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Seasonal and interannual variations of gravity wave activity in the low-latitude mesosphere and lower thermosphere over Tirunelveli (8.7° N, 77.8° E)

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Abstract. The Mesosphere and Lower Thermosphere (MLT) winds acquired by medium frequency (MF) radar at Tirunelveli (8.7° N, 77.8° E) for the years 1993–2007 are used to study seasonal and interannual variabilities of gravity wave (GW) variances in the altitude region 84–94 km. The GW variances in zonal and meridional winds show semiannual oscillation with maximum variance during March–April and August–September and minimum during June–July and November–December months. The wind variances, in general, are observed to be enhanced during and after the year 1998 and they undergo large interannual variability, in particular, during spring equinox months. An enhancement of GW variances is observed during spring equinox months of the years 2000, 2004 and 2006. These larger GW enhancements, most of the times, coincide with eastward phase of zonally averaged stratospheric QBO at 30 hPa over equator and sudden stratospheric warming occurred at high latitudes. From the zonal and meridional variances, the perturbation ellipses are calculated and they show that the predominant direction of propagation of gravity waves is in SE-NW plane.

Keywords. Meteorology and atmospheric dynamics (General circulation; Middle atmosphere dynamics; Waves and tides)

1 Introduction

The predominant semiannual variability of zonal wind and temperature in the equatorial mesosphere and lower thermosphere (MLT) is believed to be caused mainly by gravity waves. There are quite a lot of studies on gravity waves over mid-latitudes (Vincent and Fritts, 1987; Nakamura et al. 1996; Gavrilov et al., 1995; Manson et al. 1999; Jacobi et al., 2006, to state a few). However, much information on the gravity wave climatology and the wave parameters over equatorial region is lacking, though the importance of gravity waves in the equatorial mean circulation were recognized much earlier. The theoretical studies showed the important contribution of wave motions generated in the tropics to the dynamics of MLT region (Sassi and Garcia, 1997; Garcia and Sassi, 1999). The vertical propagation of the waves is influenced by the wind and temperature structure through which they propagate. There are several processes, for example, El Nino, quasi-biennial oscillation and sudden stratospheric warming which could alter the source variations and background conditions and thereby influence the variability of gravity waves in the MLT region. Gavrilov et al. (2004) studied interannual variabilities of gravtiy wave variances over Hawaii (22° N, 160° W) using 11-years of data and found correlation between gravity wave variances and southern oscillation index. Using nearly seven years of medium frequency (MF) radar wind observations over Christmas Island (2° N, 157° E), Kovalam et al. (2006) found predominant semiannual variation in the gravity wave activity with maximum variances near the solstices. They found larger enhancement of wave fluxes in the years 1997/1998 and 1993/1994 and suggested that these enhancements coincided with El Niño events when warm events normally found in the western Pacific moved to Central Pacific, resulting in increased convective activity near Christmas Island. However, more long-term data would be required to establish the correlation between the gravity wave activity and lower atmospheric variations.

In this paper we present the seasonal and interannual variations of the wind velocity variances attributed to atmospheric gravity waves having period 2–6 h using nearly 15 years of horizontal wind observations over Tirunelveli (8.7° N, 77.8° E) and their relation with stratospheric quasi-biennial

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oscillation (SQBO), southern Oscillation Index (SOI), a parameter that reflects Pacific El Nino activity and major high-latitude stratospheric warming events.

2 Data analysis

2.1 MF radar

The MF (1.98 MHz) radar at Tirunelveli (8.7° N, 77.8° E) has been installed and operated by the Indian Institute of Geomagnetism since November 1992 (Rajaram and Gurubaran, 1998). It provides horizontal wind information in the altitude region 68–98 km for every 2 km height interval and 2 min time interval. The pulse width of 30 μs limits the height resolution to around 4.5 km. The wind data for the period January 1993 to November 2007 are considered for the present study. The raw winds for every 2 min are averaged for every hour and used for further analysis.

2.2 RS (Residual) filter

As the data acceptance rate of the MF radar is relatively larger at heights between 84 and 94 km, the hourly mean winds for these heights are subjected into RS (Residual) Filter to study gravity waves having period of the order of a few hours (Gavrilov et al., 1995). The RS filtered data are obtained by estimating the variance of residual hourly values after removing mean wind and tidal harmonics. The days having hourly data points more than 16 h are only considered. This filter gives an estimate of the intensity of wind variations having periods ~2–6 h.

2.3 Southern Oscillation Index (SOI)

The SOI has been derived from the surface pressure difference between the tropical observation points of Tahiti and Darwin (Ropeleski and Jones, 1987). Positive SOI values correspond to La Nina (cool central Pacific) and negative SOI to El Nino (warm central Pacific) events. Zonal pressure gradients imply eastward or westward wind directions of the lower atmosphere near the equator, where the Coriolis force tends to zero. The El Nino data have been downloaded from the website http://www.cpc.ncep.noaa.gov.

