JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 106, NO. D23, PAGES 31817–31824, DECEMBER 16, 2001

Mean winds, tides, and gravity waves during the westward phase of the mesopause semiannual oscillation (MSAO)

S. Gurubaran and R. Rajaram[1]

Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Krishnapuram, Tirunelveli, India

Abstract. MF radar observations of mean winds, tides, and gravity waves (in the period range 30–120 min) over Tirunelveli (8.7°N, 77.8°E) during April 1993, when the mesopause semiannual oscillation (MSAO) was in the westward phase, are presented in this work. The focus herein is on the observed relationship between these dynamical parameters, which is explained in the context of the current understanding of the behavior of MSAO winds, tidal dissipation, and gravity wave-tide interactions. The observed diurnal tide amplitude and phase variations with height indicate (1,1) wave damping and subsequent westward momentum deposition. The gravity wave variances are shown to be modulated by the diurnal tide. Though the analysis does not lead to an estimation of gravity wave contributions to the time-mean zonal flow and its shears, the observations do suggest that the short-term tidal variability contributes, either directly, or indirectly through the gravity wave-tidal interactions, to the variation of the strength of the time-mean westward flow associated with the MSAO.

1. Introduction

Since the work of *Hirota* [1978], the equatorial semiannual oscillation (SAO) in the mean zonal wind at mesopause heights (~85 km) has been well documented based on the use of a variety of experimental techniques [*Hamilton*, 1982; *Avery et al.*, 1989; *Garcia and Clancy*, 1990; *Vincent*, 1993; *Tsuda et al.*, 1995; *Burrage et al.*, 1996; *Garcia et al.*, 1997; *Rajaram and Gurubaran*, 1998]. The mesopause SAO (MSAO) is characterized by westward flow during equinox months and eastward flow during solstices. The alternating wind regimes descend at a rate of ~6 km month^{-1} with considerable interannual variability [e.g., *Rajaram and Gurubaran*, 1998]. Wave-driving mechanisms involving the diurnal tide, inertia gravity waves, and equatorially trapped Kelvin and Rossby gravity waves are believed to contribute to the momentum budget associated with the MSAO. The underlying stratosphere acts like a filter for the upward propagating waves as many of the variabilities of long-period motions in the mesopause region essentially have their origin in the stratosphere. Some of the motions, for example, in the intraseasonal scales, are being linked to the tropospheric variability [*Eckermann et al.*, 1997].

There were a few attempts in the past to simulate the effects of the many dynamical forcings on the long-period variability of the mean zonal flow in the equatorial mesopause region (see *Hamilton et al.* [1995], *Mayr et al.* [1997], and for more recent work, *Garcia and Sassi* [1999]). Though these efforts succeeded in bringing out the long-term variability, for example, the SAO and the quasi-biennial oscillation (QBO), the observational support for the role of the known forcing mechanisms is lacking. For example, *Mayr et al.* [1997] proposed a model for the momentum deposition by small-scale gravity waves with which they are able to reproduce the QBO-like oscillations of the zonal circulation. Their parameterization scheme was shown to be sensitive to the chosen parameters, which are not well determined. Further, they have not incorporated the effects of diurnal tide and planetary-scale waves in their simulation. By adopting a model that incorporates forcing by unsteady convective heating, *Garcia and Sassi* [1999] have attempted to simulate the MSAO. The observational evidences for the presence of planetary and intermediate-scale waves required to produce this effect in their model, however, are not available. *Lieberman and Riggin* [1997] and *Kovalam et al.* [1999], from the satellite and MF radar observations, demonstrate that the role of equatorial Kelvin waves in the mesospheric momentum budget is small. Since the work of *Lindzen* [1981], the role of diurnal tide in providing westward momentum forcing has been well recognized. However, observational evidences for the breaking of the diurnal tide and the subsequent acceleration of the background flow are not found in the literature, though recent satellite observations do provide some insights into the breaking of the diurnal tide and the associated mean flow changes [*Lieberman*, 1997]. The role of the diurnal tide in the MSAO and its variability is yet to be quantified either.

The above arguments indicate an urgent need for long-term observations of planetary waves, tides, and gravity waves in the equatorial region with emphasis on global coverage in order to delineate the longitudinal differences. A meteor scatter detection system was installed at Christmas Island (2°N) in the central Pacific more than a decade ago, and the first ever continuous measurements of equatorial mesospheric winds were reported by *Avery et al.* [1989]. From the same location a partial reflection medium frequency (MF) radar has been used to derive useful information on mesospheric dynamical parameters for nearly a decade [see, e.g., *Vincent and Lesicar*, 1991; *Vincent*, 1993; *Kovalam et al.*, 1999]. In the Indonesian sector a meteor radar and an MF radar have been operating from the low-latitude site, Jakarta (6.4°S), and the equatorial location, Pontianak (0°N), respectively [*Tsuda et al.*, 1995; *Yoshida et al.*, 1999]. In the Indian sector an MF radar located at Tirunelveli (8.7°N, 77.8°E) yields useful information on mean winds [*Rajaram and Gurubaran*, 1998], tides [*Gurubaran and Rajaram*, 1999], and planetary waves [*Gurubaran et al.*, 2001].

Results presented in this work are based on a qualitative analysis of the data obtained by the MF radar at Tirunelveli. The focus herein is on the behavior of mean winds, tides, and gravity waves and their relationship observed during the westward phase of the mesopause semiannual oscillation. It is shown that the greatest westward motions at the mesopause heights are associated with

[1]Also at Indian Institute of Geomagnetism, Colaba, Mumbai, India.

Paper number 2001JD000325.
0148-0227/01/2001JD000325$09.00

greatest diurnal tide activity, which reveals phase structure that is in agreement with an evanescent mode. The amplitude reduction that takes place rapidly above 88 km indicates wave damping. Implications are that the diurnal tide either by itself or through high-frequency gravity wave modulation at tidal periods generates westward acceleration and causes the time-mean westward flow observed by the radar.

