GEOPHYSICAL RESEARCH LETTERS, VOL. 36, L07806, doi:10.1029/2008GL037081, 2009

Planetary and gravity waves in the mesosphere and lower thermosphere region over Tirunelveli (8.7°N, 77.8°E) during stratospheric warming events

S. Sathishkumar[1] and S. Sridharan[2]

Received 19 December 2008; revised 3 March 2009; accepted 10 March 2009; published 10 April 2009.

[1] An investigation of planetary wave (PW) activities in UKMO (UK Meteorological Office) winds during winter of the years 1998–99 and 2005–06, when major sudden stratospheric warming (SSW) events occurred, shows that the amplitude of PW of zonal wave number 1 is considerably reduced in zonal winds, when the warming event is onset and the reduced activity persists several days even after the end of the SSW event. Similar reduction of PW activity in zonal winds has been observed in the wavelet spectrum of MF radar zonal winds at altitudes 84–98 km over Tirunelveli (8.7°N, 77.8°E). During this period of reduced PW activity, enhancement in gravity wave activity is observed during 2005–06 and is not observed during 1998–99 and the mean meridional winds change to more equatorward during 2005–06 and remain poleward during 1998–99. In accordance with TIME-GCM results, our observations show that the wind reversal occurred in the stratosphere during major warming events allows more eastward gravity waves to propagate into the mesosphere and lower thermosphere (MLT) region, which causes changes in the meridional circulation from poleward to equatorward. **Citation:** Sathishkumar, S., and S. Sridharan (2009), Planetary and gravity waves in the mesosphere and lower thermosphere region over Tirunelveli (8.7°N, 77.8°E) during stratospheric warming events, *Geophys. Res. Lett.*, *36*, L07806, doi:10.1029/2008GL037081.

1. Introduction

[2] A sudden stratospheric warming (SSW) event is a transient large-scale dynamical phenomenon of winter middle atmosphere, which involves profound changes of temperature, wind and circulation in a short period of time [*Andrews et al.*, 1987]. There are many observational and theoretical studies and reviews on this event [*Labitzke and van Loon*, 1999, and references therein]. The basic mechanism, initially proposed by *Matsuno* [1971] and now widely accepted consists of an anomalous amplitude increase of the tropospheric stationary PW of zonal wavenumber (k) 1 or 2 resulting in enhanced wave propagation from troposphere to stratosphere and their interaction with mean flow. *Plumb* [1981] showed that the tropospheric stationary wave and a traveling PW aloft might engage in a self-tuning near resonance leading to wave amplification. The amplification of the quasi-stationary wave 1 produces strong westward forcing in the high latitude winter stratosphere, resulting in deceleration and/or reversal of the eastward winter winds. This process also induces a downward circulation in the stratosphere causing adiabatic heating and an upward circulation in the mesosphere causing the adiabatic cooling [*Liu and Roble*, 2002, 2005]. The deceleration and reversal of the eastward jet in the high-latitude stratosphere also changes the filtering of internal gravity waves and allows increasing amounts of eastward propagating gravity waves from lower atmosphere to penetrate into the mesosphere and lower thermosphere (MLT) and break there, while blocking westward propagating gravity waves. Therefore, the eastward forcing due to eastward propagating gravity wave breaking increases and even replaces the previously existing westward forcing in the MLT region. This also changes the meridional circulation in the upper mesosphere from poleward/downward to equatorward/upward [*Liu and Roble*, 2002]. There are no major warming events occurred in nine consecutive winters from 1989–1990 through 1997–1998 and there have been major warmings almost in every year after the year 1998. *Sridharan et al.* [2007] noted a decreasing trend in annual mean meridional winds over Tirunelveli (8.7°N, 77.8°E) with more equatorward winds in recent years. *Sridharan and Sathishkumar* [2008] observed enhancement in monthly averaged gravity wave perturbations in meridional winds over Tirunelveli during most of late winter and early spring equinox that follows mid winter major SSW events. The present study analyzes PW activities in the stratosphere and lower mesosphere using UKMO wind data and planetary and gravity wave activities in the MLT region over Tirunelveli (8.7°N, 77.8°E) during two major warming events 1998–99 and 2005–06. Meridional circulations prevailed during these winters are discussed in relation to the wave activities.

