PERGAMON

Journal of Atmospheric and Solar-Terrestrial Physics 63 (2001) 975–985

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.nl/locate/jastp

The mesospheric quasi-2-day wave over Tirunelveli (8.7°N)

S. Gurubaran[a,*], S. Sridharan[a], T.K. Ramkumar[a], R. Rajaram[a,b]

[a] *Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Krishnapuram, Tirunelveli 627 011, India*
[b] *Indian Institute of Geomagnetism, Colaba, Mumbai 400 005, India*

Received 19 September 1999; accepted 2 February 2001

Abstract

Observations of the quasi-2-day planetary wave over a period of two years with the medium frequency (MF) radar operated at Tirunelveli (8.7°N, 77.8°E), India, are presented. The observational aspects of the characteristics of the wave over the low latitude station and its possible interaction with the mean wind and the diurnal tide are studied in detail. The amplitude of the 2-day wave has been observed to be larger in winter than in summer with noticeable inter-annual variability. The period of the wave varied between 46 and 53 h with a dependence on season. The vertical wavelength during large-amplitude wave bursts has been observed to be in the range of 35–70 km. The clear anti-correlation between the diurnal tide and the quasi-2-day wave occurrences and the presence of the 16-h wave provide indications for their interaction, which might have extracted energy from the primary diurnal tide. The changes in the mean wind during the passage of the quasi-2-day wave reflect the importance of the wave in determining the mesospheric momentum budget.

Keywords: MF radar; Baroclinic instability; Wave number; Evanescent mode; Vertical wavelength; Wave–wave; Wave–meanflow interaction

1. Introduction

The quasi-2-day wave is a ubiquitous feature of the middle atmosphere as revealed by many ground-based radar observations reported in the past (Muller, 1972; Craig et al., 1980; Tsuda et al., 1988; Raghava Reddi et al., 1988; Poole, 1990; Harris and Vincent, 1993; Palo and Avery, 1995; Thayaparan et al., 1997a, b, to state a few). Satellite observations of stratospheric and mesospheric temperatures have yielded important clues to the global structure of the quasi-2-day wave (Rodgers and Prata, 1981; Burks and Leovy, 1986; Wu et al., 1993, 1996). Muller and Nelson (1978) used simultaneous radar observations from different longitudinal sectors to infer the principal wave characteristic, that of a zonal wave number–3 westward propagating disturbance. However, recent reports by a number of workers have led to the realization that the quasi-2-day wave can propagate with zonal wave numbers 2–5 (Randel, 1994; Meek et al., 1996; Thayaparan et al., 1997b; Lieberman, 1999; to state a few).

On the theoretical front, two mechanisms have been proposed for the presence of the quasi-2-day wave in the middle atmosphere. One is based on the normal mode-theory (Salby, 1981) that interprets the wave as a manifestation of the (3, 0) Rossby normal mode. Plumb (1983), in an alternate theory, suggested that the wave is excited in baroclinically unstable zones. An eastward shear in the summer easterly mesospheric jet is one such region capable of forcing an instability. Later studies by Pfister (1985) and Norton and Thuburn (1996) were in favour of this alternate theory. Recently, Fritts et al. (1999), from their calculation of the meridional gradient of quasi-geostrophic potential vorticity using HRDI winds and the CIRA 1986 model temperatures, found a region of instability in the lower and middle mesosphere extending into the subtropical latitudes, thereby providing additional evidence for the baroclinic instability to excite the quasi-2-day wave. As discussed in the literature, both mechanisms fall short in explaining certain distinct wave features, for example, the hemispheric differences in

* Corresponding author. Tel.: +91-462-579465; fax: +91-462-573306.

E-mail address: gurubara@md4.vsnl.net.in (S. Gurubaran).

1364-6826/01/$ - see front matter
PII: S1364-6826(01)00016-5

the amplitude and the wave period. Using a linearized spectral model that includes realistic mean winds and dissipation, Hagan et al. (1993) performed a series of experiments to show that weak eastward winds in the winter hemisphere can account for an increase in the wave amplitudes along with a shift in the resonant frequency of the quasi-2-day wave response, and that a reversal of the westward jet at lower thermospheric heights leads to an enhancement of the summer wave signature.

The recent increase in reports on quasi-2-day wave observations has opened up certain key issues; prominent among which are the generating mechanisms, the effects of mean winds and dissipation, and the role of the wave in the momentum budget of the middle atmosphere, that could very well be taken up with the networks of radar stations currently operating worldwide. Supported by numerical experiments such as those of Hagan et al. (1993), these observations are expected to provide a strong base for a complete understanding of the complex dynamical feature of the middle atmosphere.

The present study on the characteristics of the quasi-2-day wave was based on the mesospheric wind data obtained over Tirunelveli (8.7°N, 77.8°E), India, using a medium frequency (MF) radar. Earlier low latitude measurements reported from Trivandrum (8°N, 77°E), India, were for selected days between the years 1985 and 1987, with the duration of each data set being either 2 or 4 days (Raghava Reddi and Geetha Ramkumar, 1997). Typical amplitudes observed were in the range of 20–30 m s^{-1}. Amplitudes during summer were observed to be small in contrast to large summer amplitudes reported from mid-latitudes. Observations at other equatorial location, Christmas Island (2°N, 157°W), have revealed pronounced amplitudes in the months of July/August and January/February (Harris and Vincent, 1993).

2. Observations

The wind data utilized in the present study were acquired by the MF radar operated at Tirunelveli in the spaced antenna mode. The system details, mode of operation and the method of wind determination are the same as described by Vincent and Lesicar (1991). Important results on mean winds and tidal climatologies observed over Tirunelveli were reported earlier (Rajaram and Gurubaran, 1998; Gurubaran and Rajaram, 1999). The present study of the quasi-2-day wave is based on the data collected during the years, 1995 and 1996. Hourly values of wind measurements in the altitude region of 84–98 km were first subjected to meaningful statistics for reliable wind estimates (Rajaram and Gurubaran, 1998). Since all hourly slots may not be filled for altitudes below 84 km because of small acceptance rate, this region is not included in the present analysis. Low acceptance rates during night-time, a limiting factor for altitudes below 84 km, do not pose a problem for any inference on

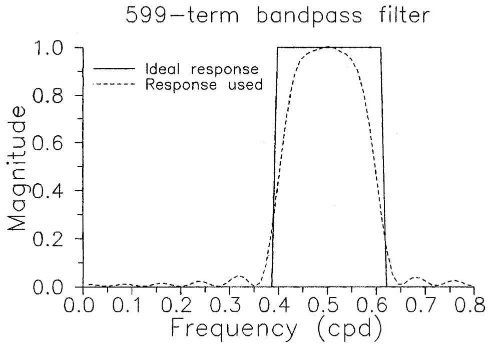

Fig. 1. The 599-term band-pass (40–60 h) FIR filter (dashed curve) together with ideal band-pass filter (continuous curve).

wave characteristics drawn for the altitude region under consideration.

