Diurnal Stratospheric Tide in Meridional Wind, 30 to 60 km, by Season

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ABSTRACT

The diurnal component in meridional wind is estimated for each season at twelve rocket stations. Amplitudes and phases are presented as a function of height-latitude or as vertical profiles. Many of the gross features of the tide persist throughout the year, but as they migrate in height and latitude the amplitude or phase at a given location may undergo large changes with season. Longitudinal variations in the diurnal tide are found in the mid-stratosphere, and it is suggested they are coupled with longitudinal variations in the tropospheric temperature structure.

1. Introduction

Large seasonal changes in the diurnal tide of wind in the lower stratosphere have been reported by several writers, most recently by Wallace and Tadd (1974). The latter suggest that large seasonal changes may occur in the upper stratosphere also, but a paucity of rocket data has discouraged attempts to identify them. Sufficient data are now available, however, to resolve the diurnal tide on a seasonal basis from 30 to 60 km at several stations and this paper presents these results for the meridional wind. In view of the current interest in seasonal changes of the tide, these results are presented now rather than waiting for such a time that resources become available to obtain the corresponding results for the zonal wind.

2. Basic data and analysis technique

Rocket stations used in this study are listed in Table 1. The period of record for each (basically 1960–71) is as given by Belmont *et al.* (1974), and extended to include 1972 data. In order to eliminate doubtful winds, only those values of the meridional wind within three standard deviations of the seasonal mean at each station and level were used in this analysis. The number of observations used at 50 km for each station and season is given in Table 1 where the seasons are also defined; as discussed below, statistical error estimates for some stations and seasons were not acceptable; in such cases a dash is entered in the table.

Seasonal mean values of the hourly meridional wind at 2 km intervals at each station were determined by averaging all observations taken between 30 min before to 29 min after the hour. Due to the irregular distribution of observation times (taken as the time of rocket launch), some hours contained no data. The resulting sets of hourly mean values were analyzed by the periodic regression technique described in Belmont *et al.* (1974). The periodic regression technique can be used to analyze time series of irregularly spaced data points, permitting some hours to contain no data, and simultaneously to determine an estimate of the statistical error of amplitude and phase for each component wave.

Initially, vertical profiles of the amplitude and phase (with errors) at 16 stations were plotted for each season. Also, the amplitude and phase values were plotted on height vs latitude diagrams. Inasmuch as very little smoothing was required (or information lost) on the height-latitude diagrams, the results are presented in that format below. Complete tabulations of the present results are given in Nastrom and Belmont (1975), or can be obtained from the authors.

It was determined by inspection of the vertical profiles that values associated with amplitude errors >3.9 m s^{-1} are unreliable, and those with amplitude errors >2.5 m s^{-1} are questionable. Typical estimates of amplitude errors will be given in Table 3. All results at four stations were therefore discarded, and results for some seasons at three other stations. The magnitude of the statistical errors depends largely on the noise (mainly synoptic variations), sample size, and hourly distribution of the data. For illustration, the distribution of observations at 50 km at the two most complete stations and at Barking Sands, where the distribution is relatively poor, is given in Table 2. The phase error also depends on amplitude, because as amplitude approaches zero, phase can take on any value. The statistical error estimates were used to identify suspicious values when drawing contours of amplitude and phase, which will be presented in Figs. 1–8. For example, the decreasing number of observations with altitude resulted in relatively large error

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TABLE 1. Rocketsonde observations used at 50 km by season. Dash indicates inadequate distribution of observations by hour.

Station	Latitude*	Longitude*	Season Spring (Mar, Apr, May)	Summer (Jun, Jul, Aug)	Autumn (Sep, Oct, Nov)	Winter (Dec, Jan, Feb)
Ascension	−7°59′	14°25′	306	272	327	289
Kwajalein	8°42′	−167°42′	68	85	87	78
Ft. Sherman	9°20′	79°59′	150	—	—	—
Antigua (48 km)	17°09′	61°47′	138	101	133	137
Barking Sands	21°54′	159°35′	325	390	370	277
Cape Kennedy	28°27′	80°32′	471	473	431	516
White Sands	32°23′	106°29′	601	663	647	503
Pt. Mugu	34°07′	119°07′	497	564	477	393
Wallops Is.	37°50′	75°29′	363	355	343	249
Ft. Churchill	58°44′	93°49′	205	186	251	277
Ft. Greely	64°00′	145°44′	—	265	—	—
Thule	76°33′	68°49′	—	122	—	—

* North or west, minus is south or east.

estimates above 48 km at Antigua (17°N) during winter through summer. In spring, when the contours of amplitude are nearly vertical above 55 km at 17°N, they have been drawn with broken lines to indicate uncertainty of the analysis since Antigua is not a useful station there. Other cases of uncertainty, resulting from large statistical errors or a lack of stations, are also drawn with broken lines.