2. Observations and Data Analysis

The MF radar mesospheric winds were obtained over the altitude region 68–98 km with a temporal resolution of 2 min. Though the altitude resolution of the radar is ~4.5 km, the echoes are received at every 2 km interval. The method of wind determination is the same as described by *Vincent and Lesicar* [1991] and will not be repeated here. Because the nighttime data coverage is poor below 84 km, the analysis is restricted to altitudes mostly above 84 km, for too few points during nighttime would bias the results of the spectral analysis and introduce an apparent peak near 24 hours. The contamination due to this effect on the spectral peaks of various frequency components will be minimum if proper precaution is taken in selecting the height range. The missing data points in the selected height range, 84–98 km, are filled in after linear interpolation. Hourly means of zonal winds are utilized for the determination of tidal amplitudes and phases. The high-frequency variations in observed winds are obtained after subjecting the 2-min samples to traditional power spectral methods. The period band is selected to lie in the range 30–120 min. Because the largest number of the useful data samples are accumulated for 84 and 86 km heights, gravity wave estimates are made only for these heights. Other heights suffer from frequent data gaps of more than tens of minutes duration because of the rejection criteria adopted in the analysis (discussed below).

In the nearly 8 years of observations the greatest westward motions at mesopause heights are detected during the spring months of 1993. This period, comprising 25 days of April, is selected for the present analysis. The data acceptance rate (given in percentage) for this observation duration at each altitude and for every hour is presented in the contour form in Figure 1. This parameter is essentially determined by the built-in rejection criteria prescribed in the full correlation analysis for the wind estimation [*Lesicar*, 1993]. Among the rejection criteria, due consideration is given to the antenna and geometrical parameters. For example, rejection of data results if the signal-to-noise ratio is too small, fading is too slow, time delays are too long, and the pattern analysis breaks down, as can happen when the randomness associated with the formation of irregularities is too strong.

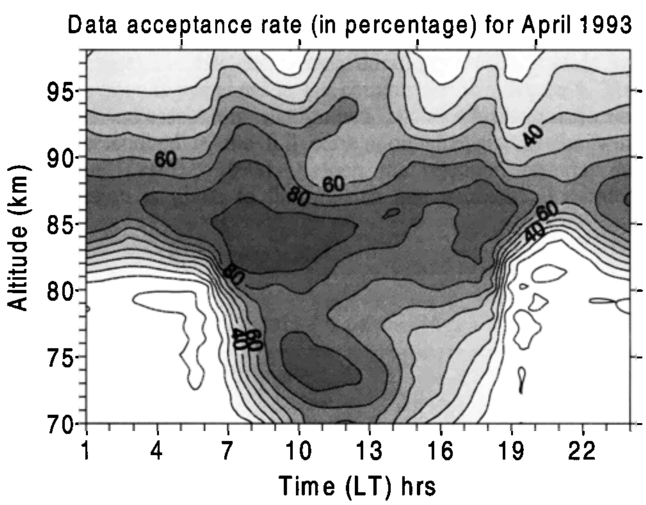

Figure 1. Height-time dependence of data acceptance rate (in percentage) for the MF radar measurements obtained during April 1993.

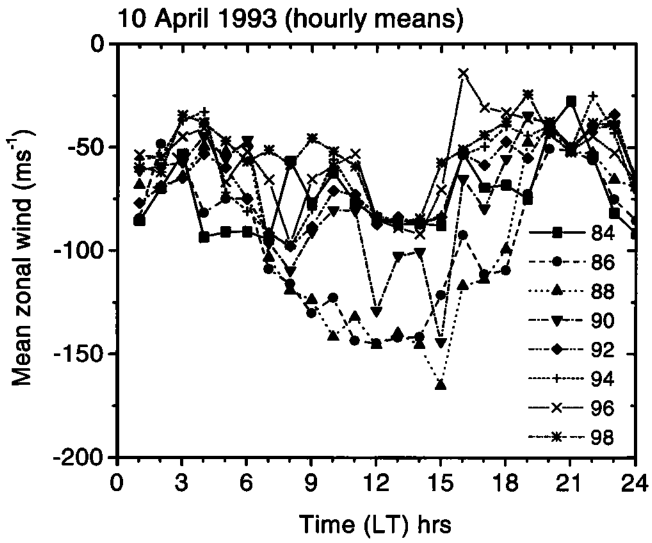

Figure 2. Diurnal variation of mean zonal wind for heights between 84 and 98 km.

As noted in Figure 1, the data acceptance rate shows the familiar U-shaped contours at heights below 80 km. At these heights during nighttime <10% of data points are considered reliable due to insufficient ionization for the radar echoes to be at detectable levels. At heights below 95 km the data acceptance rate falls to <30% during nighttime and between 30 and 40% during daytime hours. Strong echoes received between 1000 and 1200 LT due to solar ionization might have resulted in a high percentage of data points between 72 and 76 km.

At the present location (0.18°N magnetic latitude) the radar-derived motions at heights above 94 km often reflect the drift velocity of the irregularities immersed in the bottom portion of the equatorial electrojet (EEJ) [*Gurubaran and Rajaram*, 2000], an intense east-west current system flowing in an altitude region centered at ~105 km over the magnetic equator. At these times, the radar velocities above 94 km need not represent the neutral winds. It is possible that the estimates of hourly mean winds and tidal velocities at these heights are influenced by the electron drifts associated with EEJ. However, it has been noticed that the altitude profiles of mean winds and tidal amplitudes and phases are nearly continuous (not shown here) during April 1993, indicating that these effects are small or minimized when groups of 5 day means are analyzed. Gravity wave estimates in the present work are made at lower heights (84–86 km), where the EEJ effects are negligible.

Another potential problem in the interpretation of wind measurements arises when the received echoes corresponding to any of the range gates are due to the total reflection of the MF signal. The built-in rejection criteria adopted in the full correlation analysis take into account this effect and enable rejection of data. At these times the receivers go into saturation and the signal-to-noise ratio drops to zero, resulting in the rejection of the data point. However, there could be group retardation whenever the radio wave passes through a dense ionized layer. The spaced receivers will then detect a virtual height. The authors are aware of this difficulty in detecting the real height at these times. They intend to address this problem in one of the forthcoming studies that will involve ionograms obtained from a ground-based ionosonde and electron density