2.4 Stratospheric QBO

The zonally averaged stratospheric QBO winds over equator for the years 1993–2007 for 30 hPa are taken from the web site http://www.cpc.ncep.noaa.gov. The winds are products from the climate data assimilation system (CDAS).

3 Results

3.1 Seasonal variability

The daily variances obtained for the heights between 84 and 94 km by using RS filter are averaged for each month for the years 1993–2007. The 15-year averages of the zonal and meridional wind variances are plotted in the right panels of Fig. 1. The GW variance exhibits a strong semiannual variability with maximum variance in the months March–April and August/September and minimum variance in May–July and November–December. The left panels show 15-year averaged zonal and meridional winds. The monthly mean zonal winds averaged over the years 1993–2007 show mainly semiannual variation with westward winds during equinox months and relatively weaker eastward winds during solstice months. The seasonal variation of the mean meridional winds clearly shows annual variation with northward winds during winter and southward winds during summer. The semiannual variation in gravity wave variance might be due to passage of inter tropical convergence zone (ITCZ) twice the site per year.

3.2 Interannual variability

The daily zonal and meridional wind variances averaged for each month for the years 1993–2007 are plotted in Fig. 2 for the altitudes 86, 90 and 94 km. We put a criterion that each month should be represented by at least ten daily variance values in order to reduce the artifact due to smaller number of points. The altitude 86 km is relatively free from data gaps, as the percentage of data acceptance is the largest (Rajaram and Gurubaran, 1998). It can be observed from the figure that the time variation of monthly GW variance is nearly similar in both zonal and meridional winds except for a few occasions. In the year 1998, the wind variance is relatively larger than other years in fall equinox, summer and winter months. Note that there is a data gap during spring equinox months in the year 1998. The larger enhancement is observed during the year 1998 in both wind components and smaller variance is observed in the year 1999 for zonal wind and in the year 2000 for meridional wind. The GW variance in meridional winds shows larger enhancement in spring equinox months of some years, namely, 1999, 2001, 2002, 2004 and 2006. Gavrilov et al. (2004) noted the relation among interannual variability of GW variance, El-Nino events and stratospheric quasi-biennial oscillation. Since there were only two El-Nino events occurred in their long-term data sets, the authors suggested the importance of more long-term observations to confirm the relation among them. We used the long-term observations (1993–2007) over Tirunelveli (8.7° N, 77.8° E), to see the correlation among them. Figure 3 shows the monthly GW variance for the years 1993–2007 averaged for the altitudes 84–94 km (top panel), stratospheric QBO (middle panel) and Southern Oscillation