At Churchill (59°N) the amount of data and its time distribution were adequate to provide acceptable error estimates during all seasons, but at Fort Greely (64°N) and Thule (77°N) the large synoptic noise during autumn through spring resulted in excessive error estimates. Thus, only during summer are the height-latitude sections extended beyond Churchill. At Fort Sherman (9°N) the distribution of observation times is so biased toward one hour in most seasons that the resulting error estimates were acceptable only during spring. The analysis at 8°N in spring is therefore based on an average of the results at Fort Sherman and Kwajalein, while in the other seasons the analysis at 8°N is based on Kwajalein only. Latitudinal gradients of the diurnal tide in meridional wind may become larger near the equator than at other latitudes, so interpolation between 8°N and 8°S was not felt justified and results for Ascension Island (8°S) will be presented separately.

If higher harmonics of the daily variation are important, then resolving only the first harmonic could result in misleading estimates because of aliasing effects caused by the non-uniform distribution of observations. To test this possibility, the diurnal and semidiurnal tides were simultaneously resolved at the three stations listed in Table 2. Not surprisingly, due to its poor time distribution of observations, statistical errors at Barking Sands were excessive in this test (Table 3). Therefore, with the presently limited data, it was necessary to assume that aliasing by the semidiurnal tide was unimportant and all of the results given below were determined without consideration of the semidiurnal tide. This assumption is supported by the fact that at White Sands and Churchill the error estimates and the corresponding values of amplitude (Table 3)

TABLE 2. Examples of the time distribution of meridional wind observations available at 50 km.

Station	Season	Hour (local mean time) 00–04	04–08	08–12	12–16	16–20	20–24	Total
White Sands	spring	16	38	8	35	376	128	601
	summer	27	26	21	84	380	125	663
	autumn	23	25	16	59	387	137	647
	winter	30	31	8	20	281	133	503
Barking Sands	spring	46	1	1	0	7	270	325
	summer	78	0	4	9	2	297	390
	autumn	73	1	1	2	11	282	370
	winter	43	4	2	0	1	227	277
Ft. Churchill	spring	61	14	8	18	80	24	205
	summer	20	9	3	34	107	13	186
	autumn	38	16	8	48	121	20	251
	winter	52	25	6	10	142	42	277

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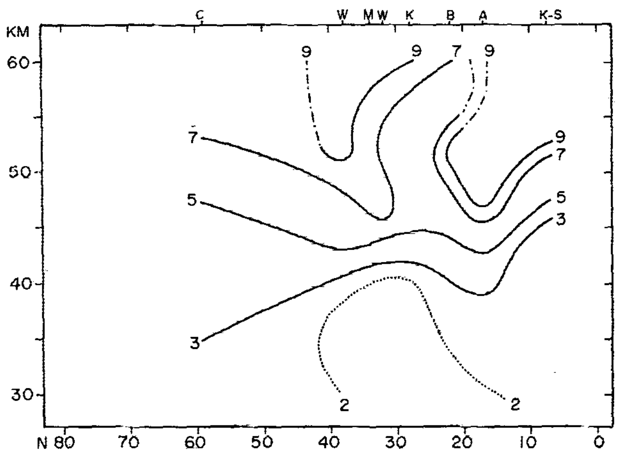

FIG. 1. Amplitude (m s⁻¹) of the diurnal wave in the meridional wind in spring. Letters at top of the figure refer to rocket stations used. A dash-dot line indicates uncertainty of the analysis due to large statistical errors or a lack of stations. Intermediate isopleths are dotted.