3. Method of analysis

In order to bring out the temporal character of the quasi-2-day wave time domain filtering with finite impulse response (FIR) filters was used in the present work. FIR filters have the advantage of easy design and stable linear phase response (Press et al., 1992). To represent very large phase changes that may be expected in the filtered time series, the filter must have a bandwidth large enough to encompass the maximum fundamental frequency of the phase shifts. A filter centered at 0.5 cpd (cycles per day) with a bandwidth between 0.2 and 0.3 cpd is adequate to represent the salient features of the wave. A 599-term FIR filter (dashed curve) designed using the method described by Press et al. (1992) is sketched in Fig. 1. The continuous curve depicted in Fig. 1 represents an ideal response function with bandwidth of 0.2 cpd. It can be seen that the response function used for the analysis approximates well the ideal response curve.

Standard Fourier methods were also used to assess the temporal variability of the wave energy. Power spectral densities were calculated for overlapping time segments of data and the dependence of the spectral behaviour on time was studied. Though the computed power spectra represent only the time-averaged spectral behaviour, it is a convenient way to summarize the variance associated with each frequency interval and it also provides relative strength of the wave under consideration.

4. Observed wave characteristics

In Fig. 2 the temporal variation of the spectra in area-preserving variance content form is depicted for the period in the range of 1.55–2.80 days for meridional (NS) (top) and zonal (EW) (bottom) winds at 86 km. The

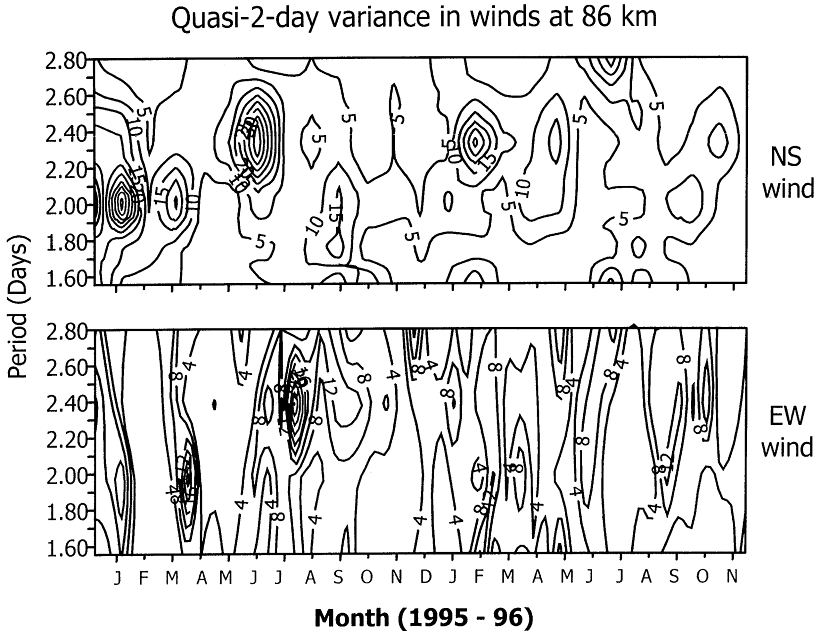

Fig. 2. Temporal variation of the spectra in area-preserving variance content form in the period range of 1.55–2.80 days for the meridional (NS) (top) and zonal (EW) (bottom) winds at 86 km.

power spectra were obtained for 336 point (hour) samples subjected to a sliding window with steps of length corresponding to 168 h. Intense bursts of wave activity may be noticed in the projected frequency band in the year 1995, during January and February, the end of March and June and July for the meridional component of the wave spectra. For the zonal component in 1995, enhanced wave activity was observed during the end of March and August. These features can very well be associated with the quasi-2-day wave events reported from other low and mid-latitudes. A noticeable feature in the power spectral distribution of Fig. 2 is the inter-annual variability in the wave. The spectral amplitudes during 1995 have been larger when compared to those observed during 1996. Further, the period of the wave in summer appears to be longer than during rest of the seasons. One can notice that the bursts of wave activity were centred around the period of 2.0 days for the meridional wind in February 1995 and between 1.9 and 2.0 days for the zonal wind in March 1995. For the July event, the wave activity in the meridional wind was centred around 2.3 days. Intense wave activity in the zonal wind during the July–August months was centred around 2.4 days.

The results of the time-domain filtering of observed zonal and meridional winds at 86 km for the years 1995 and 1996 are depicted in Figs. 3a and b. The band-pass filter adopted was the same as the one illustrated in Fig. 1. This enables effective elimination of tides and short-period gravity waves, which at times become dominant elements of the observed dynamics. Enhancements in the range of 15–25 m s^{-1} may be noted in the meridional wind (Fig. 3a). The large-amplitude zonal wind oscillations (Fig. 3b) varied in the range of 10–15 m s^{-1}. The wave events in the meridional wind during February and March, which lasted only for a few cycles, bring out the transient nature of the wave. In addition to the enhanced wave activity during the late solstice months, namely, February and July, there were sporadic bursts of occurrence during the spring (March/April) and the fall (September/October) equinox months. Though their amplitudes are comparatively less, bursts of wave activity in the zonal wind are noticed in January, February, April, July, August and October months. Comparison of time series of the filtered winds between the years under consideration reveals inter-annual variability in the wave activity mentioned above.

The transient nature of the wave may further be illustrated by focusing upon finite time segments and plotting the results for all altitudes. In Figs. 4a–d the time segments chosen were for the periods 1 January–1 March 1995 and 1 June–30 July 1995. Figs. 4a and b depict filtered time series for the meridional wind and Figs. 4c and d represent the time series for the zonal wind. In all examples presented herein high spatial and temporal coherence may be noticed for intervals of large amplitude. The largest wave activity with amplitudes of $\sim$ 40 m s^{-1} occurred at 84 km in the meridional wind during the first week of February and lasted for a few cycles. The wave amplitudes reached their maximum at 92 km for the zonal wind and 84 km for the meridional wind. One can also notice a tilt towards the right as the

