Investigation of Vertically Propagating Convectively Generated Short (~2-3 hr) Period Gravity Waves in the Atmosphere-Ionosphere system

M. Arunachalam Srinivasan[1, 2]
[1]Indian Institute of Technology Madras, Chennai-600036
[2]Department of Physics, Sri Venkateswara University, Tirupati-517502.

Received Dec. 06, 2017 Accepted Jan. 08, 2018

ABSTRACT *Short period gravity waves generated during deep convection shows significant influence on the dynamics of the middle atmosphere. The present study describes the characteristics of vertically propagating short (~2-3 hr) period gravity waves with the help of four deep convective events associated with strong vertical velocities and double pause structures in the stratopause and mesopause altitudes using Indian MST radar, MF radar, Lidar and Equatorial Electro Jet (EEJ) datasets. Among the convective events maximum vertical updraft/downdrafts are found to be ~ +16 ms^{-1}/~ -10 ms^{-1} associated with the cloud top brightness temperature (TBB) of ~185 K/~205 K corresponding to 16-17 May 2006/24 September 2008. For all the cases there exist weak echo regions in the vertical beam SNR obtained from the MST radar leading to strong entrainment of ambient air from the troposphere into the stratospheric region due to the existence of strong updraft velocities. Two dimensional FFT of Rayleigh Lidar temperatures has shown the presence of dominant ~2-3 hr period oscillations associated with vertical wavelengths of ~ 4.2 km and ~7.6 km in the stratospheric region. During all the convective events the EEJ strength is found to be positive except on 16 and 17 May 2006, which is negative (~-38 nT and ~-18 nT), related with type-I and type-II counter electro jet (CEJ) event.*

1. Introduction

Vertically propagating convectively generated short period gravity waves (GWs) play an important role in vertical coupling of atmosphere-ionosphere system (*PlougonvenandZhang*, 2014; *YigitandMedvedev,* 2014 and references therein). There is some evidence in tropics that the convective activity moves from east to west in association with the easterly waves which can trigger gravity waves and it is particularly active when the low-latitude wave intersects with a mid-latitude wave ensuring efficient transfer of warmed air away from low latitude (*Green*, 1999). Specifically, waves excited by convective activity are likely important in the tropics and southern hemisphere where there are few orographic wave sources, and convection may be a source of the high phase speed waves known to be important in the mesosphere. *Alexander* (1995, 1996) have noticed a strong response at high frequencies and at longer vertical wavelengths (6-10 km) showing the evidences of stratospheric motions above convective sources. Detailed information about the convectively generated gravity waves can be found in *Arunachalam et al.* (2014) and references therein. They are generated in the troposphere by various sources (e.g., orography, convection, spontaneous adjustment of jet streams); GWs propagate upwards with increasing amplitude due to the exponential air density decline. The increase in amplitude continues until it reaches saturation level, where GWs break, deposit momentum and accelerate or decelerate the atmosphere background flow. This process strongly depends on the refraction of the GWs by the background wind field, thus forming a two way interaction between mean winds and GWs. Hence, GWs significantly affect the global circulation and are the main driver of the quasi-biennial oscillation (QBO) (e.g., *Dunkerton*, 1997; *Ern andPreusse*, 2009; *AlexanderandOrtland,* 2010; *Evan et al.*, 2012; *Ernet al.*, 2014).

In addition, gravity waves also play a key role in wind reversals in the mesosphere and lower thermosphere (*Lindzen*, 1981; *Matsuno*, 1982; *Ern* et al., 2013), and they cause the cold summer mesopause at high latitudes (*e.g., Björn*, 1984; *Frittsand Alexander*, 2003). Moreover, GWs are widely accepted as the main driver of the summertime branch of the stratospheric Brewer–Dobson circulation (*AlexanderandRosenlof*, 2003; *FrittsandAlexander*, 2003). Also, general circulation models predict an acceleration of Brewer–Dobson circulation in a warming climate, which is influenced by GWs (*Garcia andRandel*, 2008; *Li et al*., 2008; *McLandressandShepherd*, 2009; *Butchart et al*., 2010).