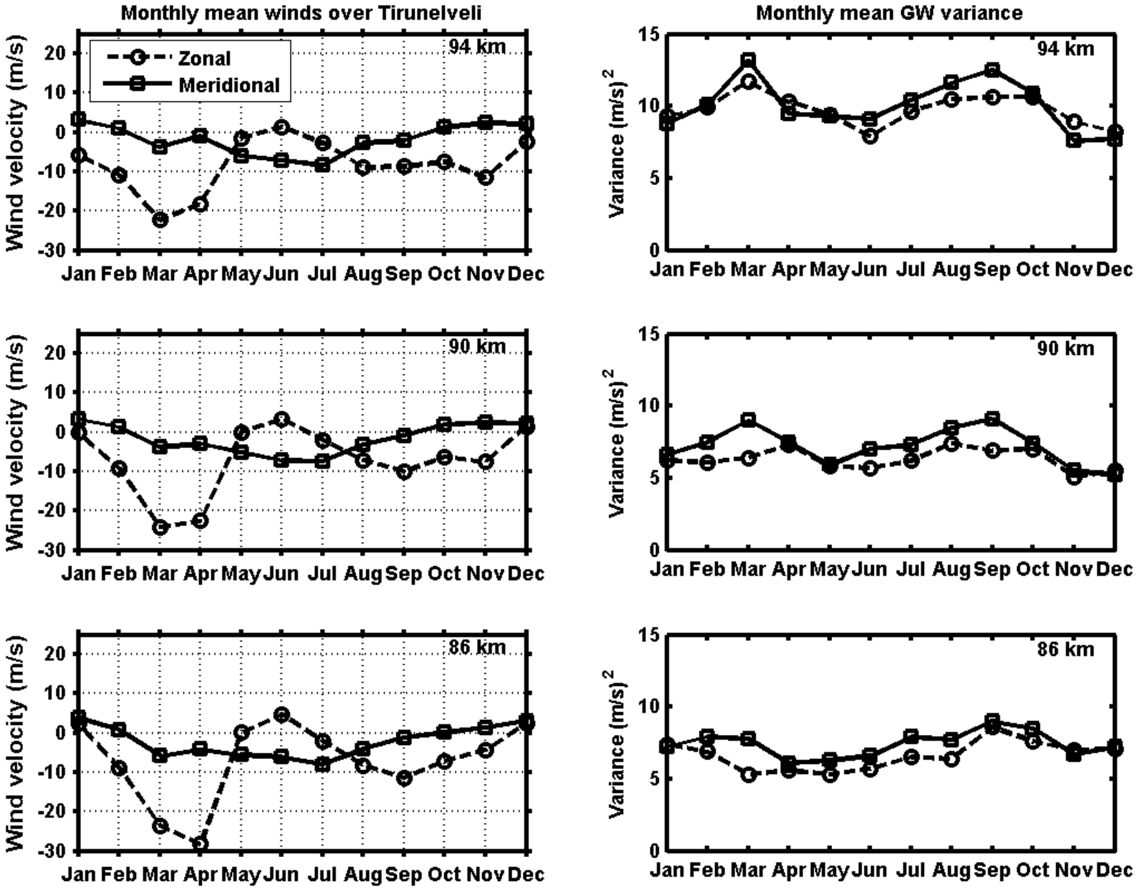

Fig. 1. Monthly mean zonal and meridional winds over Tirunelveli (left panels) and monthly mean gravity wave variances in zonal and meridional winds (right panels) for the altitudes 86, 90 and 94 km.

Index (bottom panel). The large GW enhancements are observed during spring equinox months of some years. They preferentially occur, when stratospheric QBO at 30 hPa transits towards eastward maxima. This relation can be noticed in the years 1999, 2002, 2004 and 2006. However, larger gravity wave activity is observed during the spring equinox months of the year 2002, when the stratospheric QBO winds are westward.

3.3 Interannual variation in different seasons

To show interannual variability of gravity wave activity for different seasons, monthly variances averaged for the months December–January (winter), February–April (spring equinox), May–July (summer) and August–October (fall equinox) are plotted in Fig. 4. From the figure, it is clear that the meridional wind variances during spring equinox months undergo large interannual variability when compared to other seasons. Large gravity wave activity is observed in the years 1999, 2002, 2004 and 2006. It is interesting to note that major sudden stratospheric warming events occurred in the Northern Hemisphere during these years and no major warming occurred in the years 1993–1998, except December 1998. Table 1 shows list of major warming events occurred during 1993–2007 for reference. The duration and intensity of stratospheric warming are identified using the following method. The zonal mean zonal winds and temperature for 10 hPa are obtained from the website http://www.cdc.noaa.gov/cdc/data.ncep.reanalysis.pressure.html. Using the zonal mean temperature difference at latitudes between 90° N and 60° N, stratospheric warming events are identified. The major warming events are associated with reversal of winds from eastward to westward. The duration of the warming event is calculated as duration of persistence of westward winds and strength of warming as the magnitude of wind reversal at 60° N. From the table, it can be inferred that major stratospheric warming occurred during the years December 1998, February–March 1999, February 2001, December 2001–January 2002, February 2002, 18 February 2003, January 2004, January–February 2006. It may be noted that during February 2003, the event persists for only one day with magnitude of reversal around 1 m/s. The meridional wind variances are relatively smaller in the year 2003 than in other stratospheric warming years. Though a major stratospheric