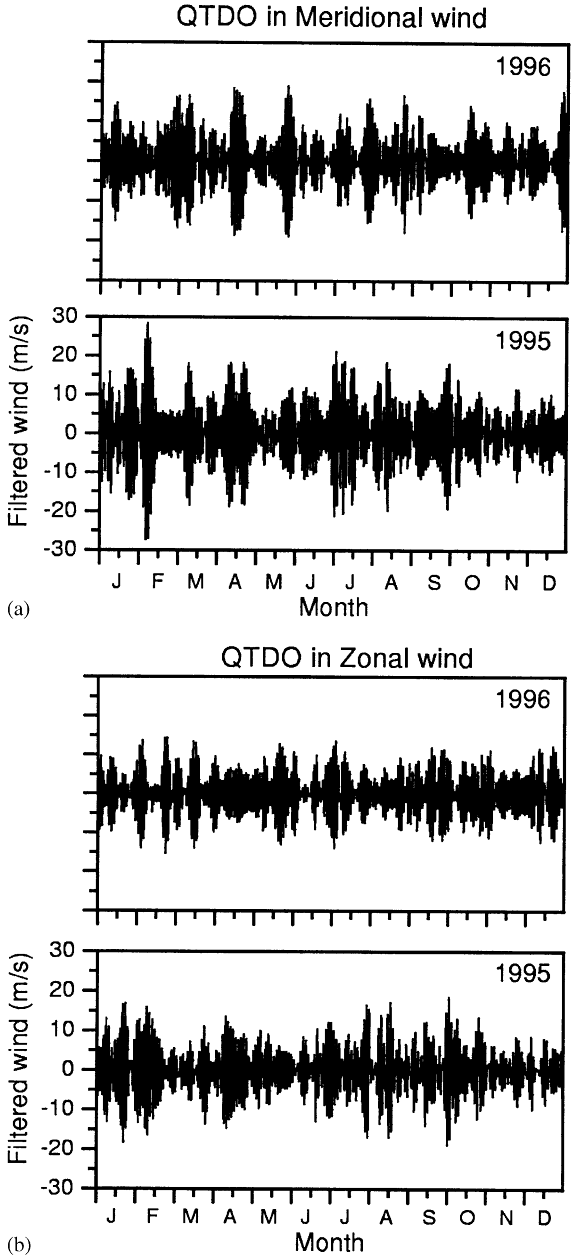

Fig. 3. Temporal variation of band-pass (40–60 h) filtered meridional wind at 86 km for the years 1995 (bottom panel) and 1996 (top panel). (b) Same as (a) but for zonal wind.

large-amplitude wave propagated upwards. The average ascent rate for the wave group is estimated to be $\sim$ 2.7 km day^{-1}. The phases of the individual waves, however, are seen to propagate downward. The strength of the wave bursts during summer months was relatively smaller ($\pm$30 m s^{-1} at 88, 90 and 92 km for NS component and $\pm$20 m s^{-1} at 84 km for EW component) when compared to the large-amplitude wave events during winter months.

4.1. Amplitude

For determining the wave characteristics, the large-amplitude wave events of 1995 corresponding to the periods 25 January–21 February and 27 June–24 July were selected for analysis. While examining the wave characteristics, the data were first separated into four-day segments. The filtered time series for each of these segments was then subjected to harmonic analysis with the period varied from 40 to 60 h and the wave parameters determined in the least squares sense. Figs. 5a and b represent the four-day mean amplitudes (top panel) and phases (bottom panel) of the quasi-2-day wave in the altitude region of 84–98 km, for the year 1995. The dashed curves represent the quasi-2-day wave in the zonal wind and the continuous curves represent the wave parameter for the meridional wind. During the winter months (Fig. 5a), the meridional amplitudes were larger ($\sim$30 m s^{-1} at 84 km during 6–9 February, the interval of peak activity), exhibiting large variation with height. The amplitudes were comparatively less ($\sim$20 m s^{-1} for the large amplitude wave) and show less variation with height during the summer months (Fig. 5b). The meridional wave amplitudes maximized at 84 km in winter (6–9 February) and in the altitude range of 86–90 km during summer (5–8 July) months. The enhancement of amplitudes occurred during days 2–9 of February and 1–8 of July in the year 1995. The year 1996 is characterized by an increasing trend in amplitude (both NS and EW) over height during winter (not shown). The amplitude changed by a factor of three between 84 and 98 km during peak wave activity. However, the largest amplitude was only $\sim$15 m s^{-1} when compared to $\sim$30 m s^{-1} observed in 1995, once again indicating the inter-annual variability in the occurrence of the quasi-2-day wave noted earlier. The variation in amplitude with height has been less during the summer months of 1996 (not shown).

4.2. Phase

The phase variation with height for each of the time segments for the selected days during winter and summer months is illustrated below the corresponding amplitude plot in Figs. 5a and b. The descending phase structures at the time of intense wave activity reveal vertical wavelengths between 35 and 70 km (February 06–09, and 10–13 in Fig. 5a; July 01–04, and 17–20 in Fig. 5b). However, evanescent modes with vertical wavelengths greater than 100 km are also noticed (January 25–February 01 in Fig. 5a, July 05–08 in Fig. 5b). The phase profiles were observed to be irregular (February 14–17 in Fig. 5a and July 13–16 in Fig. 5b) when the wave amplitudes were smaller. The phase difference between the meridional and zonal wind components was anywhere between 1 and 15 h. Sometimes the difference exceeded 15 h (for example, June 27–30 and

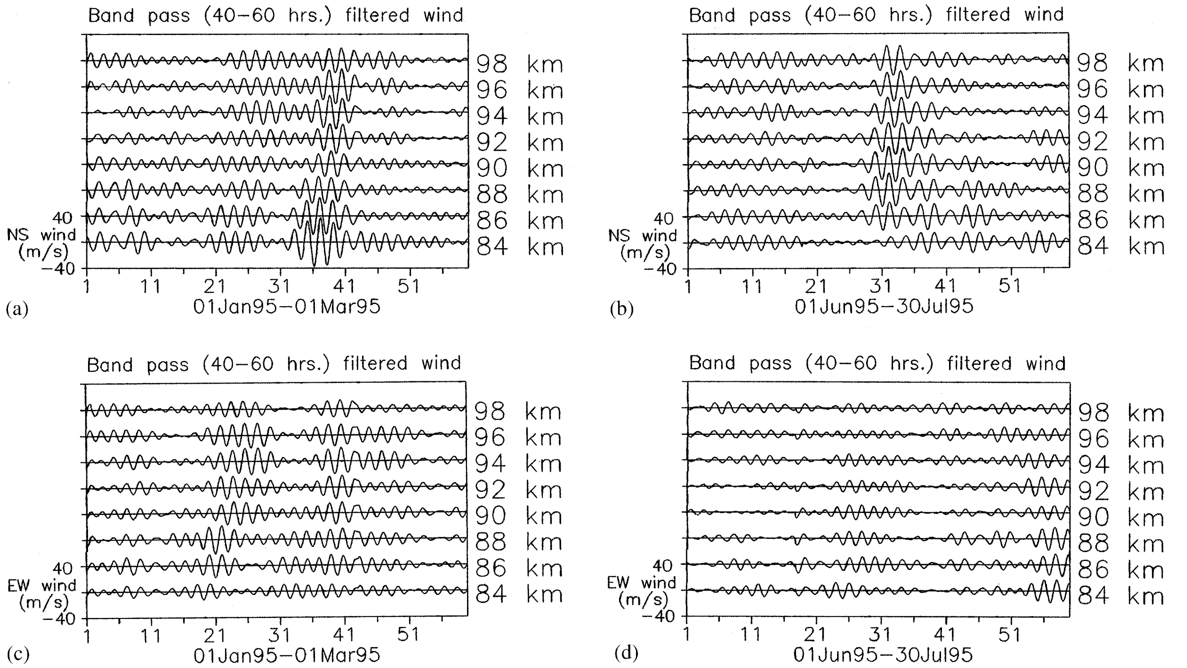

Fig. 4. (a) Filtered time series for meridional wind for the period 1 January–1 March 1995. (b) Same as (a) but for the period 1 June–1 August 1995. (c) Same as (a) but for the zonal wind. (d) Same as (a) but for the zonal wind during the period 1 June–1 August 1995.