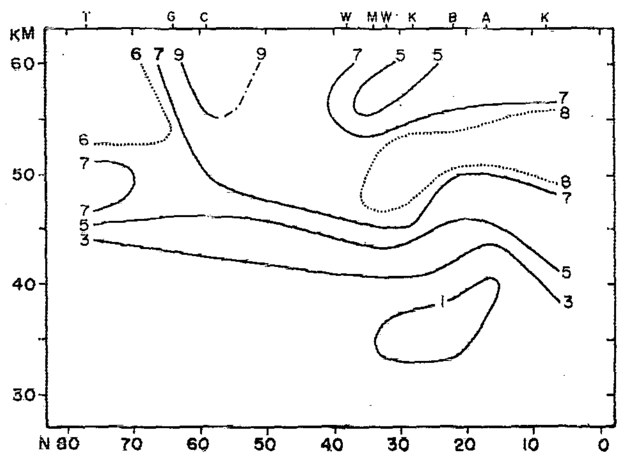

FIG. 2. As in Fig. 1 except for summer.

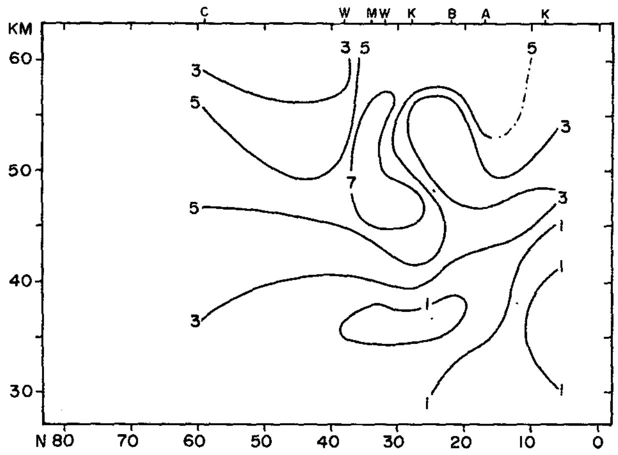

FIG. 3. As in Fig. 1 except for autumn.

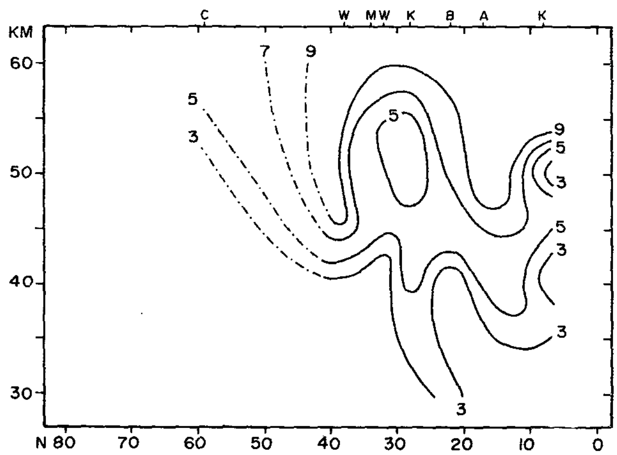

FIG. 4. As in Fig. 1 except for winter.

generally changed little when the semidiurnal wave was included.

3. Results

a. Height-latitude sections of amplitude and phase

The largest amplitudes of the diurnal tide are found in spring (Fig. 1) above 50 km near 10°N (10 m s^{-1}). Values in excess of 9 m s^{-1} are also found near 38°N in spring, 60°N in summer (Fig. 2), and near 15°N and 38°N in winter (Fig. 4). Amplitudes less than 1 m s^{-1} are found only in summer and autumn below 40 km.

A relative minimum amplitude of the diurnal tide in meridional wind is found persistently above 50 km at low latitudes. During spring (Fig. 1) the minimum extends nearly vertically at 25°N with its largest value of the year, over 6 m s^{-1}. In summer (Fig. 2) it is above 55 km near 30°N and has values slightly less than 5 m s^{-1}. It is smallest in autumn (Fig. 3), barely over 2 m s^{-1}, along an arc from 48 km at 10°N to 56 km at 20°N. During winter (Fig. 4) the minimum is closed off between 50 and 55 km near 30°N.