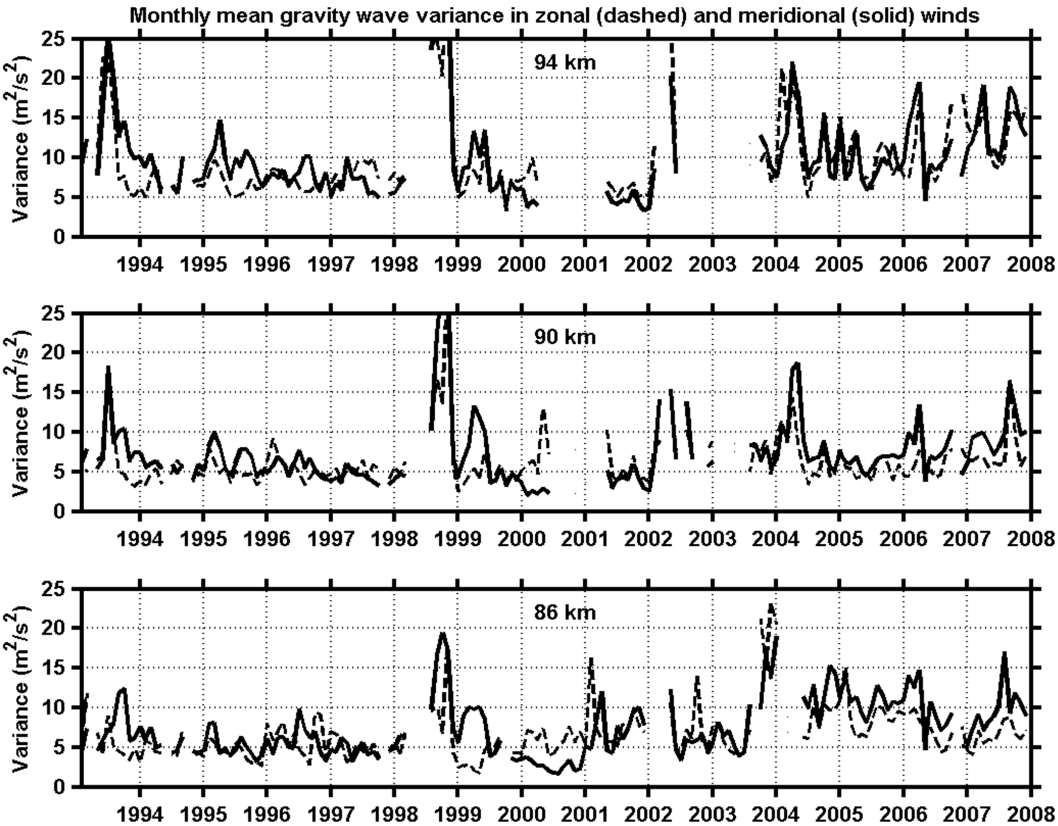

Fig. 2. Monthly mean gravity wave variances in zonal and meridional winds for the altitudes 86, 90 and 94 km and for the period 1993–2007.

warming event occurred during the year 2002, the meridional wind variances are comparable with the year 2005, when no major stratospheric warming event occurred prior to the equinox months. The relation between stratospheric warming events and wind variances is not clear and it needs further investigation with more long-term data sets.

The gravity wave activities during fall equinox and summer months are small during the years 1994–2000, except during the year 1998. After the year 2000, both wind variances gradually increase. There appears to be a decadal variability with smaller variances in the years 1994–2000 and larger variances in the years 2001–2007. In winter, zonal and meridional wind variances show slightly different interannual variabilities. The gravity wave variances in meridional winds show larger variances during the years 1993, 1998, 2003 and 2007, whereas larger zonal variances are observed in the years 2000, 2003 and 2007.

The correlation between zonal and meridional wind variances and SOI/SQBO are investigated and the correlation coefficients are estimated for each month. Figure 5 shows monthly variation of correlation coefficient between zonal and meridional variances and SOI (top panel) and SQBO (bottom panel). The larger positive correlation of 0.6 is observed in the month of August between meridional wind variance and SOI, whereas the larger negative correlation of −0.4 is obtained between zonal wind variances and SOI in the month of June. The correlation between gravity wave variances in meridional wind and stratospheric QBO winds show larger positive correlation in the months February–May with the largest coefficient value of 0.4 during April. The correlation coefficient is nearly zero during June–July and negative during August–December.

3.4 Direction of propagation

The perturbation ellipses have been calculated using the following equation (Gavrilov et al., 1995; Jacobi et al., 2006),

$$\xi' = u' \sin\varphi + v' \cos\varphi$$

with ϕ being the direction Vs North. The total variance ξ'^2 in the direction ϕ:

$$\overline{\xi'^2} = \overline{u'^2}\sin^2\varphi + \overline{v'^2}\cos^2\varphi + r\sqrt{\overline{u'^2 v'^2}}\sin 2\varphi$$

with r as the correlation coefficient between u' and v'. The above equation describes an ellipse with the direction of the main axis as the preferred propagation direction to be calculated using

$$\varphi_{\mathrm{pref}} = \frac{1}{2}\left(n\pi + a\tan\frac{2r\sqrt{\overline{u'^2 v'^2}}}{v'^2 - u'^2}\right).$$