2. Observations and Data Analysis

2.1. UKMO Data

[3] The UKMO (United Kingdom Meteorological Office) data set is a result of assimilation of in situ and remotely sensed data into numerical forecast model of the stratosphere and troposphere. The description of the original data assimilation system is given by *Swinbank and O'Neill* [1994], while the new three dimensional variational systems are given by *Swinbank and Ortland* [2003]. The outputs of the assimilation are global fields of daily temperature, geopotential heights, and wind components at pressure levels from the surface up to 0.1 hPa. The generated data fields have global coverage with 2.5° and 3.75° steps in latitude and longitude respectively. The UKMO data well

[1]Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Tirunelveli, India.
[2]National Atmospheric Research Laboratory, Gadanki, India.

0094-8276/09/2008GL037081$05.00

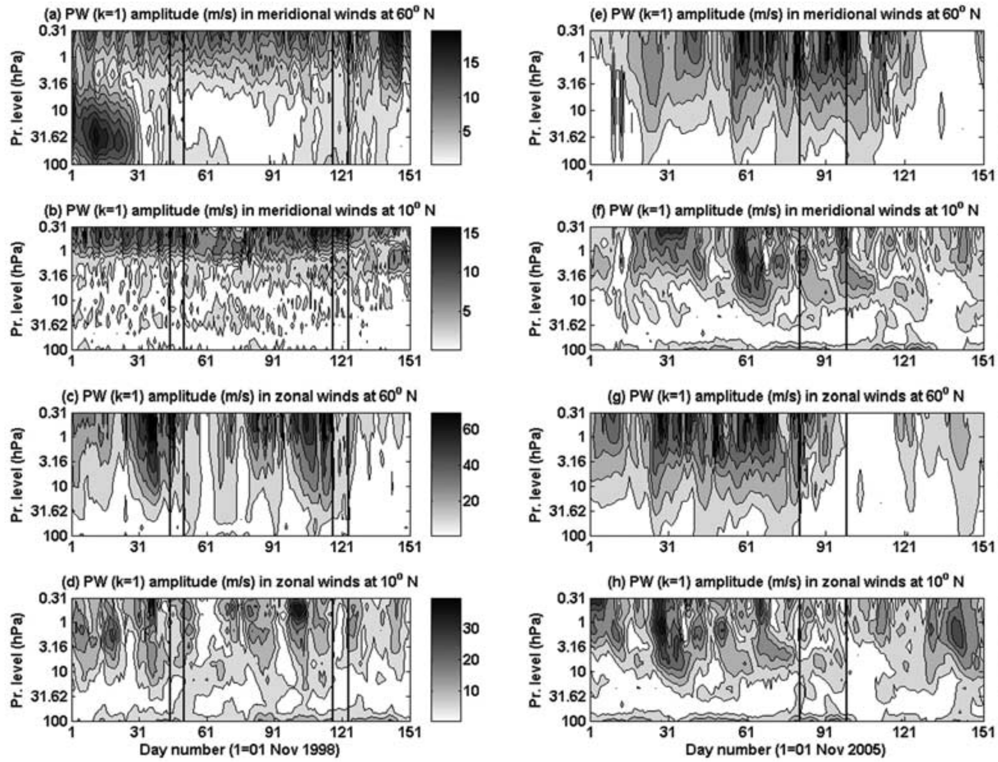

Figure 1. Daily variation of the amplitude of planetary wave of k = 1 in UKMO winds at 60°N and 10°N for 1–151 days starting (a)–(d) from 01 November 1998 and (e)–(h) from 01 November 2005 for the pressure levels 100–0.31 hPa. The duration of major SSW events is shown as vertical lines.

represent the global features of stratospheric thermodynamics and have been used by many researchers to study different dynamical events in the stratosphere including PW [*Fedulina et al.*, 2004] and SSWs [*Dowdy et al.*, 2004; *Cho et al.*, 2004]. The present study utilizes UKMO wind data for the pressure levels 100–0.31 hPa mainly for the latitudes 10°N and 60°N for November–February of the years 1998–99 and 2005–06.

2.2. Medium Frequency Radar

[4] The Meridional Frequency (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 minute time interval. The pulse width of 30 μsec limits the height resolution to around 4.5 km. The raw winds for every 2 minutes are averaged for every hour. In the present study, these hourly winds are used to extract gravity and PW information at 86–98 km altitudes.

