boundary region separating mesospheric and lower thermospheric circulation patterns. The wintertime circulation described is an average situation appropriate to a time interval of the order of a month, from which appreciable deviations are indicated on shorter timescales by, for example, the day-to-day wind variations that are observed close to 90 km. Long term variations, such as a solar cycle dependence for wintertime winds, have been identified in mean meridional winds at particular sites and indicate corresponding long term modulations of the circulation.

Meridional circulations in the middle atmosphere cannot be studied observationally without an extensive coverage of global wind data that is far in excess of that available or likely to be available for some time. Evidence of the nature of meridional transport may, however, be indirectly obtained if other observable effects exist that are dependent upon it. Two ways in which wintertime mean meridional circulations may be relevant to middle atmosphere aeronomy are considered to be worthy of further examination: these are the mixing of air of mesospheric–equatorial origin with that of thermospheric–polar origin at about 90 km over mid latitudes, and the effect of such circulations on the internal atmospheric conditions appropriate to the winter anomaly in radio-wave absorption.

14.2. *Diurnal variations*

The principal frequency components of wind variations at meteor ionization heights are solar diurnal and semidiurnal (Teptin 1972): the same components predominate in surface pressure oscillations (Chapman & Lindzen 1970). In §§ 7–13 diurnal and semidiurnal components obtained from short series of rocket launchings are presented and discussed for the intermediate region of approximately 25–60 km.

The results of early series of launchings at White Sands and Ascension Island for diurnal components have previously been reported (Beyers *et al.* 1966; Beyers & Miers 1968): the conclusion reached was that a dominant diurnal tidal oscillation existed at the stratopause at the mid-latitude site whereas at the low-latitude site a well-defined diurnal variation was not evident being masked or distorted by some other short term disturbance. The larger body of data that has now been analysed supports these conclusions with the rider that at low latitudes both diurnal and semidiurnal variations are affected by short term disturbances although only intermittently. Greater clarification of the frequency of such disturbances cannot be given with the very few sets of data available.

Comparisons between phase and amplitude profiles for the same location at different times rarely show similarities and it would seem that at these heights the tidal motions are steady for only short intervals of time, possibly a few days, although no reliable estimate can be given of this variability as data are not available over adequate intervals of time.

It has also been possible to compare results at different stations at the same time including

pairs of stations at almost the same latitude in opposite hemispheres (Wallops Island and Mar Chiquita, Kourou and Natal, and Fort Sherman and Ascension Island). Comparisons between phase and amplitude profiles rarely show similarities indicating a detailed horizontal structure to tidal motions including a longitudinal dependence. From the longitudinal separation of the above pairs of stations, variations are significant over distances of *ca.* 10^3 km.

At latitudes greater than about 30°, phase profiles of W–E and S–N wind components usually represent wind vectors that rotate with height (clockwise in the Northern Hemisphere and anti-clockwise in the Southern Hemisphere). Rates of rotation with height are, however, greater than those corresponding to excitation of the leading diurnal or semidiurnal modes, being appropriate to higher-order modes whose latitudinal structure would require significant variations in the source of excitation over *ca.* 10° changes of latitude. Support for the interpretation of observed oscillations in terms of tidal modes is provided by phase profiles at high latitude (Fort Churchill), which differ characteristically from those at lower latitudes for the diurnal component but not for the semidiurnal: the diurnal phases at Fort Churchill are more nearly constant with respect to height than those at lower latitudes in accord with the properties of positive and negative sequences of diurnal models, whereas for the semidiurnal component only one sequence of modes exists.

An area for further investigation is the identification of the relatively localized sources of excitation that seem to be implied by the observations. Significant variations in tropospheric conditions over distances of *ca.* 10^3 km are common enough, but the requirement is for steady or quasi-steady diurnal and semidiurnal frequency components of an adequate magnitude to generate the stratospheric winds observed.

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