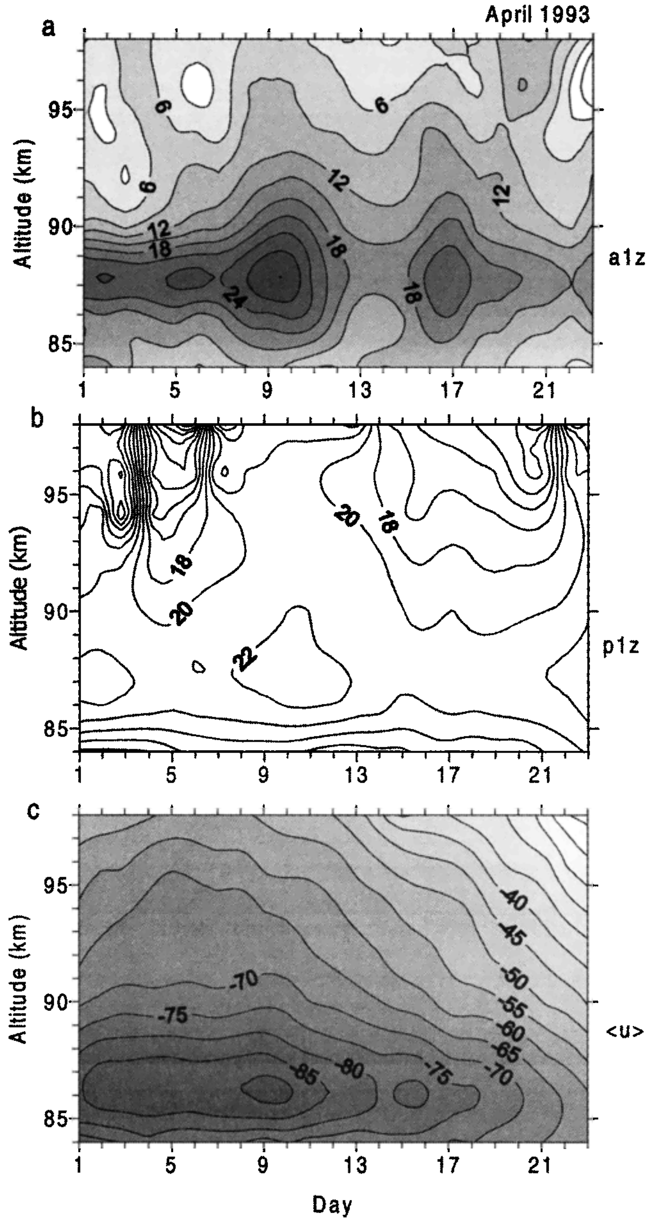

Figure 3. Time-height variation of the (a) amplitude and (b) phase of the diurnal tide and the (c) mean wind, all in the zonal directions. Composites of 5-day mean were used to obtain the above contours.

profiles from past rocket soundings, both from the nearby site, Trivandrum.

3. Results

Figure 2 shows the hourly mean time series for April 10, 1993, for all heights between 84 and 98 km. There has been a time-mean westward flow at all times on this day. The daytime speeds at 86 and 88 km average more than 100 m s^{-1}, with the largest speed of 165 m s^{-1} observed at 1500 LT. There appears to be a large diurnal trend in the mean zonal wind on this day. The diurnal tide amplitude at 88 km in the zonal direction is ~50 m s^{-1}. Such large diurnal velocities are unusual considering the latitude of the observation site (see *Hays et al.* [1994] for a comparison with satellite-derived diurnal tide amplitudes). The diurnal tide in the meridional wind field is found to have a modest amplitude of ~30 m s^{-1} at 86 km.

In Figure 3 the time-height behavior of mean winds and tidal parameters is depicted. Figure 3a represents the amplitude, Figure 3b shows the phase, and Figure 3c depicts the mean wind variation with height and time. Five-day composites were used to derive the tidal characteristics. The diurnal tide has the largest amplitude at 88 km centered around April 10. The amplitude decreases from ~30 m s^{-1} at 88 km to ~9 m s^{-1} at 96 km, a factor of 3 reduction within an altitude interval of 8 km. The phase does not seem to have any height variation during this period. Strongest mean westward flow with velocities more than 90 m s^{-1} is noticed at 86 km around this time. As the tidal activity is reduced in the subsequent days, the westward speed decreases. In the second half of the month the phase shows downward progression with height indicating tidal propagation upward.

Figure 3 suggests that the evolution of the mean zonal wind is related to the temporal variation of the diurnal tide activity. It is anticipated that as the westward propagating migrating tide dissipates, a time-mean westward acceleration of the zonal flow should result above the level where the momentum deposition occurs. Figure 3 perhaps illustrates this feature observationally. Though quantitative verification has not been done at this stage, it is the view of the authors that this relationship is possible. With April 1995, another period of intense westward motions was examined (results not presented here), and similar behavior has been noticed. A difficulty in the interpretation of observations in both years is that the diurnal tide peaks at heights above where the intense westward flow appears. This could be partially explained based on the altitude resolution adopted for the radar operation. The 4.5-km-altitude resolution might not be sufficient to detect the exact height where the momentum deposition occurs and the mean flow acceleration takes place.

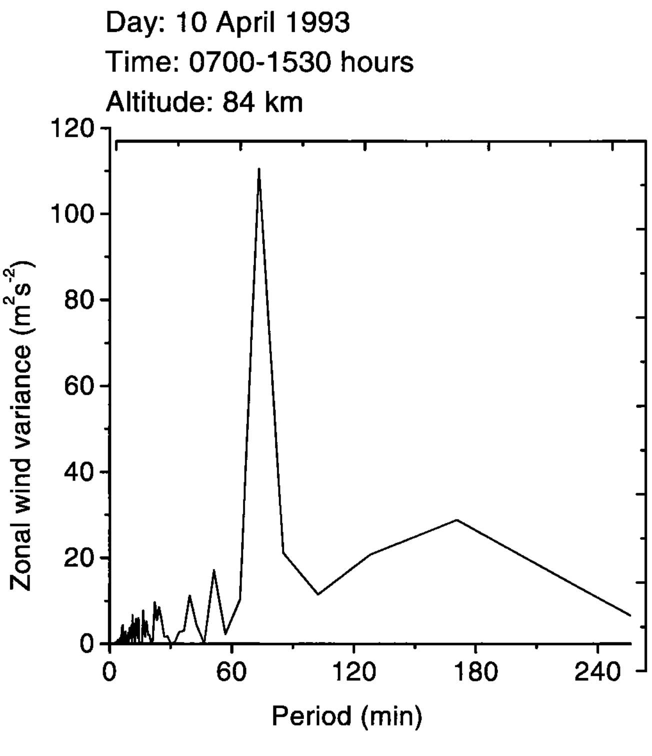

Figure 4. High-frequency gravity wave spectrum computed for the period 0700-1530 LT on April 15, 1993.