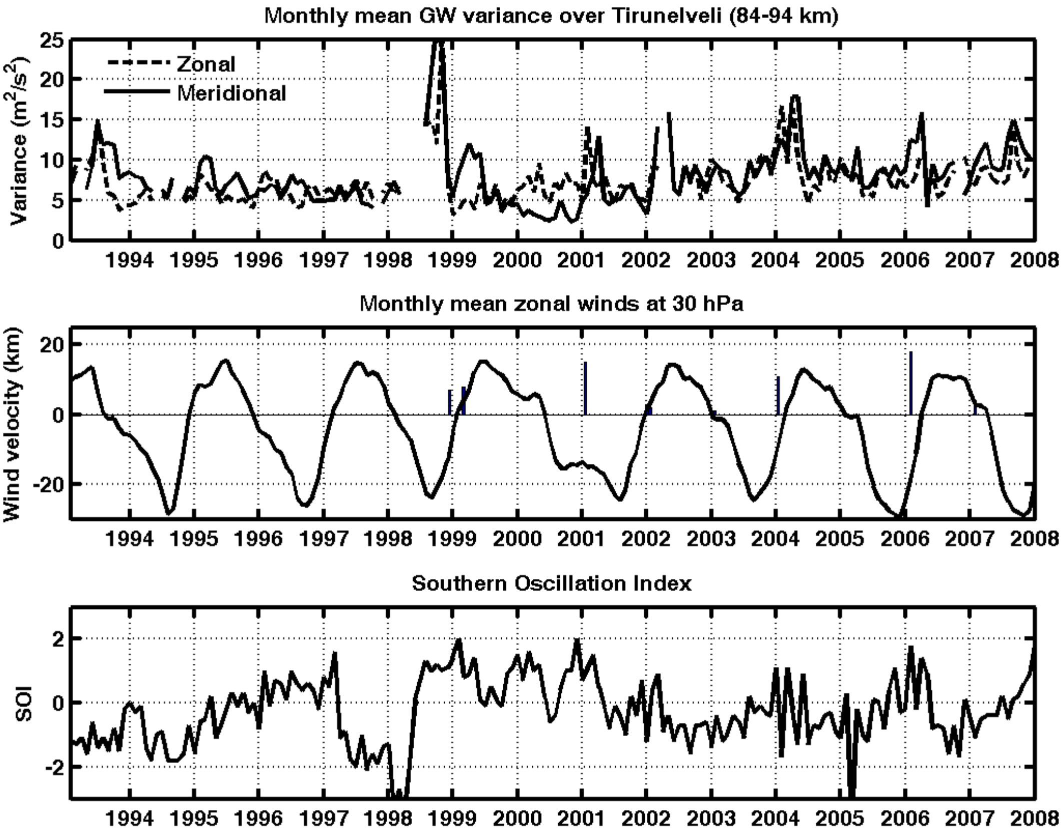

Fig. 3. Monthly mean gravity wave variances in zonal and meridional winds (top panel), zonal averaged stratospheric QBO winds at 30 hPa (middle panel) and Southern Oscillation Index (bottom panel). The bars in the middle panel shows the occurrence time of major stratospheric warming events and the height of the bar shows duration of the event in days.

Table 1. Major stratospheric warming events, their duration and magnitude of wind reversal.

Sl. No.	Sudden stratospheric warming dates	Duration (days)	Magnitude of wind reversal at 60° N (m/s)
1	15 December 1998–21 December 1998	7	20
2	25 February 1999–4 March 1999	8	8
3	10 February 2001–25 February 2001	15	16
4	31 December 2001–2 January 2002	3	3
6	18 January 2003–19 January 2003	2	3.3
7	04 January 2004–14 January 2004	11	12
8	21 January 2006–7 February 2006	18	24
9	24 February 2007–27 February 2007	4	9

Figure 6 shows the perturbation ellipses for each month of the years 1993–2007 obtained for the height region 84–94 km over Tirunelveli. The propagation direction is in general northwest-southeast direction. However, when there is an enhancement of gravity wave activity during fall equinox months of the year 1997, the gravity wave propagation direction is in E-W plane. The predominant SE-NW propagation direction may be due to location of convectively active maritime continent, Indonesia, which is located southeast of India. Though there is 180° ambiguity in determining the direction, considering the more active convective zone southeast of India, the propagation direction would be from southeast to northwest, rather than from northwest to southeast.