In fact, observations indicate that there is a broad spectrum of gravity waves in the mesosphere, and that the largest momentum fluxes tend to be associated with high-frequency gravity waves (*Fritts and Vincent*, 1987). Such waves may be generated by a variety of processes, but among these, convective activity is the most important one. High frequency gravity waves are attributed to convective sources are frequently observed in the mesopause region with help of airglow imagers. Generally, convection occurs in many forms, and the morphology of gravity waves generated by various types of convective cloud is not yet understood. Present work deals with the characteristics of vertically propagating (2-3 hr) short period gravity waves from the troposphere to ionospheric altitudes during four different convection events with help of MST radar, MF radar and EEJ data sets.

2. Data

2.1. MST and MF Radar Datasets

Continuous high resolution (150 m vertical and ~1 min temporal resolution) vertical wind information in the altitude of 3.65 km to 22.5 km from MSTRadar, Gadanki and hourly zonal wind (with 2 km vertical resolution; 70 km to 100 km altitude) from MF Radar, Tirunelveli used to study four different convective events (27 September 2004, 29 September 2004, 16-17 May 2006 and 24 September 2004).

High spatial (0.05°) and temporal (hourly) resolution cloud top equivalent blackbody temperature datasets from MTSAT-1R of Japan Meteorological Agency (JMA) through Kochi University, Japan has been utilized as a measure of deep convection. In addition to this, high resolution temperature datasets from Rayleigh Lidar located at Gadanki has been utilized. Finally, hourly equatorial electro jet (EEJ) datasets from EGRL, Tirunelveli has also been utilized.

3. Results

3.1. Background Meteorological Conditions

Observation of deep convection events associated with strong vertical updrafts and downdrafts on 27 September 2004, 29 September 2004, 16-17 May 2006, and 24 September 2008 has been considered for the present study. **Figure 1** shows cloud top equivalent blackbody temperature (TBB) over Gadanki (13.47°N, 79.18°E) (blue line), ±2º (green line) and ±4º (red line) centering Gadanki region, obtained from MTSAT-1R satellite measurements for the present study. The events for which the value of TBB<235 K is considered to be associated with intense convective events (*ArkinandMeisner*, 1987; *Chen et al.*, 1996).

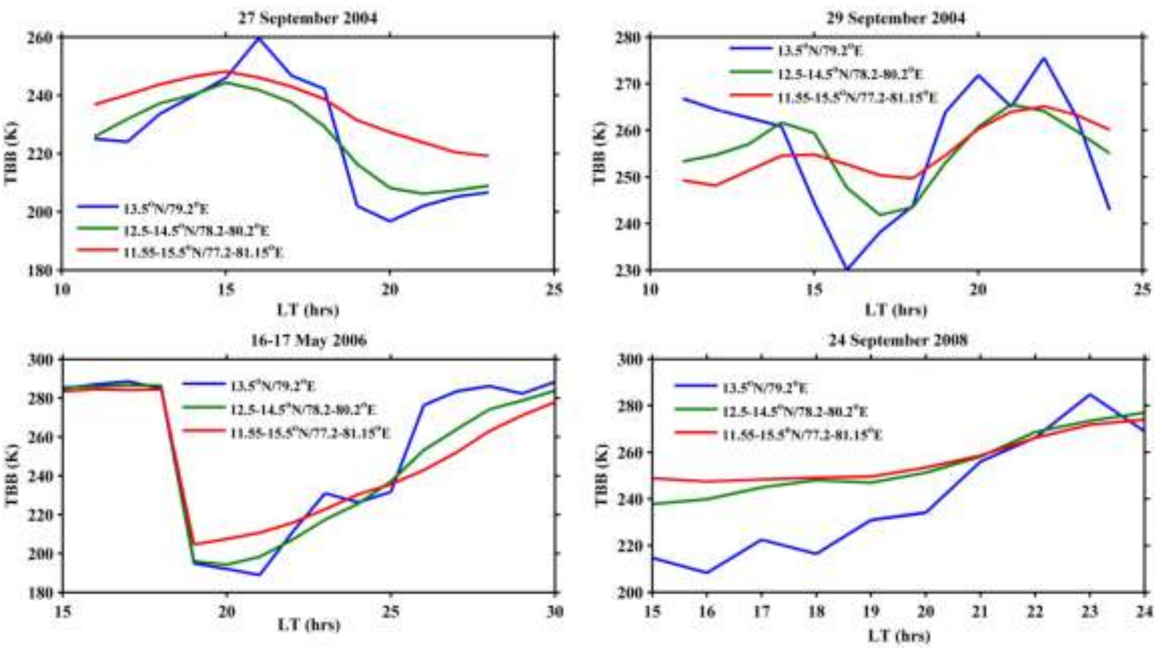

Figure 1 *Time series cloud top equivalent blackbody temperature (TBB) over Gadanki (13.47°N, 79.18°E) (blue line), ±2º (green line) and ±4º (red line) centering Gadnaki region corresponding to 27 September 2004 (top left), 29 September2004 (top right), 16-17 May 2006 (bottom left) and 24 September 2008 (bottomright).*