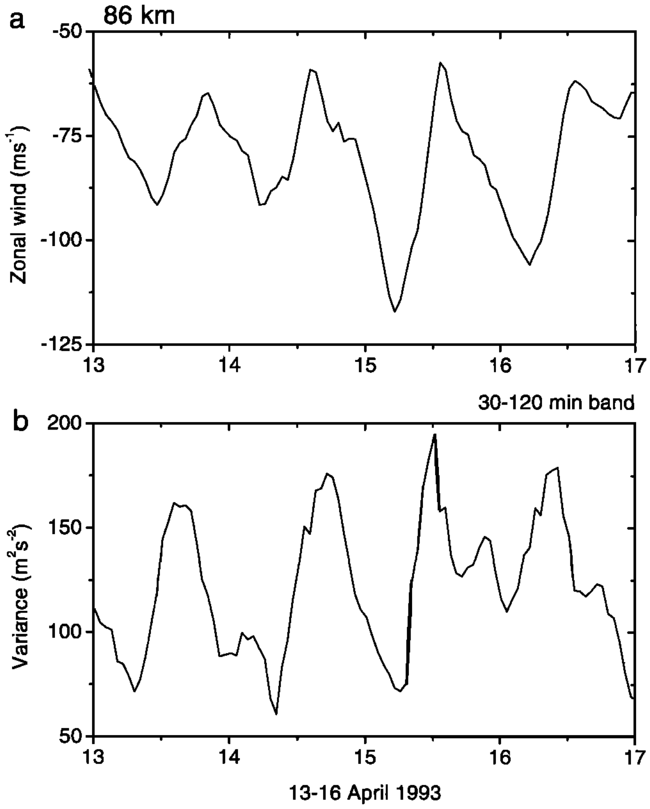

Figure 5. Temporal variation of (a) mean zonal wind and (b) gravity wave variance at 86 km between April 13 and 16, 1993.

The little phase variation with height supports the above suggestion that the propagating diurnal tide (1,1) might have dissipated its energy and momentum near 88 km as the evanescent phase structure shows. This behavior has been modeled by *Forbes and Hagan* [1988] in an earlier work. Further, there is a tendency for the phase to increase with height at lower altitudes (altitude profiles, not shown here, reveal this behavior), to remain constant at intermediate heights, and to show a decrease above 90 km. As noted in Figure 3, the temporal variation of tidal amplitudes is similar to the temporal variation of the strength of the time-mean westward flow and hence provides credence to the view that the diurnal tide is perhaps responsible for the evolution of the background flow during these times.

The behavior of high-frequency variations in the observed wind field representing gravity waves is next examined. For this analysis the raw 2-min samples are utilized. Power spectra are computed for 512-min sample sets using Fourier techniques and the "integrated" power spectral amplitudes corresponding to the period range 30–120 min are examined. This period range is too low to be contaminated directly by the tidal contributions and high enough for determining statistically meaningful estimates of gravity wave parameters. The stringent rejection criteria adopted for the wind determination do not permit meaningful analysis for periods <30 min.

Because of the constraints posed by data sparsity, information about the high-frequency gravity waves can be retrieved only for the 84 and 86 km heights. There has been one occasion on April 10, 1993, when data acceptance rates close to 100% for the 84 km height permitted determination of high-frequency variations. The power spectrum for the observation duration between 0700 and 1530 LT on April 10 is shown in Figure 4. A dominant peak at 73 min is noticed in the power spectrum. This is clearly well above the peak at other periods. This shows the dominance of this period in the spectrum of high-frequency gravity waves propagating upward around this time.

We next examine the temporal behavior of variances in the selected high-frequency band (30–120 min). It is found the wave variances are sensitive to the changes in the mean wind. Two examples are presented in Figures 5 and 6 wherein hourly values of gravity wave variances and the mean winds (represented by 24-hour running averages at steps of 1 hour) in the zonal and meridional directions at 86 km are plotted. The period selected for both zonal and meridional directions is April 13–16, 1993. In this exercise the power spectral amplitudes representing high-frequency variances are computed for every 8.5-hour (corresponding to 512 min) window at steps of 1 hour.

As is evident in Figure 5 the diurnal peaks (least westward speeds) are well correlated with the peaks in the gravity wave activity. In other words, the gravity wave variances maximize when the diurnal tide has its minimum westward perturbation, and therefore they are in phase with the tide. Considering a simple model in which the saturated gravity wave amplitudes are limited to (c-$\langle u \rangle$), where $\langle u \rangle$ is the background wind and c is the zonal phase speed of the gravity wave, it follows that the stratospheric mean zonal flow must be eastward so that gravity waves with westward phase speeds can participate in controlling the mean flow at mesopause levels. It is often observed that the mesospheric mean zonal flow is out of phase with the stratospheric mean flow [e.g., *Garcia et al.*, 1997]. It may be recalled that the observations reported in the present work are made when the mesopause region is characterized by a strong mean westward flow. *Manson et al.* [1998] observed an out-of-phase relationship between the 12-hour tide and gravity wave variances over the midlatitude station, Saskatoon (52°N) during the winter months.

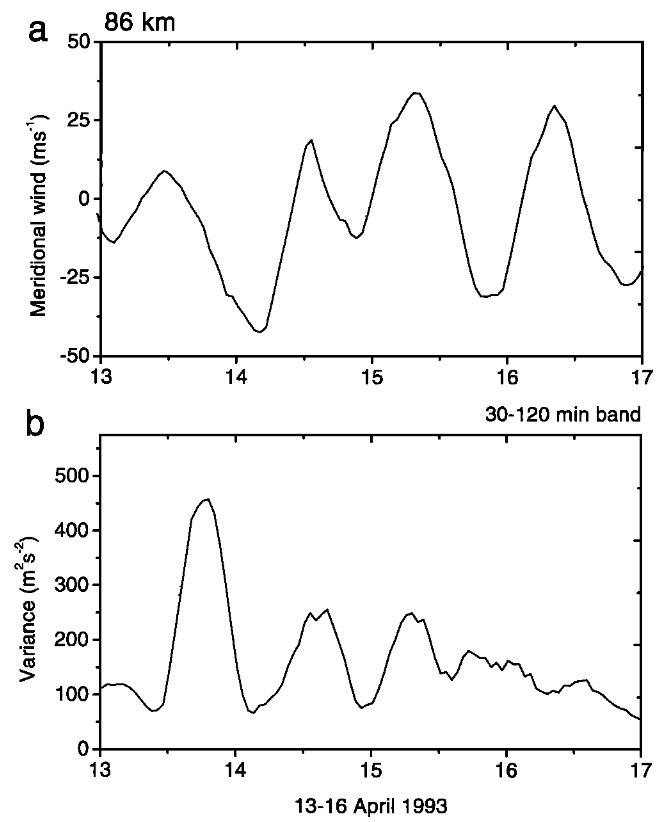

Figure 6. Same as Figure 5 but for the wind and gravity wave variances in the meridional direction.