In general, the phase (Figs. 5–8) progresses downward from highest levels to near 40 km below which the phase reverses once or twice between 40 and 30 km. In winter there is continuous downward progression at all latitudes shown. Note that the regions of rapid

TABLE 3. Estimates of the amplitude (m s^{-1}) and error (in parentheses) of the diurnal tide in meridional wind at 50 km for the stations in Table 2. The upper rows of results were determined fitting the data with only the diurnal (D) wave while the bottom rows were determined fitting the data with both the diurnal and semidiurnal (SD) waves.

		Season			
Station	Waves	Spring	Summer	Autumn	Winter
Ft. Churchill	D	6.5 (0.6)	7.7 (0.7)	6.4 (0.7)	1.0 (0.4)
	D+SD	6.0 (0.7)	5.9 (0.8)	5.9 (0.8)	4.1 (0.7)
White Sands	D	8.0 (0.6)	7.5 (0.5)	6.6 (0.7)	5.7 (0.8)
	D+SD	7.4 (0.7)	7.4 (0.6)	5.9 (0.8)	6.0 (0.9)
Barking Sands	D	7.4 (1.9)	6.6 (0.8)	2.7 (1.1)	7.9 (1 9)
	D+SD	11.3 (4.4)	9.0 (2.4)	3.6 (2.6)	29.3 (8.5)

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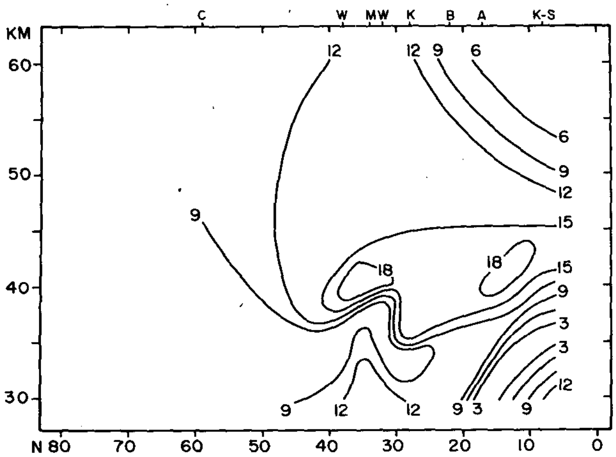

FIG. 5. Phase (hour of maximum northward speed) of the diurnal tide in the meridional wind in spring. Letters at top of the figure refer to rocket stations used.

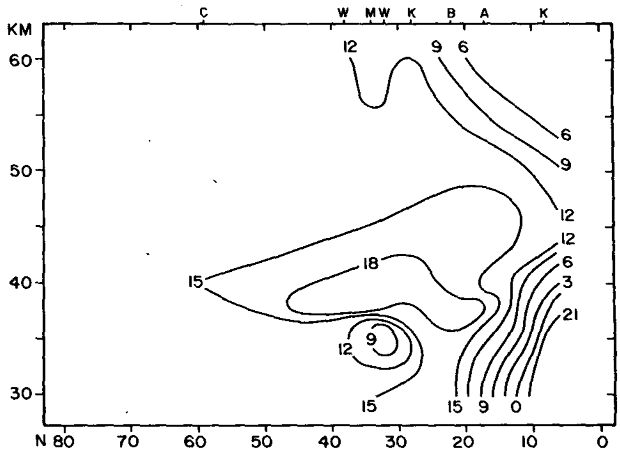

FIG. 7. As in Fig. 5 except for autumn.

phase change during spring through autumn are where the amplitudes are very small and hence the phase pattern has little significance. The results in Figs. 2 and 6 agree in general with the corresponding results for summer given by Reed *et al.* (1969), except for the phase at 20°N near 40 km, where the phase is least reliable because of small amplitude.

b. *Vertical profiles at Ascension Island*

Results for Ascension Island are presented separately because of possible problems in interpolating across the equator. Also, this station has more data than any other within 20° of the equator. Vertical profiles of amplitude at Ascension Island (Fig. 9), where summer is defined as December through February, show maxima near 35 and 50 km, with minima near 30, 40 and 55–60 km. Near the maxima at 35 and 50 km, amplitudes are largest in summer and smallest in winter.

On the average, the wave progresses downward about 30 km in 36 h (Fig. 10) with some large changes and even reversals in rate and direction between 30 and 40 km. Note that phase here is the time of maximum southward wind, unlike Figs. 5–8.