In general, thunderstorms often occur during pre- and post-monsoon periods (April-May and September), respectively over Southern Indian region. In the present study, the characteristics of short period gravity waves with the help of four cases, one corresponding to pre-monsoon period and remaining three belong to post-monsoon period have been investigated. Among the four cases, 27 September 2004 is a thunderstorm event and 29 September 2004, 16-17 May 2006 and 24 September 2008 are squall-line events.

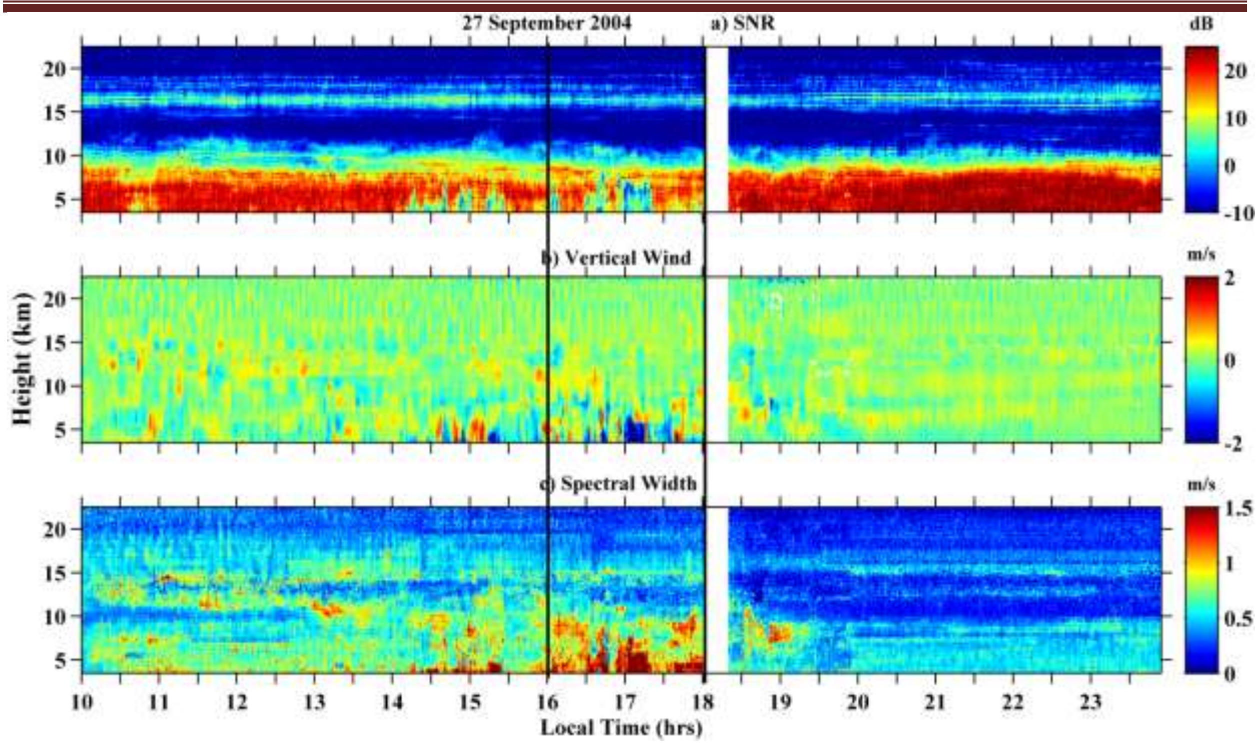

Figure 2a *Height Time intensity plots of MST radar moments a) SNR (dB), b) vertical wind (m/s) and c) spectral width (m/s) corresponding to 27 September 2004. The gaps in this* ***Figure*** *indicate that the radar is operated either in six beam mode orno data. Black lines indicate the mature stage of convection.*