July 13–16, 1995). A feature that stands out in the present analysis is that during summer the zonal wind tends to lead the meridional wind whereas the reverse appears to hold good during winter.

4.3. Period

The period of the quasi-2-wave was determined at all heights by the harmonic analysis method applied in the least squares sense. The mean periods were found to be 47 ± 0.4 and 48 ± 1 h for the meridional and zonal components, respectively during the winter season of the year 1995 (for the selected days only). For the days during summer, these values were 52 ± 2 and 49 ± 2 h, respectively. The year 1996 was characterized by the periods 49 ± 1 h for both zonal and meridional components during winter and 49 ± 1 and 50 ± 1 h, respectively during summer. These results suggest that the mean periods for summer are slightly larger than those estimated for winter.

5. Simultaneous observations of diurnal tide, quasi-2-day and the 16-h wave

Having studied the wave characteristics for the selected days during the years under consideration, we next examine the correlation between the occurrence times of the quasi-2-day wave and the diurnal tide. The MF radar observations at Saskatoon, Canada, by Manson et al. (1982) and Manson and Meek (1990) showed the presence of 16-h oscillation at the time of a large 2-day wave. One suggested mechanism is that the 16-h component is generated by non-linear interaction between the quasi-2-day wave and the tidal component (Manson and Meek, 1990; Teitelbaum and Vial, 1991; Vial, 1993). Recent mid-latitude observations are in favour of the non-linear interaction mechanism (Mitchell et al., 1996; Beard et al., 1997). Wind measurements at Tirunelveli were utilized to examine the correlation between the occurrence times of the quasi-2-day wave and the diurnal tide and the possible generation of the 16-h wave through this non-linear interaction process.

In Figs. 6a–d the seasonal variations of the two primary waves, namely, the diurnal tide and the quasi-2-day wave and the secondary wave they are expected to generate, namely, the 16-h wave, are depicted. The results are presented in the area-preserving variance content form. Top panels illustrate the variation for the 16-h wave and the bottom panels depict variations for the quasi-2-day wave (solid curve) and the diurnal tide (dashed curve). A first look at the comparison plots suggests that the wave activity was more prominent in 1995 than in 1996. The inter-annual variability was more pronounced in the meridional wind than in the zonal wind.

During the year 1995 (Figs. 6a and b), the comparison reveals a clear anti-correlation between the occurrence times of quasi-2-day wave activity and the diurnal tide. Enhanced

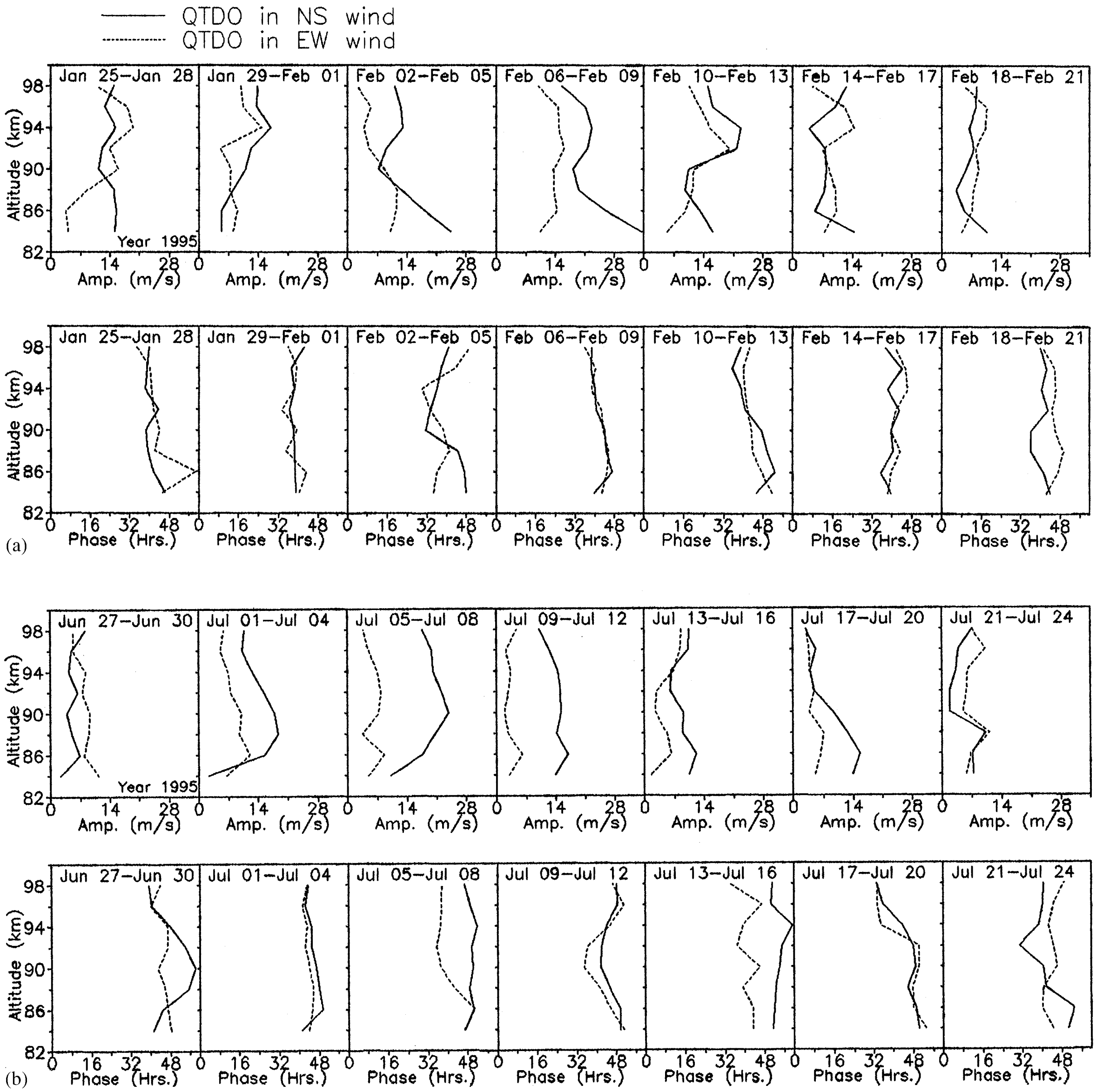

Fig. 5. (a) Altitude profiles of amplitude (top panel) and phase (bottom panel) of the quasi-2-day wave in the altitude region of 84–98 km for the winter months (January and February) of 1995. (b) Same as (a) but for summer months (June and July) of 1995.