3. Results

[5] We considered two major warming events which occurred during 15 December–21 December 1998 and 21 January–7 February 2006. One final warming also occurred during 24 February 1999–04 March 1999 (day numbers: 117–124). The duration of the major warming period is defined as events where both the zonal mean temperature gradient and zonal mean winds at 10 hPa reverse sign poleward of 60° [*Pawson and Naujokat*, 1999]. Figure 1 shows the time variation of the amplitude of PW of k = 1 in zonal wind at 60°N and 10°N for 1–151 days starting from 01 November 1998 (Figures 1a–1d) and from 01 November 2005 (Figures 1e–1h) for the pressure levels 100–0.31 hPa. The durations of the major warming events are day numbers 45–51 and 81–99 for 1998–99 and 2005–06 events respectively. During 1998–99, the PW amplitudes in zonal wind enhanced nearly two weeks before the onset of the SSW event at 60°N and their amplitudes rapidly decrease, when the onset day is approaching. The wave amplitudes decrease considerably during the SSW event (day numbers: 45–51). The reduction in wave amplitudes continues even after the end of the SSW event and persists approximately for about a month. PW amplitudes begin to increase and however could survive only till the end of February (day number ~120) due to the seasonal transition of winds from eastward to westward, which are not favourable for westward propagating PW. At 10°N, PW, in general, are having smaller amplitude. Similar to that at 60°N, there is significant reduction in wave amplitudes during and several days after the SSW event. During 2005–06 also, there is significant enhancement of PW amplitudes above 20 hPa for nearly about two months prior to the date of onset of SSW event (day no: 81). However, as seen in the previous case, there is considerable reduction in PW amplitudes during the SSW event. The reduction in wave amplitudes continued even for about a month after the event also. PW (k = 1) in meridional winds has smaller amplitude at both 60°N and 10°N during 1998–99. Though it shows larger amplitude at 60°N during 2005–06, its variabilities are not related to

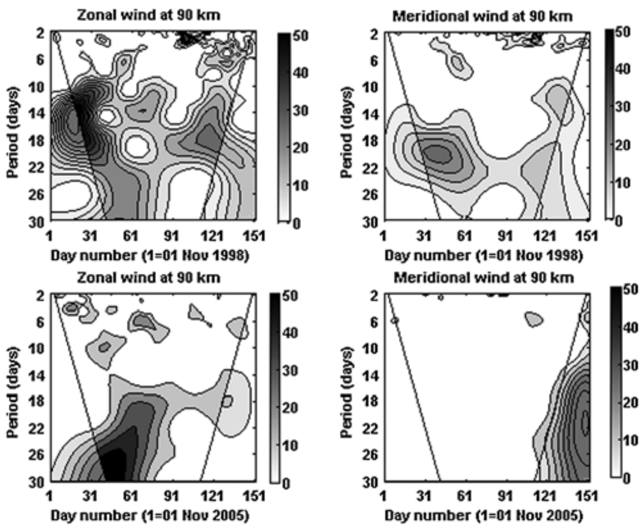

Figure 2. Wavelet spectra of (left) MF radar zonal and (right) meridional winds at 90 km for 1–151 days starting from 01 November of the years (top) 2005–06 and (bottom) 1998–99.

the occurrence of the SSW events. The PW activity is not significantly present at 10°N.

[6] In order to investigate the temporal variation of PW activity at MLT altitudes over tropical region, the hourly mean MF radar zonal winds at 88 km over Tirunelveli (8.7°N, 77.8°E) are subjected to wavelet analysis. The wavelet analysis is becoming a common tool for analyzing localized variations of power within a time series. By decomposing a time series into time-frequency space, it is possible to determine both the dominant modes of variability and how those modes vary in time [*Daubechies*, 1992]. For the present study, we use Morlet wavelet function as mother wavelet. Localization of signal characteristics in time and frequency domains can be accomplished with this wavelet function. Figure 2 shows normalized wavelet spectra of zonal and meridional winds at 90 km for 1–151 days starting from 01 November for the years 1998–99 and 2005–06. The wavelet spectrum for zonal winds shows that before the onset of SSW event during 1998–99, the PW having period 10–20 days are quite dominant. Their energies decrease in time periods less than 20 days, as the onset date approaches. The decrease of PW activity in these periods continues even after the SSW event, which ends on day number 51, for more than 30 days. However, extra-long period PW activity (>20 days) is present in both zonal and meridional wind spectrum during December 1998. The activity of PW with longer periods activity is also observed in both zonal and meridional winds during the final warming event occurred during late February 1999. In the 2005–06 event also, PW activity with periods ~20 days and ~6 days are dominant before the onset of wave event. Similar to the PW activity in the stratosphere and lower mesosphere, these waves are not significantly present after the onset of wave event and the reduction in PW energies is observed until the day number 120. This suggests that PW variabilities in MLT region are significantly influenced by the major SSW events. The meridional wind spectrum does not show significant PW activity and extra-long PW activity till the end of February 2006. *Pancheva et al.* [2008] noted opposite relationship between the variability of the MLT zonal wind at high and low latitudes and indicated the presence of zonally symmetric waves in the MLT zonal wind, *Hoffmann et al.* [2007] observed enhanced gravity wave activity at high latitude MLT region, when amplitudes of stratospheric PW are reduced at stratospheric heights. In order to investigate temporal variation of gravity wave activity in the MLT region, the MF radar hourly mean meridional winds for the heights 84–98 km (data acceptance rate is more at 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 components (24-h, 12-h, and 8-h). Only the days having hourly data points more than 16 h are considered. This filter gives an estimate of the intensity of wind variations having periods ~2–6 h. The gravity wave activity in the meridional winds for the year 2005–06, presented in Figure 3c, shows that there are enhancements in wave activity around the day of onset of SSW event (~day number 80) and it persists till the end of the period shown in Figure 3c. Though the major SSW event occurred only during day numbers between 81 and 99 inferred from the reversal of zonal mean zonal wind at 10 hPa and at 60°N shown in Figure 3a, the weaker amplitude of PW (k = 1) amplitude (Figure 3b) in zonal wind at 10 hPa continues even after the end of the SSW event as already evident from Figure 2. The enhancement of PW amplitudes at 35°N could be due to bending of PW towards tropics. *Sivakumar et al.* [2004] showed evidence of propagation of