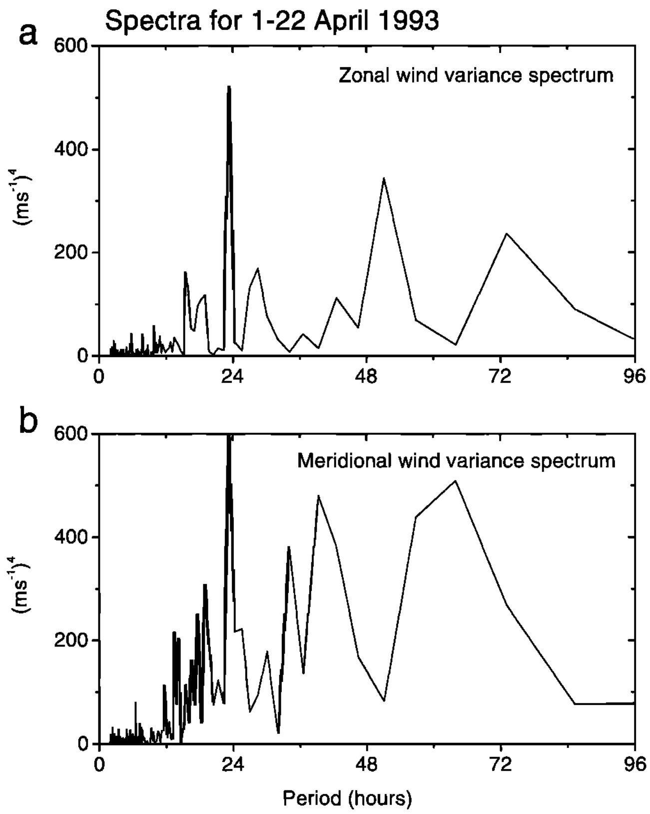

Figure 7. Power spectrum results for the gravity wave variances in the (a) zonal and (b) meridional directions.

In Figure 6 the maximum northward perturbation agrees well with the variance peaks on April 14 and 15. On April 13 the peak is offset by about 6 hours, whereas on April 16 there is no pronounced peak in the gravity wave variance, although the diurnal tide activity (as noticed from the shape of the mean wind curve) was strong on this day. *Manson et al.* [1998] observed groups of days when the gravity wave variances are strongly modulated at tidal periods and days when no such distinctive feature was observed.

The variance spectrum for the entire observation period (April (1–22, 1993) was next examined, and the results are plotted in Figure 7. Figure 7a represents the results for the zonal wind, and Figure 7b shows the power spectrum computed for the meridional direction. In this exercise, too, the 512-min data sets are subjected to the power spectrum analysis, and the variances are calculated for the 30–120-min period range as the window is shifted every 1 hour. A separate Fourier analysis applied to the resulting time series then yields the power spectra depicted in Figure 7. The tidal peaks at 24 hours in the gravity wave variance spectrum are clearly evident. Statistical significant tests were carried out, and these peaks were found to be significant at better than 95% confidence level. Results presented herein thus show that the dominant tidal winds observed by the radar do contribute to the modulation of gravity wave variances. This is in accord with many observational and modeling results reported earlier [see, e.g., *Walterscheid*, 1981; *Fritts and Vincent*, 1987; *Wang and Fritts*, 1991; *Isler and Fritts*, 1996]. The spectral energy corresponding to the tide-modulated gravity wave variances in the meridional direction is greater than the energy in the zonal direction. Further, additional peaks are noticed at ~50 hours in the zonal variances. A separate analysis shows that the wind fields in the mesopause region over Tirunelveli during this month (April 1993) are influenced by the quasi 2-day planetary wave. In response to this wave the gravity wave variances are modulated at quasi 2-day periods as well. The meridional variances show peaks at ~40 and 61 hours. The reasons for the presence of these peaks are not known at this moment.

Figure 8 depicts the variabilities of diurnal tide and the high-frequency wave variances at 86 km in the zonal (Figure 8a) and meridional (Figure 8b) directions during the spring month of April. The tidal amplitudes are computed for every day, whereas the gravity wave variances are for a 512-min window computed at intervals of 1 hour. In the zonal direction the diurnal tide and the wave variances are well correlated at least up to April 12. Peaks in variances on April 4, 7, and 10 are accompanied by peaks in tidal activity. The variations in these dynamical parameters are less correlated after April 15 and nearly throughout the observation duration for the meridional direction. This irregular nature of the modulation of gravity wave variances was noted by *Manson et al.* [1998], who attributed this feature to the intermittent nature of the strength and direction of gravity wave sources and the background wind at lower heights.

4. Discussion

The primary focus of the present work is to demonstrate the relationship between mean winds, tides, and gravity waves during the westward phase of the tropical mesopause semiannual oscillation. MF radar observations over Tirunelveli (8.7°N) were made use of for this purpose. The westward phase of the MSAO occurs during the equinoxes, with the first equinox phase during March–April being stronger than the second phase during September–October (see *Vincent* [1993] for a review). The interannual variability in the occurrence of the westward phase (spring equinox) of the MSAO is well documented in the literature [*Burrage et al.*, 1996; *Garcia et al.*, 1997; *Rajaram and Gurubaran*, 1998].