quasi-2-day wave activity was almost always accompanied by weak diurnal tide and vice versa. For example, the variance in the quasi-2-day wave in the meridional wind in January and July was large when the variance in the diurnal tide was small. On the other hand, the sporadic maxima in diurnal tide activity observed all through the year 1995 appear to occur when the quasi-2-day wave activity was minimum. The variation for the 16-h wave was nearly similar to the variation for the quasi-2-day wave.

The year 1996 (Figs. 6c and d) is characterized by weaker amplitudes in both quasi-2-day wave and the diurnal tide. The anti-correlation that was observed during 1995 was not noticeably present in 1996. Rather, on certain occasions the two wave amplitudes varied in phase when the events occurred in bursts. The observed relationship between the three wave parameters for the meridional wind in 1995 was less clear for the year 1996 and not so clear for the zonal component.

6. Interaction of wave with mean wind

The vertically propagating wave encounters the background mean flow and its interaction with the mean flow may

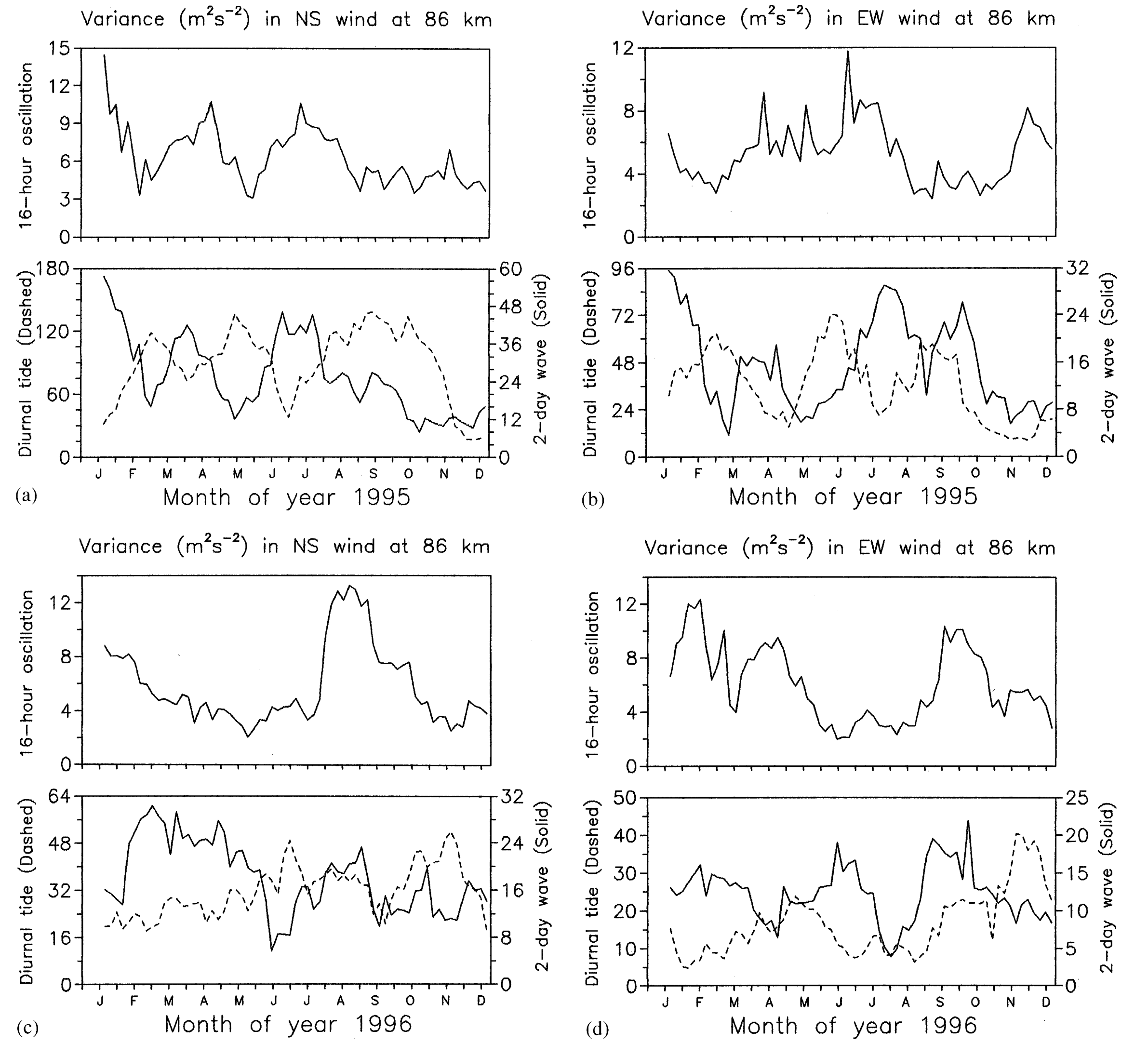

Fig. 6. (a) Temporal variation of the diurnal tide (bottom panel, dashed), the quasi-2-day wave (bottom panel, solid) and the 16-h oscillation (top panel) in the meridional wind at 86 km for the year 1995. Area-preserving variance content form has been used for depicting the seasonal progression of the wave. (b) Same as (a) but for zonal wind. (c) Same as (a) but for meridional wind for the year 1996. (d) Same as (a) but for zonal wind for the year 1996.

cause any of these: reflection, absorption, dissipation of the wave or destabilization of the atmosphere. Among these, the critical level absorption of the wave plays a vital role in the dynamics of the middle atmosphere in all scales. The upward propagating waves with westerly (easterly) phase speed deposit their eastward (westward) flow velocity and thereby determine the momentum and energy budget of the atmosphere (for example, Lindzen, 1981). The changes in the prevailing circulation were shown to be the response of the flow to the passage of the wave pulse (Plumb et al., 1987).