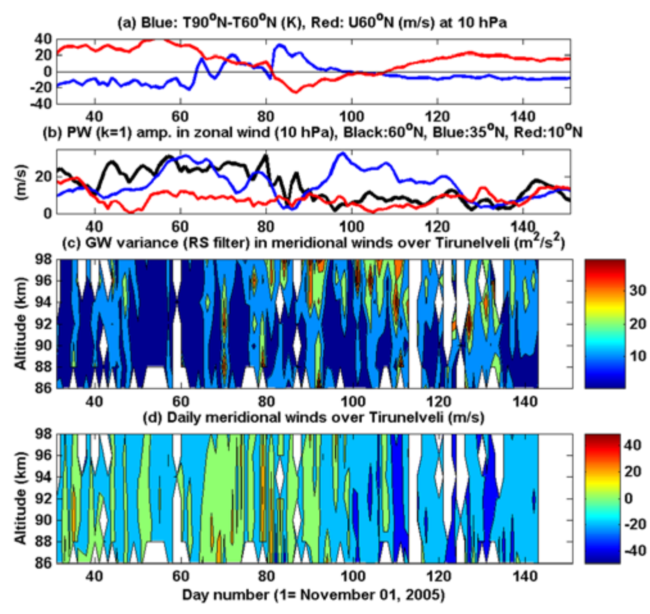

Figure 3. (a) Zonal mean temperature difference (T90°N–T60°N) and zonal mean zonal wind (U) at 60°N, (b) time variation of amplitude of PW of zonal wavenumber 1 in zonal wind for 10 hPa at latitudes 60°N, 35°N and 10°N, (c) altitude-time cross section of gravity wave variances in meridional winds over Tirunelveli, and (d) altitude-time cross section of daily values of meridional winds over Tirunelveli for the day numbers 30–151 (day number 1 is November 1, 2005).

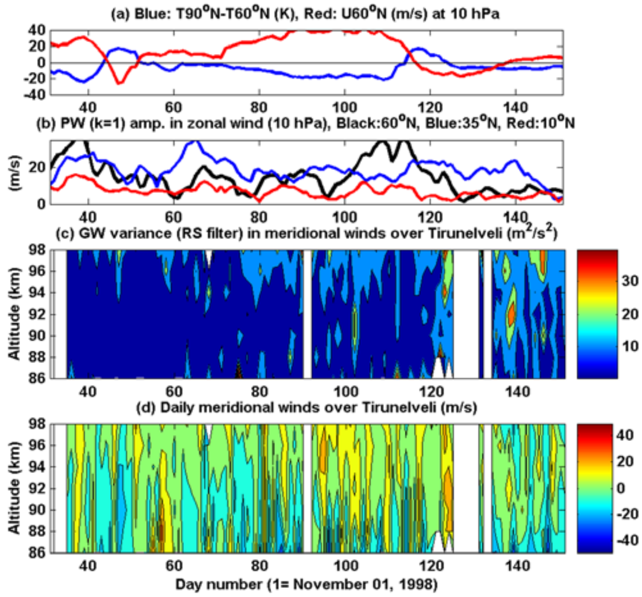

Figure 4. Same as Figure 3 but for the day numbers 30–151 (day number 1 is November 1, 1998).