For the present work the analysis is restricted to the data accumulated during April 1993. Westward winds as large as 165 m s^{-1} with vertical shears as high as 18 m s^{-1} km^{-1} were observed on April 10. The largest tidal amplitude observed on this day has been ~50 m s^{-1}. These peculiar features are not observed at other times of the year (1993) nor during any of the subsequent years. This period, characterized by the largest variation in zonal mean flow, offers an opportunity to examine the tide-gravity wave interactions and to determine the role of this interplay in the evolution of the mean zonal flow. Excellent data quality at intermediate heights (84–86 km) permitted computation of reliable estimates of gravity wave variances. The period of the dominant high-frequency wave at 84 km on April 10 turned out to be ~73 min. Because of the sparsity of continuous 2-min data at other heights it was not possible to ascertain the altitude behavior of this high-frequency gravity wave.

Altitude behavior of diurnal tide amplitudes and phases reveal noticeable features: The amplitude after reaching a maximum around 88 km is reduced sharply above, and the phase shows little variation with height. The rapid decrease in the diurnal tide activity at higher altitudes suggests that wave damping has taken place. Westward acceleration of zonal wind during the first week of April provides indications for the occurrence of this process. The High Resolution Doppler Imager instrument on board the UARS satellite has yielded information on regions of intense westward motions in the equatorial lower thermosphere, which occur during periods of intense westward acceleration provided by the diurnal tide driving [*Lieberman*, 1997]. The computed vertical convergence of the (1,1) vertical flux of westward momentum exhibits pronounced variations in the semiannual and interannual timescales.

As mentioned in section 3, it was not possible to determine the exact height where the tide deposits its momentum. In spite of this limitation the authors believe that the evolution of the mean zonal

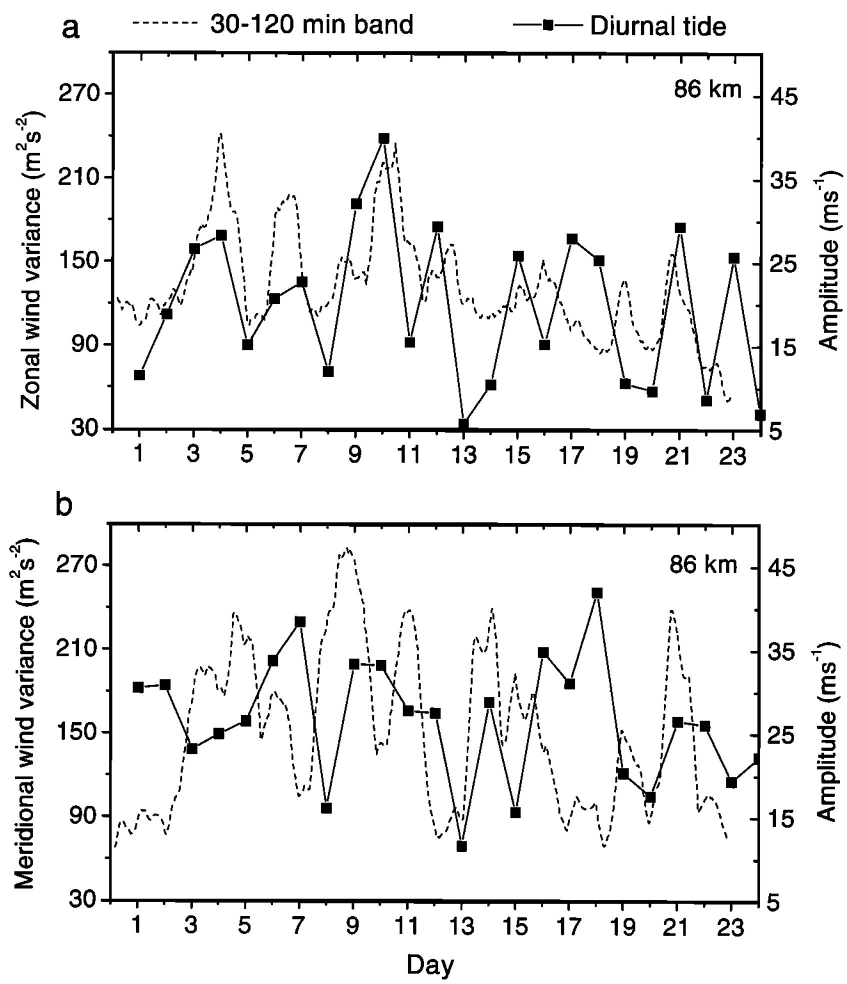

Figure 8. Temporal variation of gravity wave variances and the amplitude of the diurnal tide in the (a) zonal and (b) meridional directions.

flow is related to the temporal variation in the diurnal tide activity. A separate analysis for the observations made during April 1995 confirms this relationship. It is possible that the tide-induced changes in gravity wave momentum fluxes are such that the gravity wave breaking and the associated mean flow acceleration occur at a height lower than the height where the tidal amplitudes maximize.

The small phase variation with height could have possibly been due to the effect of dissipation of the migrating tide as modeled by *Forbes and Hagan* [1988]. The model results based on a parameterization of mechanical and thermal dissipation through Rayleigh friction and Newtonian cooling coefficients predict an increase in vertical wavelength with a height from 80 to 100 km and a spreading of the tidal oscillation to higher latitudes. The near-zero phase slopes (altitude profiles reveal this feature) observed over Tirunelveli at higher altitudes could very well represent a trapped mode as the propagating mode dissipates. This feature was reproduced earlier by the numerical model of *Forbes and Hagan* [1988].

Turning our attention to the gravity wave variances, there are a few observational aspects that need to be discussed here. The wave variance shows a distinct relationship with the mean wind as noted in the example presented in Figure 5. This behavior can be explained, considering that the saturated gravity wave perturbation is proportional to its intrinsic phase velocity and is given by $|(c-\langle u\rangle)|$, where c is the phase velocity of the wave measured at the ground and $\langle u\rangle$ is the mean wind speed. As $\langle u\rangle$ develops a strong vertical shear in a direction opposite to c, the intrinsic phase velocity grows in its magnitude and hence the wave variance. This is the effect of Doppler shifting on gravity wave variances as studied by *Fritts and Wang* [1991] and by A. H. Manson and coworkers [*Manson et al.*, 1997, 1999]. For example, an anisotropic gravity wave spectrum with phase velocities in the westward direction will have variance enhancements at times or heights when the tide-induced wind speed reaches a maximum in the eastward direction. As $\langle u\rangle$ develops eastward shears or when it becomes less westward in time, the gravity wave spectrum with predominantly westward propagating waves will have enhanced variances.