The wave events during the summer and winter months of 1995 described in the earlier sections were selected for the purpose of examining the background flow changes during the passage of the wave. Fig. 7 shows the variation of mean zonal wind with altitude before, during and after, the 2-day wave activity. The left panel depicts results for winter (January and February) and the right depicts results for the summer (June and July) events. It may be noted that during the winter months, prior to the 2-day wave burst, eastward wind speeds up to 12 m s^{-1} were observed below 84 km. During the times of intense wave activity, the mean wind became more westward ($\sim$ 16 m s^{-1} at 86 km) especially at lower heights. At higher heights, the mean wind was more or less the same as before the activity. Immediately after the wave event, one can notice larger westward flow at heights above 84 km.

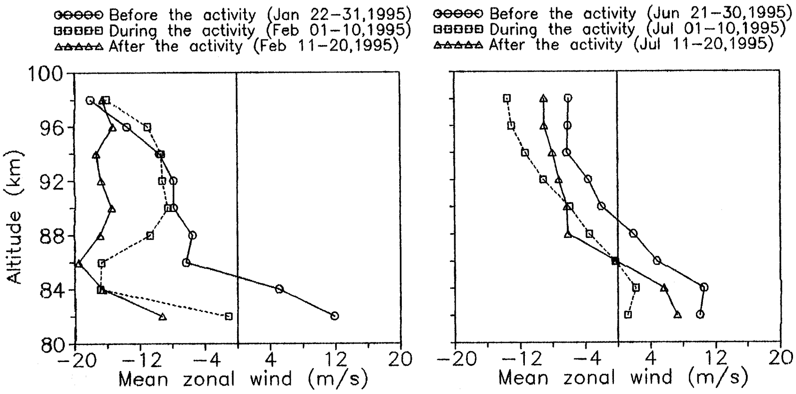

Fig. 7. Altitude variation of mean zonal wind before, during and after, the 2-day wave activity for January—February (left panel) and for June—July (right panel).

During June–July, the eastward flow had undergone a transition at 88 km to become westward at higher heights. During the intense wave activity, the flow became more westward at all heights as may be noted in Fig. 7. The impact of the quasi-2-day wave may be seen as a westward acceleration in the mesopause region. Once the wave activity recedes, the background flow tends to become less westward or more eastward at all heights except 88 km. The changes in the observed mean zonal circulation are interpreted to be due to the impact of the quasi-2-day wave on the background flow.

7. Discussion

Some of the earlier work from mid-latitude observations revealed the quasi-2-day wave as a late-summer phenomenon (Kingsley et al., 1978; Muller and Nelson, 1978; Craig et al., 1983; Thayaparan et al., 1997a) whereas the observations from equatorial and low latitude stations (Palo and Avery, 1995; Harris and Vincent, 1993) indicate that the activity is stronger in both summer and winter in the meridional component and is found to be much stronger in January–February (winter) than in June–July (summer). The low latitude observations from Tirunelveli reported in the present work provide indications for a larger wave amplitude in January–February in agreement with reports from other longitudes. There were also occasions when sporadic bursts of wave activity were observed during the equinox months. It may be noted that the peak amplitude in April 1995 was about 60% of the amplitude maximum in February and has been comparable to the summer event. In retrospect, some earlier radar observations in the northern hemisphere have revealed the presence of quasi-2-day wave round the year with pronounced activity in the winter and summer months (for example, Kingsley et al., 1978; Manson et al., 1982; Clark, 1989; Thayaparan et al., 1997a). Deng et al. (1997), followed by Palo et al. (1997), utilized globally coordinated observations over a 10-day winter campaign period and showed the presence of a strong 2-day wave during this period whose amplitude has been much larger than the diurnal and semidiurnal tides.

Radar observations also show that the quasi-2-day wave activity is more in meridional component than in zonal component (for example, Craig et al., 1980; Clark et al., 1993; Tsuda et al., 1988; Ito et al., 1984). Observations from Tirunelveli presented herein agree with these reports in that the amplitude of the meridional component during intense wave activity was larger in the range of 20–30 m s^{-1} than the zonal component which was observed to be less than 20 m s^{-1}, and maximized between 84 and 98 km in both the years under consideration. This is in contrast to the more or less equal amplitudes that were observed from the nearby station, Trivandrum, reported by Raghava Reddi and Geetha Ramkumar (1997).

The quasi-2-day wave activity reported in the present work was stronger in the year 1995 when compared to 1996 revealing inter-annual variability, similar to reports from elsewhere (for example, Thayaparan et al., 1997a, from London, Canada). A similar inter-annual variability was reported by Raghava Reddi and Geetha Ramkumar (1997).

The observed period of the quasi-2-day wave was mostly in the range of 48–51 h, with a noticeable seasonal dependence. The period during summer was higher than the period observed during winter. The shift in the wave period from summer to winter months reported in the present work agrees with the earlier report by Harris and Vincent (1993).

On many occasions the observed phase profile is characterized by the decrease of phase with height indicating upward propagation of the quasi-2-day wave, while on a few occasions the wave shows an evanescent structure for which case very little variation of phase with height was observed. There were also times when the phase increased with height. The propagation of the wave is known to be affected by the temperature profile of the intervening atmosphere. Reflection of the upward propagating waves may occur due to sudden temperature changes near the mesopause region. The upward propagating wave and the reflected wave may interfere to form a standing wave pattern when both of their amplitudes are equal. If one of the waves is relatively strong, the phase profile will show the decreasing or increasing trend corresponding to the strongest of the two (Raghava Reddi and Geetha Ramkumar, 1997).

The vertical wavelength of the quasi-2-day planetary wave was calculated from the rate of change of phase with height and was found to be in the range of 35–70 km during times of intense wave activity in winter. This is shorter than that observed at Kyoto (35°N) (Tsuda et al., 1988) and Adelaide (35°S) (Craig et al., 1980). Harris and Vincent (1993) observed vertical wavelength of 70 km for Christmas Island radar winds. From the same location, but using the meteor technique, Palo and Avery (1995) estimated vertical wavelengths between 36 and 44 km but for a different observation period. Thayaparan et al. (1997a) observed vertical wavelengths over London (43°N), Canada, greater than 150 km when the amplitudes were larger, though smaller vertical wavelengths of 60–80 km were also estimated at certain times of the observation. Raghava Reddi and Geetha Ramkumar (1997) observed simultaneous existence of two modes over Trivandrum—a stronger mode with a vertical wavelength greater than 100 km and a shorter mode with a vertical wavelength of 20 km. Since the observed meridional component was as strong as the zonal component, they ruled out the possibility of the presence of Kelvin wave which is a zonally propagating wave. Rather, their calculations yielded a vertical wavelength of 43 km for the Rossby wave with a zonal wave number of 3. Since the quasi-2-day wave observed over Tirunelveli has a much stronger meridional component with vertical wavelengths in the range of 35–70 km, the possibility of the observed wave events to be associated with the Rossby gravity wave with zonal wave number 3 need not be ruled out. Muller and Nelson (1978) used simultaneous radar observations from different longitudinal sectors to infer a zonal wave number—3 westward propagating disturbance. However, Randel (1994) showed evidence for the 2-day wave to be associated with zonal wave numbers 3 and 4. Using meteor and MF radar observations in the mid-latitude Northern Hemisphere, Meek et al. (1996) obtained zonal wave number 4, though the choice between zonal wave numbers 3 and 4 was not clear for one of the selected events. Recently, Lieberman (1999) observed 2-day wave events in the HRDI winds with zonal wave numbers 2–4. Identification of zonal wave number from a single station observation thus remains an elusive problem.