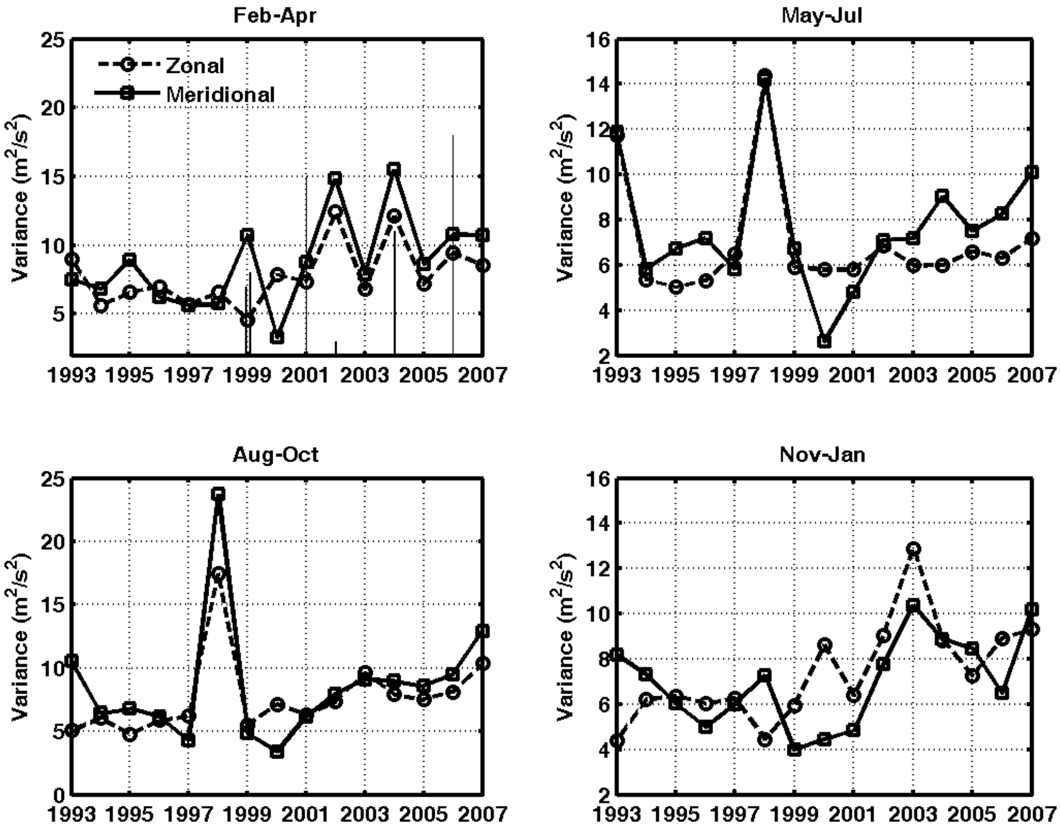

Fig. 4. Monthly mean gravity wave variances in zonal and meridional winds for 1993–2007 and for spring equinox (left top), summer (right top), fall equinox (left bottom) and winter (right bottom) months. The vertical bars in the top left panel denote the duration (days) of stratospheric warming.

4 Discussion

The seasonal and interannual variabilities in the variances of the gravity waves having periods 2–6 h at mesospheric heights over Tirunelveli (8.7° N, 77.8° E) are presented. The GW variance shows semiannual variability with larger variance during spring equinox months and smaller during solstice months. The primary source for the gravity waves in the tropical region is convection. As the location of the convectively active intertropical convergence zone moves back and forth across the equator following the sun's zenith and it passes twice over Tirunelveli in a year, it can be considered as a reason for the semiannual variability observed in gravity wave variance. However, the semiannual variability of gravity wave variance has also been observed over Hawaii (22° N) (Gavrilov et al., 2004), over which ITCZ passes only once. The reason for the semiannual variability is probably due to filtering of gravity waves due to strong winds at stratospheric heights. The mesospheric SAO winds is out of phase with stratospheric SAO winds, which suggests that they are driven partly by gravity waves which are selectively filtered as they propagate through the stratospheric wind system (Dunkerton, 1982).

In the present study, the meridional wind variances during spring equinox months show a large interannual variability with smaller variances during the years 1993–1997 and after the year 1998, there is an enhancement in every 2–3 years (1999, 2002, 2004, and 2006). Other than these spring equinox enhancements, gravity wave variances are notably larger in the summer and fall equinox months of the years 1993 and 1998. These enhancements are interesting, as there was the longest El Nino event (negative SOI) during 1990 to 1994 and a strong El Nino event occurred during 1997–1998. It may be noted that the strong El-Nino event (negative SOI) occurred during 1997–1998 prior to the largest GW variance during when negative SOI became positive. The correlation coefficient between GW variance and SOI index shows positive values during most of the months with maximum values of 0.5–0.6 during August–September.

Gavrilov et al. (1999, 2001) studied gravity wave activity using long-term wind observations over Japan (35° N, 136° E), and Collm (52° N, 15° E) and noted correlation between the gravity wave intensity and dynamical processes in the troposphere. Gavrilov et al. (2004) noted gravity wave enhancement in the years 1993 and 1997 and suggested that they might be related to El-Nino activity. As the ENSO