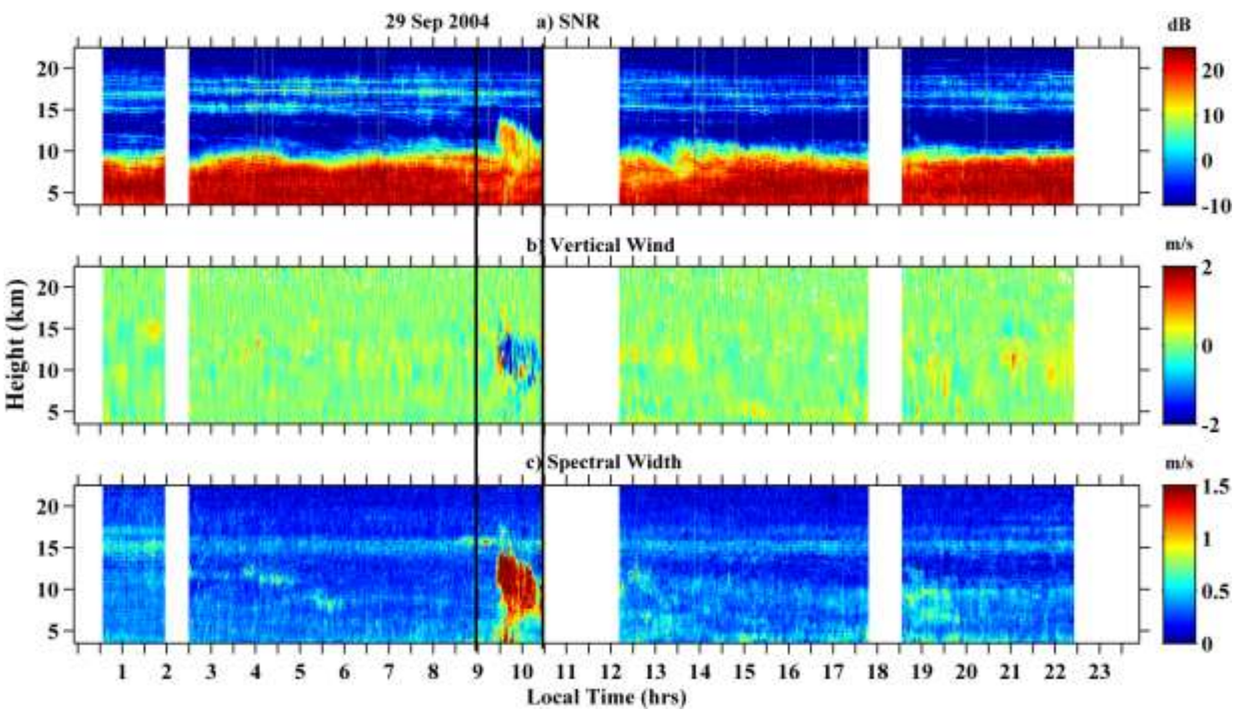

Figure 2b *Same as* ***Figure 2a****, but for 29 September 2004.*

Figure 2a-2d shows the moments derived from continuous observations of MST radar in the zenith direction containing Signal to Noise Ratio (SNR, top panel), vertical velocity (w, middle panel) and Spectral width (SW, bottom panel) for the present case studies. The gaps in the **Figure 2** indicate that the radar is operated either in six beam mode or no data. Detailed information about 27th and 29th September 2004 events are explained in *Arunachalam et al.* (2014), 16-17 May 2007 event in *Dutta et al.* (2008) and 24 September 2008 event in *Radhakrishna et al.* (2010). The height profiles of vertical velocities are found to show maximum updrafts in the middle and upper tropospheric region which can be attributed to sublimation and condensate loading and peak downdrafts include blocking effect associated with precipitation in the mid-troposphere, indicating that the maximum latent heat is being released at these heights. These profiles are very important for numerical simulations of the convective systems which differ significantly from one geographic location to the other (*Kishore Kumar et al.*, 2005).