It is known that the mesopause SAO is out of phase with the underlying stratopause SAO [e.g., *Garcia et al.*, 1997]. During the westward phase of the mesopause SAO the stratopause mean winds are in the eastward phase. At these times the gravity waves with eastward phase speeds will be filtered out, and the spectrum reaching mesopause heights will be dominated by westward propagating waves. Eastward propagating waves with phase velocities exceeding the stratopause mean wind speeds may also propagate upward without undergoing critical level absorption. At saturation heights the wave variances which depend on the intrinsic phase velocity given by $|(c-\langle u\rangle)|$ will respond promptly to the tide-induced background wind changes. In particular, the wave variances will be sensitive to the amplitude and phase of the dominant tide. In the example presented in Figure 5 the variance enhancements are in phase with the diurnal tide, suggesting that the gravity wave spectrum at these heights is dominated by westward propagating waves.

It may be noted that the above relationship between the gravity wave variances and diurnal tide amplitudes is not markedly seen for days other than those depicted in Figures 5 and 6. This irregular behavior could be attributed to the variabilities associated with the wave sources at lower heights, which can complicate the simple scenario discussed above. The variabilities of lower level mean zonal wind will add to this complexity in the interpretation of gravity wave-tide interactions at higher levels [*Manson et al.*, 1998].

Several observational studies in the recent past have addressed the gravity-tidal interaction processes discussed above [*Wang and Fritts*, 1991; *Thayaparan et al.*, 1995; *Isler and Fritts*, 1996; *Nakamura et al.*, 1997; *Manson et al.*, 1998]. The limitation of the present analysis is that it is not possible to ascertain whether the gravity wave, in turn, feeds back its momentum on the tidal fields. Phase and amplitude changes of the tide that modulate gravity wave momentum fluxes were reported in the literature (see *Fritts* [1995] for a review). Some reports indicate amplitude reduction for the dominant tide, and some other studies discuss amplitude enhancements during such interactions.

Apart from the complexities introduced by gravity wave-tide interactions, the present study shows that the variability of the tidal activity is related to the variation of the strength of the time-mean westward flow. The rapid decay of tidal amplitudes and the little phase variation with height provide indications for the damping of the (1,1) diurnal tide. Largest westward velocities are observed when the diurnal tide activity is at its maximum (for example, around April 10). The weakening of the MSAO westward motion occurs when the diurnal tide activity diminishes. This indicates the role of diurnal tide in causing the westward phase of the MSAO, although the role of gravity waves in this process either directly, or indirectly through the gravity wave-tidal interaction, cannot be ruled out.

5. Conclusion

MF radar observations of mean winds, tides, and gravity waves were used in the present work to examine the forcings responsible for the intense westward winds associated with the tropical MSAO. A distinct relationship exists between these dynamical parameters that were explained on the basis of the current understanding of the behavior of MSAO winds, tidal dissipation, and gravity wave-tide interactions. The altitude dependence of diurnal tide amplitude and phase is in accord with the expected variation due to the damping of (1,1) mode. Because the tidal activity varies in phase with the mean westward wind, the inference is that the diurnal tide possibly contributes to the temporal evolution of the MSAO westward flow. On many days the gravity wave variances are modulated at the period of the diurnal tide. The gravity wave momentum flux divergences due to the tide-induced mean wind changes in turn would cause acceleration or deceleration of the mean flow that would appear tidal. This may turn out to be an important forcing mechanism for the occurrence of time-mean westward flow associated with the MSAO.

The complexities of the feedback effects of gravity wave-tidal interactions on the tide itself and the resulting impact on the MSAO momentum budget are among the outstanding problems of the equatorial mesospheric dynamics. Future coordinated observations in the equatorial/tropical locations under the frame of Equatorial Processes Including Coupling, a SCOSTEP program, are expected to provide important clues to understanding the physics of these complex dynamical interactions occurring in the mesopause region.

Acknowledgments. S.G. thanks Maura Hagan for useful suggestions that improved the quality of this work. The authors thank the reviewers for raising many important points that were to be addressed in a work of this kind. The MF radar system at Tirunelveli is operated by the Indian Institute of Geomagnetism with financial support from the Department of Science and Technology, Government of India.

References

Avery, S. K., R. L. Obert, and J. P. Avery, Observations of equatorial mesospheric mean winds and tides, in *Handbook for Middle Atmosphere Program SCOSTEP Secr., 28*, 64–67, 1989.

Burrage, M. D., R. A. Vincent, H. G. May, W. R. Skinner, N. F. Arnold, and P. B. Hays, Long-term variability in the equatorial mesosphere and lower thermosphere zonal winds, *J Geophys Res.*, *101*, 12,847–12,854, 1996.

Eckermann, S. D., D. K. Rajopadhyaya, and R. A. Vincent, Intraseasonal wind variability in the equatorial mesosphere and lower thermosphere: Long-term observations from the central Pacific, *J. Atmos Terr Phys*, *59*, 603–627, 1997.

Forbes, J. M., and M. E. Hagan, Diurnal propagating tide in the presence of mean winds and dissipation: A numerical investigation, *Planet. Space Sci.*, *36*, 579–590, 1988.

Fritts, D. C., Gravity wave-tidal interactions in the middle atmosphere: Observations and theory, in *The Upper Mesosphere and Lower Thermosphere: A Review of Experiment and Theory, Geophys. Monogr. Ser.*, vol. 87, edited by R. M. Johnson and T. L. Killeen, pp. 121–131, AGU, Washington, D. C., 1995.

Fritts, D. C., and R. A. Vincent, Mesospheric momentum flux studies at Adelaide, Australia: Observations and a gravity wave-tidal interaction model, *J. Atmos Sci.*, *44*, 605–619, 1987.

Fritts, D. C., and D.-Y. Wang, Doppler-shifting effects on frequency spectra of gravity waves observed near the summer mesopause at high latitudes, *J. Atmos. Sci.*, *48*, 1535–1544, 1991.

Garcia, R. R., and R. T. Clancy, Seasonal variation in equatorial mesospheric temperatures observed by SME, *J. Atmos. Sci.*, *47*, 1666–1673, 1990.

Garcia, R. R., and F. Sassi, Modulation of the mesospheric semiannual oscillation by the quasibiennial oscillation, *Earth Planets Space*, *51*, 563–570, 1999.

Garcia, R. R., T. J. Dunkerton, R. S. Lieberman, and R. A. Vincent, Climatology of the semiannual oscillation of the tropical middle atmosphere, *J. Geophys. Res.*, *102*, 26,019–26,032, 1997.