planetary-wave activity from high to mid and low latitudes subsequent to the major warming episode over the pole. In the year 1998–99 (Figure 4c), the GW variances are less during and even after the SSW event, which occurred during day numbers 45–51 (Figure 4a), in spite of similar reduction of PW amplitude (Figure 4b). Larger GW variances are observed only during the end of the observation period, during and after the final warming event, which is also preceded by enhanced PW amplitude. As the mean meridional winds at MLT heights are driven by gravity waves, the daily mean meridional winds, are in general, more equatorward during and after the SSW events for the winter 2005–06 (Figure 3d), whereas for the winter 1998–99 (Figure 4d), the winds are only weakly equatorward during when major SSW events occurred and remain poleward during the rest of the observation period. The poleward winds weaken at the end of the observation period, as a normal seasonal transition.

4. Discussion and Conclusion

[7] The UKMO winds for the latitudes 10°N and 60°N and MF radar winds over Tirunelveli are used to investigate PW activities in the middle atmosphere during winters of the years 1998–99 and 2005–06, when major SSW events occurred. In both the cases (1998–99 and 2005–06), the PW is enhanced in both stratosphere and MLT heights several days before the onset of SSW events and is considerably reduced, when the warming event is onset. The reduced PW activity persists even several days after the end of the SSW events. During this period of reduced PW activity, enhancement in gravity wave activity is observed at MLT heights during the year 2005–06 and not during the year 1998–99. *Hoffmann et al.* [2007] also observed enhancement in GW activity at high-latitude MLT heights, when there was reduction in PW activity in the stratosphere during periods 2005–06.

[8] *Dunkerton and Butchart* [1984] performed ray-tracing study of gravity wave propagation through a sudden warming and demonstrated that the presence of large amplitude PW leads to propagating and forbidden zones thus reducing gravity wave propagation into the mesosphere. Our observations also show smaller GW variances before the onset of SSW events, when PW amplitudes are larger. The large amplitude PW produces strong westward forcing in the high latitude winter stratosphere, causing the reversal of the stratospheric jet. The reversed jet forms a critical layer for the upward propagation of PW and leads to breakdown of the wave. As there is no significant PW flux above the critical layer, the PW amplitudes at MLT heights also reduced, coinciding with the onset of major SSW event.

[9] The GW variance in meridional winds over Tirunelveli shows larger values from day number ~70 even before the reversal of stratospheric eastward winds during 2005–06. It could be a response to weakening/reversal of eastward winds and reduced PW amplitudes at stratospheric heights, which enable gravity waves having larger eastward phase speeds to propagate upward. The daily mean meridional winds change from poleward to equatorward, coinciding with larger GW variance. The TIME-GCM model results of *Liu and Roble* [2002] show that eastward gravity wave forcing in the winter hemisphere induces an equatorward [see *Liu and Roble*, 2002, Figure 13] and upward flow at upper mesospheric heights and downward above.

[10] During 1998–99, though the wind conditions are favourable for the vertical propagation of gravity waves, the waves of sufficiently larger energies might not exist to reverse the winds to more equatorward. As a result, the meridional winds are weakly equatorward during major SSW events and they remain largely poleward without reversal after the event. The dynamical response in the MLT region to the major SSW events appears to be highly variable in one warming event to other. The variability is mainly due to variability in GW activity at MLT heights, which is influenced by the wave source mechanisms, by background winds through which they propagate and by the presence of PW of large amplitudes.

[11] **Acknowledgments.** We are grateful to the UKMO and the BADC for access to the data on http://www.badc.rl.ac.uk/data/assim.

References

Andrews, D. G., J. R. Holton, and C. B. Leovy (1987), *Middle Atmospheric Dynamics*, 489 pp., Elsevier, New York.

Cho, Y.-M., G. G. Shepherd, Y.-I. Won, S. Sargoytchev, S. Brown, and B. Solheim (2004), MLT cooling during stratospheric warming events, *Geophys. Res. Lett.*, *31*, L10104, doi:10.1029/2004GL019552.

Daubechies, I. (1992), *Ten Lectures on Wavelets*, 357 pp., Soc. for Ind. and Appl. Math., Univ. Sci. Cent., Philadelphia, Pa.