Reed *et al.* (1969) estimated the mean yearly diurnal tide in meridional wind at Ascension Island by consolidating data for all months. Thus, direct comparison of their results with those in Figs. 9 and 10 is not possible although it should be noted that their amplitude profile is generally within the envelope of amplitudes given in Fig. 9. Their phase profile shows that the phase at 42 km lags that at 36 km by 14 h while the phase values in Fig. 10 at 42 km lead those at 36 km by 6–9 h. This difference illustrates the sensitivity of phase to differing data samples, especially when the amplitude is small.

4. Discussion

Many of the seasonal changes found in Figs. 1–8 at a given location are larger than predicted by theory (Lindzen, 1967). However, the theoretical calculations are for an atmosphere at rest on a uniform sphere, and are based on highly idealized models of the distribution of water vapor and ozone. McKenzie (1968) has found

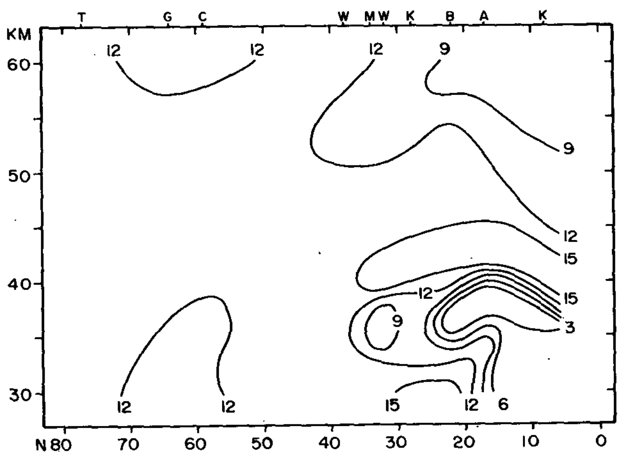

FIG. 6. As in Fig. 5 except for summer.

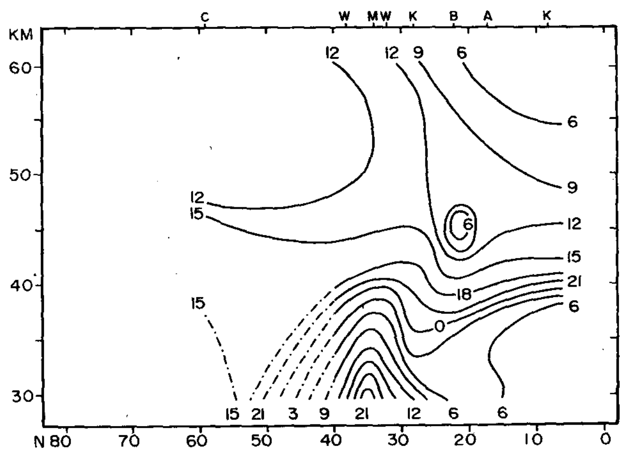

FIG. 8. As in Fig. 5 except for winter.

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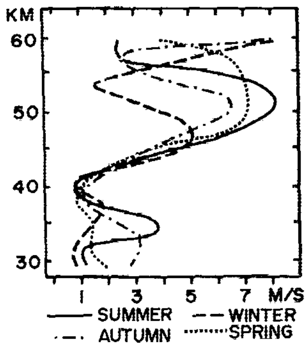

FIG. 9. Amplitude of the diurnal tide in the meridional wind at Ascension Island for each Southern Hemisphere season.

that changes as large as 100% in amplitude and several hours in phase can result when a different distribution of water vapor is assumed. As both water vapor (Mastenbrook, 1974) and ozone (Heath, 1974) are now known to have large seasonal variations, quantitative comparison of the present results with those of theory does not seem warranted. Further, seasonal changes in the influence of topography, e.g., land-sea heating differences, tropospheric temperature structure (Lindzen, 1968), tropospheric wind structure (Wallace and Tadd, 1974), and perhaps other factors may account for some of the present seasonal variations in the diurnal tide. Some qualitative features predicted by theory are discussed below.