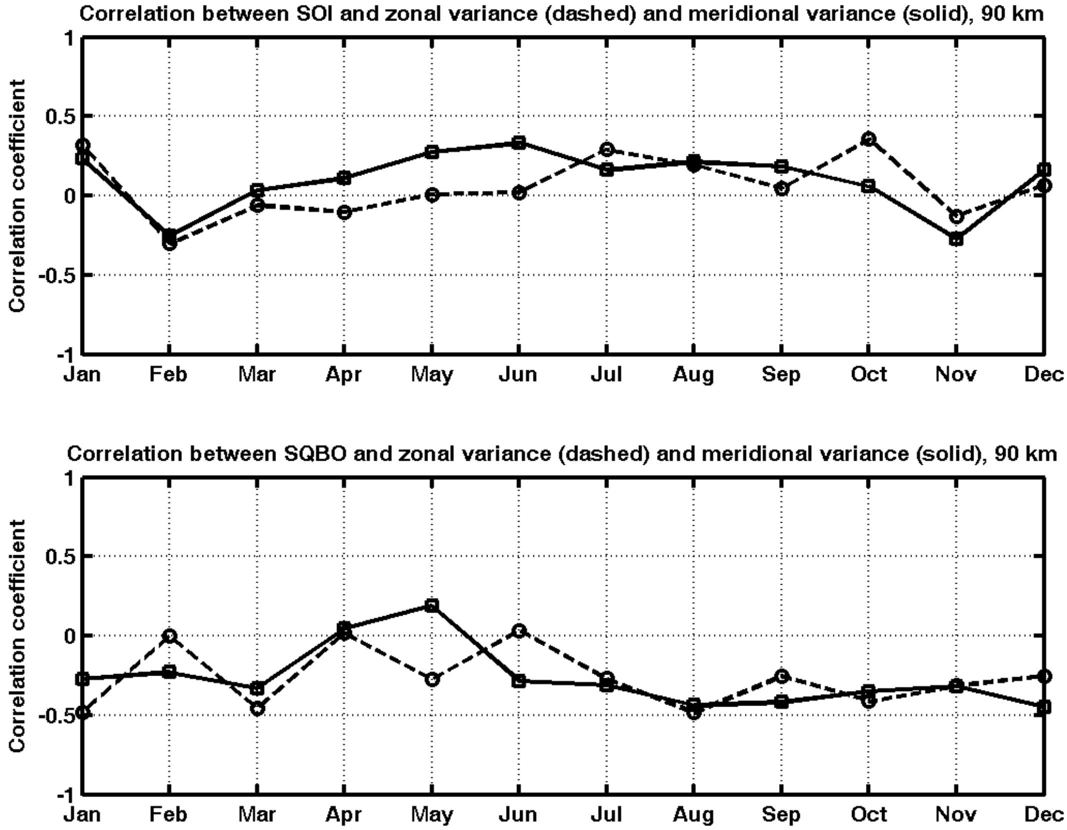

Fig. 5. Monthly variation of correlation coefficient between wind variances and southern oscillation (top panel) and stratospheric QBO (bottom panel).

events may produce changes in circulation and the strength of wave sources in the tropical tropo-stratosphere, it was expected correlation between wind variances in the MLT region and SOI. They obtained a negative correlation around 0.4–0.6 obtained between GW variance and SOI during winter months. They suggested that the correlation between the two could be due to changes in the conditions of wave generation and propagation due to changes in atmospheric dynamics caused by variations of Pacific surface temperatures.

There seems to be a correlation among meridional GW variances at MLT heights, eastward phase of stratospheric QBO and major sudden stratospheric warming events. It may also be noted that major sudden stratospheric warming occurred during the years 1999, 2002, 2004 and 2006 and no major warming events occurred in the years 1993–1997. Delisi and Dunkerton (1988) noted correlation between eastward phase of stratospheric QBO and sudden stratospheric warming events occurring at mid latitudes. Using observations from the Nimbus 3 satellite, Fritz and Soules (1970) were the first to show that the perturbations in the stratosphere at the higher latitudes are related to those at the tropics: the SSW at high latitudes in winter was accompanied by simultaneous cooling in the tropical winter stratosphere and in the summer hemisphere. Mukherjee (1990) observed in rocketsonde temperatures low latitude cooling in stratosphere and warming in mesosphere during the SSW events. The linkage between high and low-latitudes is due to the fact that the upward propagating planetary waves accompany poleward heat flux which heats the high latitudes and cools the low latitudes and these differential heating induces zonal mean upward motion at higher latitudes and downward motion at lower latitudes.

Liu and Roble (2002) examined sudden stratospheric warming events using model studies and concluded that the deceleration and reversal of the stratospheric jet allowed more eastward propagating gravity waves into the MLT region, forcing an equatorward-directed meridional circulation responsible for the upper mesosphere cooling. It may be noted that the annual mean meridional winds over Tirunelveli (8.7° N, 77.8° E) were more southward after the year 1998 (Sridharan et al., 2007), when major stratospheric warming events occurred in most of the years. Using ground and satellite based observations of many stratospheric warming events, Shepherd et al. (2007) observed mesospheric cooling at the time of stratospheric warming at the tropics correlative with stratospheric warming events at middle and high latitudes. Enhanced planetary wave activity was also noticed by the authors during sudden stratospheric warming events.