A clear anti-correlation between the diurnal tide and the quasi-2-day wave has been observed for the meridional wind at least for one of the years of observations when the wave activity was more pronounced implying that the dominance of one wave field suppresses the strength of the other. Harris and Vincent (1993) observed reduced diurnal tidal amplitudes over Christmas Island during periods of enhanced 2-day wave activity during the month of February. It is interesting to note that this feature has not been observed over Christmas Island during July. Thayaparan et al. (1997a) studied the interaction of the 2-day wave with the diurnal tide from the mid latitude station, London, Canada. They observed that the tide achieved peak amplitudes in bursts lagging behind the 2-day wave activity. There were also times when the tide and the 2-day wave amplitudes over London maximized at the same instant. Norton and Thuburn (1997) in their extended UGAMP model showed that the large-amplitude 2-day wave occurs at times when the diurnal tide is weak, suggesting that a possible interaction between the two may be causing the weak tidal amplitudes.

A prominent feature noted in the present work is that at times when the diurnal tide amplitude varied out of phase with the quasi-2-day wave as observed for the meridional component in 1995, the 16-h wave amplitude varied in phase with the quasi-2-day wave. There is a possibility that the secondary wave that is generated from the interaction between the primary waves grows at the expense of one of the primary waves. The observational features presented in this work suggest that the 16-h wave, which is believed to be the product of the interaction between the diurnal tide and the quasi-2-day wave, grows at the expense of the diurnal tide, thereby suppressing the tidal amplitudes.

The changes in the mean zonal circulation observed during periods of intense quasi-2-day wave activity reflect the importance of the wave in determining the mesospheric momentum budget.

8. Conclusion

The observations reported in this work provide additional information on the behaviour of the quasi-2-day planetary wave from a different geographical location. The overall characteristics of the wave were found to be the same as other equatorial locations. On many of the occasions a clear anti-correlation between the occurrences of the quasi-2-day wave and the diurnal tide was observed and reported herein. This feature provides confirmation for the association of the 16-h wave with the non-linear interaction between the 2-day wave and the diurnal tide. More observations planned for the future under the global PSMOS (Planetary Scale Mesopause Observing System) and EPIC (Equatorial processes Including Coupling) programmes, supported by modelling efforts, may help to resolve some of the key issues, namely, the forcing mechanisms, factors contributing to the different zonal wave numbers reported elsewhere and the actual role played by the 2-day wave in determining the energy and momentum budgets of the middle and upper atmosphere.

Acknowledgements

The authors thank K. Unnikrishnan Nair for his technical support in running the radar system. S.S. and T.K.R. thank the Director, Indian Institute of Geomagnetism, Mumbai, for offering a research scholarship. This work is supported by the Department of Science and Technology, Government of India.

References

Beard, A.G., Mitchell, N.J., Williams, P.J.S., Jones, W., Muller, H.G., 1997. Mesopause-region tidal variability observed by meteor radar. Advances in Space Research 20, 1237–1240.

Burks, D., Leovy, C., 1986. Planetary waves near the mesospheric easterly jet. Geophysical Research Letters 13, 193–196.

Clark, R.R., 1989. The quasi 2-day wave at Durham (43°N): solar magnetic effects. Journal of Atmospheric and Terrestrial Physics 51, 617–622.

Clark, R.R., Vincent, A.C., Manson, A.H., Meek, C.E., Avery, S.K., Palo, S.E., Aso, T., 1993. Global properties of the 2-day wave from mesosphere–lower thermosphere radar observations. Journal of Atmospheric and Terrestrial Physics 43, 1279–1288.

Craig, R.L., Vincent, R.A., Fraser, R.I., Muller, H.G., 1980. The quasi 2-day wave in the Southern Hemisphere mesosphere. Nature 289, 319–320.

Craig, R.R., Vincent, A.C., Kingsley, S.P., Muller, H.G., 1983. Simultaneous observations of the quasi 2-day wave in the northern and southern hemispheres. Journal of Atmospheric and Terrestrial Physics 45, 539–541.

Deng, W., Salah, J.E., Clark, R.R., Franke, S.J., Fritts, D.C., Hoffmann, P., Kuerschner, D., Manson, A.H., Meek, C.E., Murphy, D., Nakamura, T., Palo, S.E., Riggin, D.M., Roble, R.G., Schminder, R., Singer, W., Tsuda, T., Vincent, R.A., Zhou, Q., 1997. Coordinated global radar observations of tidal and planetary waves in the mesosphere and lower thermosphere during 20–30 January 1993. Journal of Geophysical Research 102, 7307–7318.

Fritts, C.D., Isler, J.R., Lieberman, R.S., Burrage, M.D., Marsh, D.R., Nakamura, T., Tsuda, T., Vincent, R.A., Reid, I.M., 1999. Two-day wave structure and mean flow interactions observed by radar and High Resolution Doppler Imager. Journal of Geophysical Research 104, 3953–3969.

Gurubaran, S., Rajaram, R., 1999. Long-term variability in the mesospheric tidal winds observed by MF radar over Tirunelveli (8.7°N, 77.8°E). Geophysical Research Letters 26, 1113–1116.

Hagan, M.E., Forbes, J.M., Vial, F., 1993. Numerical investigation of the propagation of the quasi 2-day wave into the lower thermosphere. Journal of Geophysical Research 98, 23,193–23,205.

Harris, T.J., Vincent, R.A., 1993. The quasi-two-day wave observed in the equatorial middle atmosphere. Journal of Geophysical Research 98, 10,481–10,490.

Ito, R., Tsuda, T., Aso, T., Kato, S., 1984. Long period oscillations in the meteor winds observed over Kyoto during 1978–1983. Journal of Geomagnetism and Geoelectricity 36, 173–188.

Kingsley, S., Muller, H.G., Nelson, L., Scholefield, A., 1978. Meteor winds over Sheffield. Journal of Atmospheric and Terrestrial Physics 40, 917–922.

Lieberman, R.S., 1999. Eliassen–Palm fluxes of the 2-day wave. Journal of Atmospheric sciences 56, 2846–2861.

Lindzen, R.S., 1981. Turbulence and stress owing to gravity wave and tidal breakdown. Journal of Geophysical Research 86, 9707–9714.