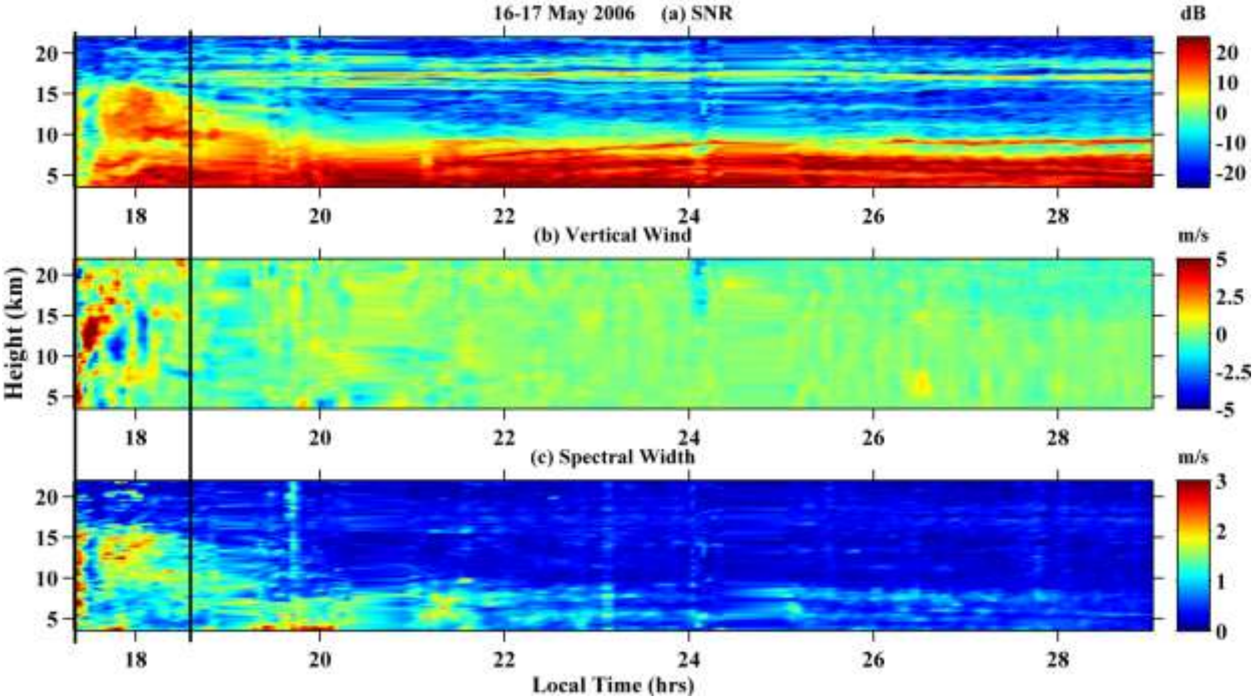

Figure 2c *Same as **Figure 2a**, but for 16-17 May 2006.*

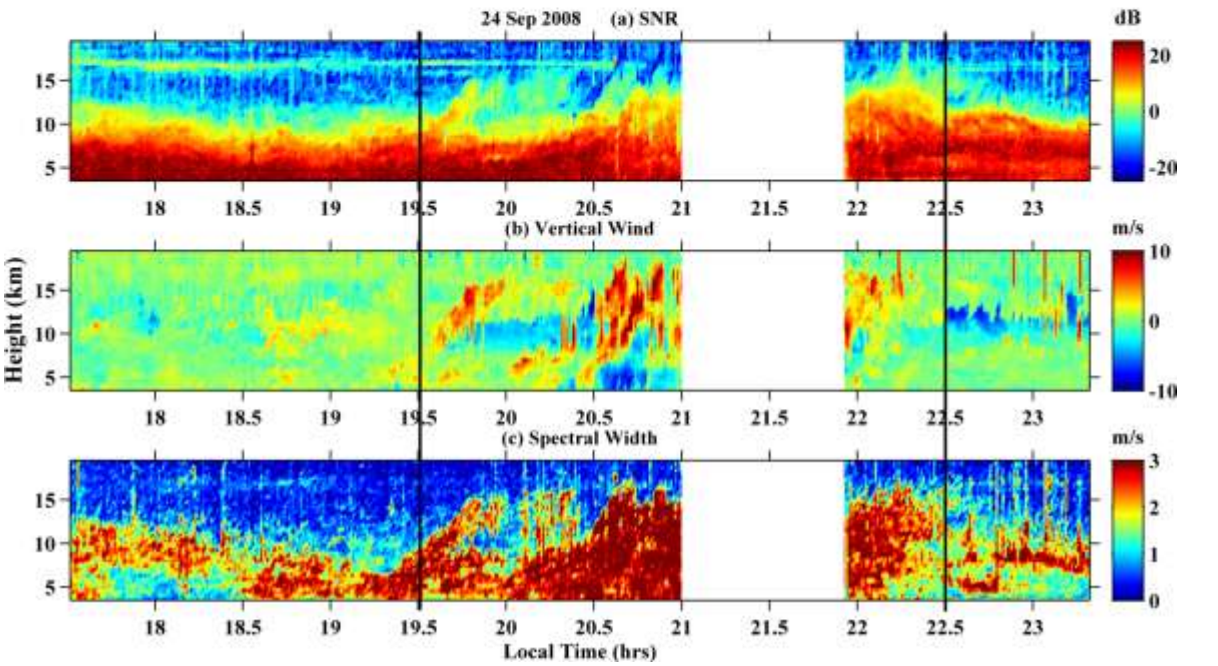

Figure 2d *Same as **Figure 2a**, but for 24 September 2008.*

For all the cases of the present observation, the atmosphere is associated with strong convective turbulence in the troposphere and the lower stratospheric region with maximum values of spectral width ~1.5-3.5 m/s. During the mature stage of the convective event i.e., at 16-18 hrs on 27 September 2004, ~9-10:30 hrs on 29 September 2004, ~17.5-18.5 hrs for 16-17 May 2006 and ~19.5-22.5 hr and on 28 September 2008, the SNR is found to be weak within ~8-16 km region, where the vertical velocities and spectrum width are found to be strong and are called as weak echo regions (WERs) which usually exist above the melting layer (*Kumar et al.*, 2005). Also, these WERs are found at the periphery of the updraft. This is because of most of the mixing of ambient air and cloud mass may take place at the outer regions of the strong updraft and hence, WER are found at this region. An important feature that can be observed from the **Figure 2** is that except on 27 September 2004, there exists convective overshooting for all the cases near the tropopause region, which is