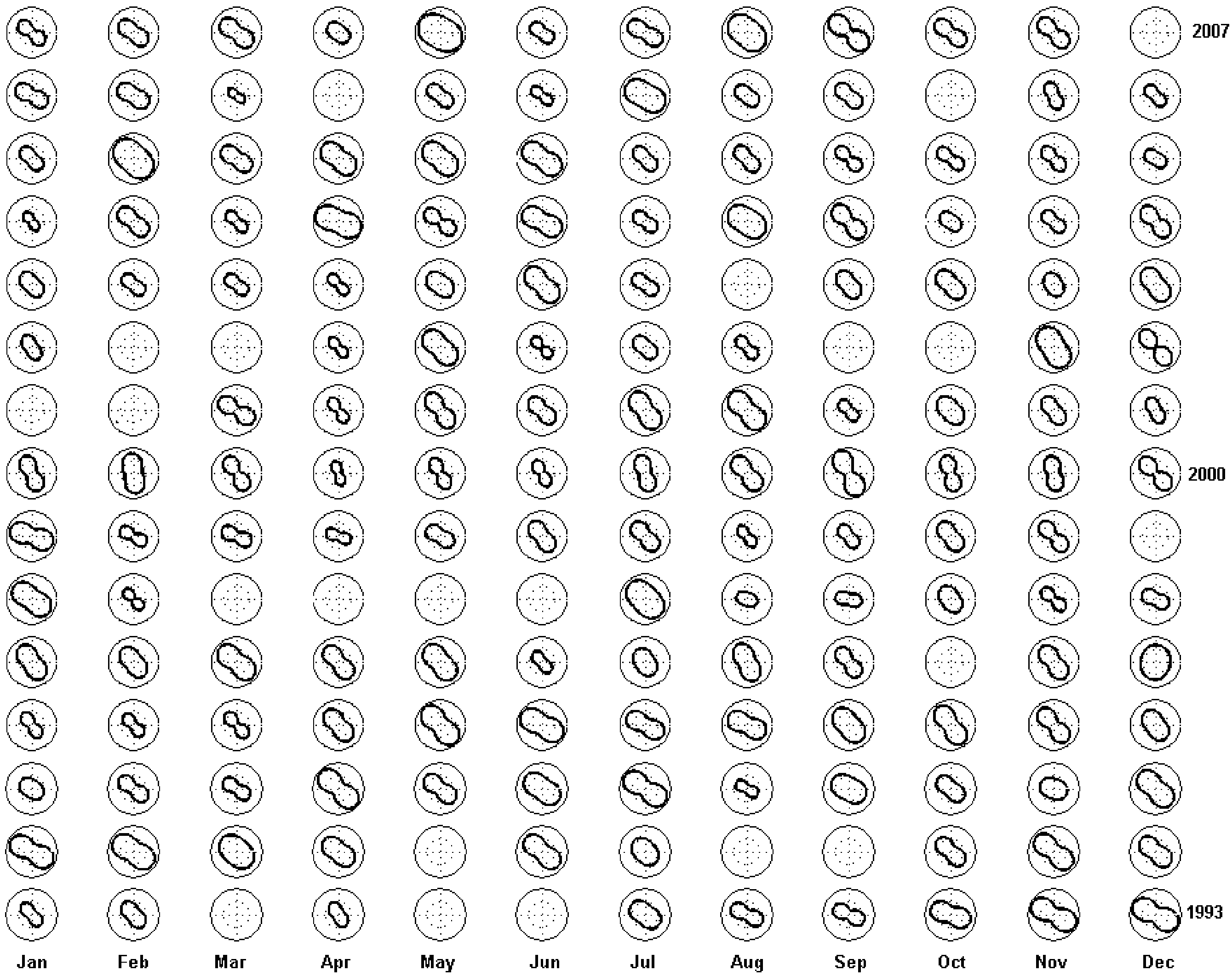

Fig. 6. Perturbation ellipses for each month of the years 1993–2007 obtained for the height region 84–94 km. The radius of the outer circle is 25 m^2/s^2.

Using a composite analysis of twelve stratospheric warmings from 1979 to 2001, Kudera et al. (2006) observed that the meridional circulation change associated with stratospheric warming in the polar region produces a lower temperature in the equatorial upper troposphere and lower stratosphere (UTLS) region leading to enhancement of convective activity near the equatorial Southern Hemisphere (10° S-equator) but a suppression in the tropics of the Northern Hemisphere (5° N–15° N). Garfinkel and Hartmann (2007) noted that the tropical convective activity could have a significant impact on polar vortex, the breaking of which causes major sudden stratospheric warming at high latitudes. These observations suggest that low and high latitude dynamics are coupled. Whiteway and Carswell (1994) observed enhancement of gravity wave activity in the high latitude middle atmosphere during Northern Hemisphere stratospheric warming event. Venkat Ratnam et al. (2004) also found enhanced gravity wave activity in the high latitude UTLS region during a Southern Hemisphere stratospheric warming event occurred in the year 2002. We suggest that the enhancement of meridional GW variances during the spring equinox months followed by sudden stratospheric wave events could be due to equatorward propagation of gravity waves at MLT heights from mid-latitudes to low-latitudes. Buhler et al. (2003) studied the equatorward propagation of inertia gravity waves due to steady and intermittent wave forcing and showed that even wave sources outside the equatorial region can robustly produce potential energy spectra that peak at the equator. Tsuda et al. (1990) found gravity wave motions of period centered around 8.6 h in the MU radar observations having equatorward component of the meridional propagation.

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