Lindzen (1968) found that changes in the tropospheric temperature structure can cause large changes in the diurnal tide at stratospheric levels. His calculations for 25° latitude show that the propagating mode with 12 km vertical wavelength is dominant when there is a low, cold tropopause. In winter (Fig. 8) at 30°N to 38°N the phase lag between 30 and 36 km is about 12 h which, when extrapolated, corresponds to 12 km vertical wavelength. It is not clear, however, why a propagating mode is dominant at the relatively high latitude 38°N, as classical theory predicts that trapped modes dominate poleward of about 30°.

Longitudinal variations probably account for some of the detailed features found in Figs. 1–8, but in most cases the stations are too widely separated in *latitude*

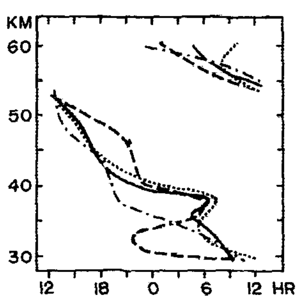

FIG. 10. Phase (hour of maximum southward speed) of the diurnal tide in the meridional wind at Ascension Island for each Southern Hemisphere season.

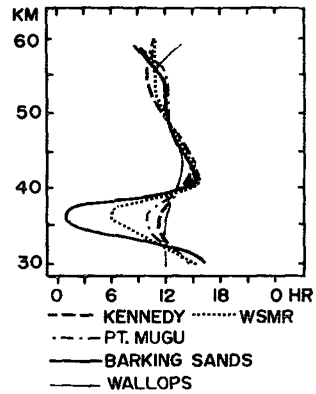

FIG. 11. Phase of the diurnal tide in the meridional wind in summer at selected rocket stations.

to detect longitudinal variations. Between 28°N and 38°N, however, the station coverage is adequate to suggest that the relatively early phases near 33°N at 36 km in summer (Fig. 6) and autumn (Fig. 7) are due to longitudinal variations. For direct comparison, the summer phase profiles at Wallops, Mugu, White Sands and Kennedy are shown in Fig. 11. Barking Sands is included in the figure to illustrate the phase at even lower latitude. Note that in the range 30–40 km the profiles at Wallops, Kennedy and Barking Sands indicate increasing phase variability as latitude decreases, but that White Sands and Mugu both have more variability than Kennedy despite their higher latitudes. Since the topography and mean state of the lower atmosphere in summer differ significantly between the southwestern United States and the east coast, the anomalous (with respect to Kennedy and Wallops, i.e., 80°W) summer phases at White Sands and Mugu are probably due to longitudinal differences.

There is also theoretical reason for expecting longitudinal variations such as the above. Lindzen (1968) has shown that the tropospheric temperature structure, especially near the tropopause, can significantly affect the stratospheric diurnal tide. Data given by Crutcher and Meserve (1970) indicate that in July the change of lapse rate at the tropopause is less, and the mean lapse rate from 700 to 200 mb is greater, over New Mexico than at 80°W, 33°N. Thus, this longitudinal difference in tropospheric temperature structure between 80°W and the southwestern United States could give rise to the different summer phase profiles at White Sands and Mugu. This hypothesis is supported by the similarity of the phase profiles from 28°N to 38°N during winter (Fig. 8; although those at White Sands and Mugu are shifted a few kilometers higher), for in January there is little difference in the tropospheric temperature structures over New Mexico and at 80°W, 33°N.

In this one case longitudinal differences in the stratospheric diurnal tide are apparently coupled with the tropospheric temperature structure. Other mechanisms which have been suggested to explain longitudinal dif-

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ferences in the diurnal tide, such as longitudinal differences in tropospheric winds or the non-uniform heating cycle due to land and sea differences, may be important at other times or in other places, but the present data are too limited to discuss them.

5. Conclusions

1) Largest amplitudes of the diurnal tide in meridional wind at 30–60 km are found near the stratopause during all seasons. In the Northern Hemisphere tropics and subtropics, largest amplitudes of the year near the stratopause occur in spring and the smallest in autumn.

2) Equatorward of 40°N the latest phase is near 40 km except during winter when the latest phases are below 30 km.

3) Because the above features of the diurnal tide vary with season, the tidal wind at a given location and time of day will vary in magnitude, and may change sign, from season to season.

4) Further observations and analysis are needed to determine the significance of, and factors which influence, longitudinal variations in the diurnal tide in the mid and upper stratosphere.

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