Gurubaran, S, and R Rajaram, Long-term variability in the mesospheric tidal winds observed by MF radar over Tirunelveli (8 7°N, 77.8°E), *Geophys. Res. Lett.*, *26*, 1113–1116, 1999.

Gurubaran, S., and R. Rajaram, Signatures of equatorial electrojet in the mesospheric partial reflection drifts over magnetic equator, *Geophys. Res. Lett.*, *27*, 943–946, 2000.

Gurubaran, S, S. Sridharan, T. K. Ramkumar, and R. Rajaram, The mesospheric quasi-2-day wave over Tirunelveli (8.7°N), *J. Atmos. Sol. -Terr. Phys.*, *63*, 975–985, 2001.

Hamilton, K., Rocketsonde observations of the mesospheric semiannual oscillation at Kwajalein, *Atmos. Ocean*, *20*, 281–286, 1982.

Hamilton, K., R. J. Wilson, J. D. Mahlman, and L. J. Umscheid, Climatology of the SKYHI troposphere-stratosphere-mesosphere general circulation model, *J. Atmos. Sci*, *52*, 5–43, 1995.

Hays, P. B., D L. Wu, and HRDI Science Team, Observations of the diurnal tide from space, *J. Atmos. Sci.*, *51*, 3077–3093, 1994.

Hirota, I., Equatorial waves in the upper stratosphere and mesosphere in relation to the semi-annual oscillation of the zonal wind, *J. Atmos. Sci.*, *35*, 714–722, 1978

Isler, J. R., and D. C. Fritts, Gravity wave variability and interaction with lower-frequency motions in the mesosphere and lower thermosphere over Hawaii, *J. Atmos Sci.*, *53*, 37–48, 1996.

Kovalam, S., R. A. Vincent, I. M. Reid, T. Tsuda, T. Nakamura, K. Ohnishi, A. Nuryanto, and H. Wiryosumarto, Longitudinal variations in planetary wave activity in the equatorial mesosphere, *Earth Planets Space*, *51*, 665–674, 1999.

Lesicar, D., Study of the structure of partial reflection radar scatterers and their application in atmospheric measurements, Ph.D. thesis, Univ. of Adelaide, Australia, 1993.

Lieberman, R. S, Long-term variations of zonal mean winds and (1,1) driving in the equatorial lower thermosphere, *J Atmos. Sol. Terr. Phys.*, *59*, 1483–1490, 1997.

Lieberman, R. S., and D. Riggin, High resolution Doppler imager observations of Kelvin waves in the equatorial mesosphere and lower thermosphere, *J. Geophys. Res.*, *102*, 26,117–26,130, 1997.

Lindzen, R. S., Turbulence and stress owing to gravity wave and tidal breakdown, *J. Geophys. Res.*, *86*, 9707–9714, 1981.

Manson, A. H., C. E. Meek, and Q. Zhan, Gravity wave spectra and direction statistics for the mesosphere as observed by MF radars in the Canadian Prairies (49°N–52°N) and at Tromso (69°N), *J. Atmos. Sol. Terr. Phys*, *59*, 993–1010, 1997.

Manson, A. H., C. E. Meek, and G. E. Hall, Correlations of gravity waves

and tides in the mesosphere over Saskatoon, *J. Atmos. Sol Terr. Phys.*, *60*, 1089–1107, 1998.
Manson, A. H., C. E. Meek, C. Hall, W. K. Hocking, J. MacDougall, S. Franke, K. Igarashi, D. Riggin, D. C. Fritts, and R. A. Vincent, Gravity wave spectra, directions and wave interactions: Global MLT-MFR network, *Earth Planets Space*, *51*, 543–562, 1999.
Mayr, H. G., J. G. Mengel, C. O. Hines, K. L. Chan, N. F. Arnold, C. A. Reddy, and H. S. Porter, The gravity wave Doppler spread theory applied in a numerical spectral model of the middle atmosphere, 2, Equatorial oscillations, *J. Geophys. Res.*, *102*, 26,093–26,105, 1997.
Nakamura, T., D. C. Fritts, J. R. Isler, T. Tsuda, R. A. Vincent, and I. M. Reid, Short-period fluctuations of the diurnal tide observed with low-latitude MF and meteor radars during CADRE: Evidence for gravity wave/tidal interactions, *J. Geophys. Res.*, *102*, 26,225–26,238, 1997.
Rajaram, R., and S. Gurubaran, Seasonal variabilities of low latitude mesospheric winds, *Ann. Geophys.*, *16*, 197–204, 1998.
Thayaparan, T., W. K. Hocking, and J. MacDougall, Observational evidence of tidal/gravity wave interactions using the UWO 2 MHz radar, *Geophys. Res. Lett.*, *22*, 373–376, 1995.
Tsuda, T., et al., A preliminary report on observations of equatorial atmosphere dynamics in Indonesia with radars and radiosondes, *J. Meteorol. Soc. Jpn.*, *73*, 393–406, 1995.
Vincent, R. A., Long-period motions in the equatorial mesosphere, *J. Atmos. Terr. Phys.*, *55*, 1067–1080, 1993.
Vincent, R. A., and D. Lesicar, Dynamics of the equatorial mesosphere: First results with a new generation partial reflection radar, *Geophys. Res. Lett.*, *18*, 825–828, 1991.
Walterscheid, R.L., Inertio-gravity wave induced acceleration of mean flow having an imposed periodic component: Implications for tidal observations in the meteor region, *J. Geophys. Res.*, *86*, 9698–9706, 1981.
Wang, D.-Y., and D. C. Fritts, Mesospheric momentum fluxes observed by the MST radar at Poker Flat, Alaska, *J. Atmos. Sci.*, *47*, 1511–1521, 1991.
Yoshida, S., T. Tsuda, A. Shimizu, and T. Nakamura, Seasonal variations of 3.0–3.8-day ultra-fast Kelvin waves observed with a meteor wind radar and radiosonde in Indonesia, *Earth Planets Space*, *51*, 675–684, 1999.

S. Gurubaran and R. Rajaram, Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Krishnapuram, Tirunelveli 627 011, India. (gurubara@md4.vsnl.net.in; rrajaram@iig.iigm.res.in)

(Received January 4, 2001; revised July 11, 2001;
accepted July 14, 2001.)