Dowdy, A. J., R. A. Vincent, D. J. Murphy, M. Tsutsumi, D. M. Riggin, and M. J. Jarvis (2004), The large-scale dynamics of the mesosphere–lower thermosphere during the Southern Hemisphere stratospheric warming of 2002, *Geophys. Res. Lett.*, *31*, L14102, doi:10.1029/2004GL020282.

Dunkerton, T. J., and N. Butchart (1984), Propagation and selective transmission of internal gravity waves in a sudden warming, *J. Atmos. Sci.*, *41*, 1443–1460.

Fedulina, I. N., A. I. Pogoreltsev, and G. Vaughan (2004), Seasonal, interannual and short-term variability of planetary waves in Met Office stratospheric assimilated fields, *Quat. J. R. Meteorol. Soc.*, *130*, 2445–2458.

Gavrilov, N. M., A. H. Manson, and C. E. Meek (1995), Climatological monthly characteristics of middle atmosphere gravity waves (10 min.–10 hrs.) during 1979–1993 at Saskatoon, *Ann. Geophys.*, *13*, 285–295.

Hoffmann, P., W. Singer, D. Keuer, W. K. Hocking, M. K. Kunze, and Y. Murayama (2007), Latitudinal and longitudinal variability of mesospheric winds and temperature during stratospheric warming events, *J. Atmos. Sol. Terr. PhyS.*, *69*, 2355–2366.

Labitzke, K., and H. van Loon (1999), *The Stratosphere: Phenomena, History, and Relevance*, Springer, New York.

Liu, H.-L., and R. G. Roble (2002), A study of a self-generated stratospheric sudden warming and its mesospheric–lower thermospheric impacts using the coupled TIME-GCM/CCM3, *J. Geophys. Res.*, *107*(D23), 4695, doi:10.1029/2001JD001533.

Liu, H.-L., and R. G. Roble (2005), Dynamical coupling of the stratosphere and mesosphere in the 2002 Southern Hemisphere major stratospheric sudden warming, *Geophys. Res. Lett.*, *32*, L13804, doi:10.1029/2005GL022939.

Matsuno, T. (1971), A dynamical model of the stratospheric sudden warming, *J. Atmos. Sci.*, *28*, 1479–1494.

Pancheva, D., et al. (2008), Latitudinal wave coupling of the stratosphere and mesosphere during the major stratospheric warming in 2003/2004, *Ann. Geophys.*, *26*, 467–483.

Pawson, S., and B. Naujokat (1999), The cold winters of the middle 1990s in the northern lower stratosphere, *J. Geophys. Res.*, *104*, 14,209–14,222.

Plumb, R. A. (1981), Instability of the distorted polar night vortex: A theory of stratospheric warmings, *J. Atmos. Sci.*, *38*, 2514–2531.

Rajaram, R., and S. Gurubaran (1998), Seasonal variabilities of low-latitude mesospheric winds, *Ann. Geophys.*, *16*, 197–204.

Sivakumar, V., B. Morel, H. Bencherif, J. L. Baray, S. Baldy, A. Hauchecorne, and P. B. Rao (2004), Rayleigh lidar observation of a warm stratopause over a tropical site, Gadanki (13.5°N, 79.2°E), *Atmos. Chem. Phys.*, *4*, 1989–1996.

Sridharan, S., and S. Sathishkumar (2008), Seasonal and interannual variations of gravity wave activity in the low-latitude mesosphere and lower thermosphere over Tirunelveli (8.7°N, 77.8°E), *Ann. Geophys.*, *26*, 3215–3223.

Sridharan, S., T. Tsuda, and S. Gurubaran (2007), Radar observations of long-term variability of mesosphere and lower thermosphere winds over Tirunelveli (8.7°N, 77.8°E), *J. Geophys. Res.*, *112*, D23105, doi:10.1029/2007JD008669.

Swinbank, R., and A. O'Neill (1994), A stratosphere–troposphere data assimilation system, *Mon. Weather Rev.*, *122*, 686–702.

Swinbank, R., and D. A. Ortland (2003), Compilation of wind data for the Upper Atmosphere Research Satellite (UARS) Reference Atmosphere Project, *J. Geophys. Res.*, *108*(D19), 4615, doi:10.1029/2002JD003135.

S. Sathishkumar, Equatorial Geophysical Research Laboratory, Indian Institute of Geomagnetism, Tirunelveli 627 011, India.

S. Sridharan, National Atmospheric Research Laboratory, Gadanki 517 112, India. (susridharan@narl.gov.in; ssri_dhar@rediffmail.com)