Manson, A.H., Meek, C.E., Gregory, J.B., Chakrabarty, D.K., 1982. Fluctuations in tidal (24-, 12-h) characteristics and oscillations (8-h 5-d) in the mesosphere and lower thermosphere (70–110 km) : Saskatoon (52°N, 107°W). Planetary Space Science 30, 1283–1294.

Manson, A.H., Meek, C.E., 1990. Long period (~8–20 h)wind oscillations in the upper middle atmosphere at Saskatoon (52°N); evidence for non-linear tidal effects. Planetary Space Science 38, 1431–1441.

Meek, C.E., Manson, A.H., Franke, S.J., Singer, W., Hoffmann, P., Clark, R.R., Tsuda, T., Nakamura, T., Tsutsumi, M., Hagan, M., Fritts, D.C., Isler, J., Portnyagin, Yu.I., 1996. Global study of northern hemisphere quasi-2-day wave events in recent summers near 90 km altitude. Journal of Atmospheric and Terrestrial Physics 58, 1401–1411.

Mitchell, N.J., Williams, P.J.S., Beard, A.G., Buesnel, G.R., Muller, H.G., 1996. Non-linear planetary/tidal wave interactions in the lower thermosphere observed by meteor radar. Annales Geophysicae 19, 364–366.

Muller, H.G., 1972. Long period meteor wind oscillations. Philosophical Transactions of Royal Society 271A, 585–598.

Muller, H.G., Nelson, L., 1978. A travelling quasi 2-day wave in the meteor region. Journal of Atmospheric and Terrestrial Physics 40, 761–766.

Norton, W.A., Thuburn, J., 1996. The two day wave in the middle atmosphere GCM. Geophysical Research Letters 23, 2113–2116.

Norton, W.A., Thuburn, J., 1997. The mesosphere in the extended UGAMP GCM. In: Hamilton, K. (Ed.), Gravity Wave Processes and their Parameterization in Global Climate Models, Vol. 50. Springer, New York, pp. 383–401.

Palo, S.E., Avery, S.K., 1995. Observations of the meridional quasi two-day wave in the mesosphere and lower thermosphere at Christmas Island. The upper mesosphere and lower thermosphere: a review of experiment and theory. Geophysical Monograph 87, 101–110.

Palo, S.E., Hagan, M.E., Meek, C.E., Vicent, R.A., Burrage, M.D., Mclandress, C., Franke, S.J., Ward, W.E., Clark, R.R., Hoffmann, P., Johnson, R., Kurschner, D., Manson, A.H., Murphy, D., Nakamura, T., Portnyagin, Yu.I., Salah, J.E., Schminder, R., Singer, W., Tsuda, T., Virdi, T.S., Zhou, Q., 1997. An intercomparison between the GSWM, UARS, and ground based radar observations: a case-study in January 1993. Annales Geophysicae 15, 1123–1141.

Plumb, R.A., 1983. Baroclinic instability of the summer mesosphere: a mechanism for the quasi-two-day wave? Journal of Atmospheric Sciences 40, 262–270, 1983.

Plumb, R.A., Vincent, R.A., Craig, R.L., 1987. The quasi-two-day wave event of January 1984 and its impact on the mean mesospheric circulation. Journal of Atmospheric Sciences 44, 3030–3036.

Poole, L.M.G., 1990. Characteristics of the mesospheric two day wave as observed at Grahamstown (33.3°S, 26.5°E). Journal of Atmospheric and Terrestrial Physics 52, 259–268.

Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P., 1992. Numerical Recipes in FORTRAN: The Art of Scientific Computing, 2nd Edition. Cambridge University Press, New York, 963pp.

Pfister, L., 1985. Baroclinic instability of easterly jets with application to the summer mesosphere. Journal of Atmospheric Sciences 42, 313–330.

Raghava Reddi, C., Geetha Ramkumar, 1997. Climatologies of quasi 2-day and 16-h wind oscillations in the meteor region over Trivandrum. Indian Journal of Radio and Space Physics 26, 1–14.

Raghava Reddi, C., Geetha, A., Lekshmi, K.R., 1988. Quasi 2-day wave in the middle atmosphere over Trivandrum. Annales Geophysicae 6, 231–238.

Rajaram, R., Gurubaran, S., 1998. Seasonal variabilities of low-latitude mesospheric winds. Annales Geophysicae 16, 197–204.

Randel, W.J., 1994. Observations of the 2-day wave in NMC stratospheric analyses. Journal of Atmospheric Sciences 51, 306–313.

Rodgers, C.D., Prata, A., 1981. Evidence for a travelling 2-day wave in the middle atmosphere. Journal of Geophysical Research 86, 9661–9664.

Salby, M.L., 1981. The 2-day wave in the middle atmosphere: observations and theory. Journal of Geophysical Research 86, 9654–9660.

Teitelbaum, H., Vial, F., 1991. On tidal variability induced by nonlinear interaction with planetary waves. Journal of Geophysical Research 96, 14,169–14,178.

Thayaparan, T., Hocking, W.K., MacDougall, J., 1997a. Amplitude, phase, and period variations of the quasi 2-day wave in the mesosphere and lower thermosphere over London, Canada (43°N, 81°W), during 1993 and 1994. Journal of Geophysical Research 102, 9461–9478.

Thayaparan, T., Hocking, W.K., MacDougall, J., Manson, A.H., Meek, C.E., 1997b. Simultaneous observations of the 2-day wave at London (43°N, 81°W) and Saskatoon (52°N, 107°W) near 91 km altitude during the two years of 1993 and 1994. Annales Geophysicae 15, 1324–1339.

Tsuda, T., Kato, S., Vincent, R.A., 1988. Long period oscillations observed by the Kyoto meteor radar and comparison of the quasi-2-day wave with Adelaide HF radar observations. Journal of Atmospheric and Terrestrial Physics 50, 225–230.

Vial, F., 1993. Causes of tidal variability. Coupling Processes in the Lower and Middle Atmosphere. Kluwer Academic Publishers, Dordrecht, pp. 137–151.

Vincent, R.A., Lesicar, D., 1991. Dynamics of the equatorial mesosphere: first results with a new generation partial reflection radar. Geophysical Research Letters 18, 825–828.

Wu, D.L., Hays, P.B., Skinner, W.R., Marshall, A.R., Burrage, M.D., Lieberman, R.S., Ortland, D.A., 1993. Observations of the quasi 2-day wave from the high resolution Doppler imager on UARS. Geophysical Research Letters 20, 2853–2856.

Wu, D.L., Fishbein, E.F., Read, W.G., Waters, J.W., 1996. Excitation and evolution of the quasi-2-day wave observed in UARS/MLS temperature measurements. Journal of Atmospheric Sciences 53, 728–738.