located at ~ 15.5-17 km as noticed with the help of radiosonde temperature profile from nearest station Chennai (13.0N, 80.1E), at a distance of 120 km from the radar site, indicates the presence of strong mass exchange between the troposphere and stratosphere.

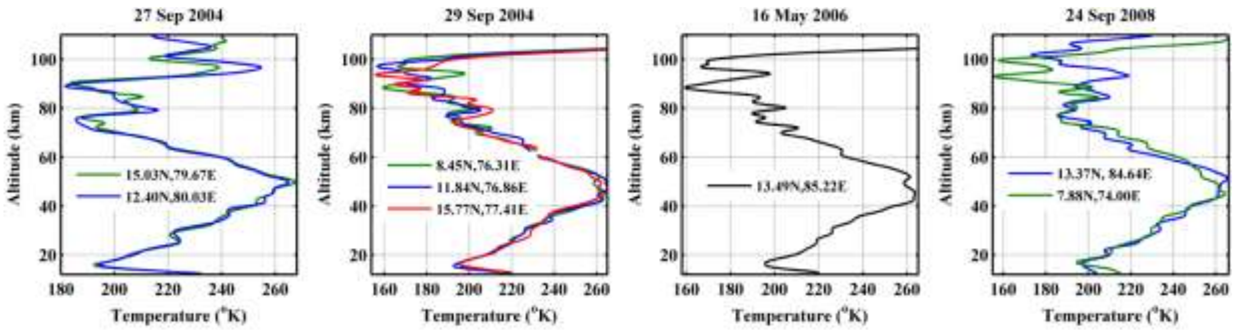

Figure 3 *SABER temperature (K) profiles corresponding to 27 September 2004, 29 September 2004, 16 May 2006 and 24 September 2008 for nearest grid region centering around Gadanki.*

There was a strong convective turbulence associated with shear especially above the convective cloud associated with strong vertical updrafts and downdrafts with a maximum of ±10 m/s on 24 September 2008, +16 m/s and -6 m/s during 16-17 May 2006, ±6 m/s on 29 September 2004 and ±4.5 m/s on 27 September 2004 (**Figure 2**). For all the events, there is a large scale cloud motion from east associated with strong low level wind shear and there is a cyclonic event over/near China region during 16-17 May 2006 and 24 September 2008. During all the case studies double stratopause and mesopause structures are noticed in and around Gadanki location as shown in **Figure 3**, which means that there was a significant momentum transport from the lower to middle atmosphere.

3.2 Wavelet analysis

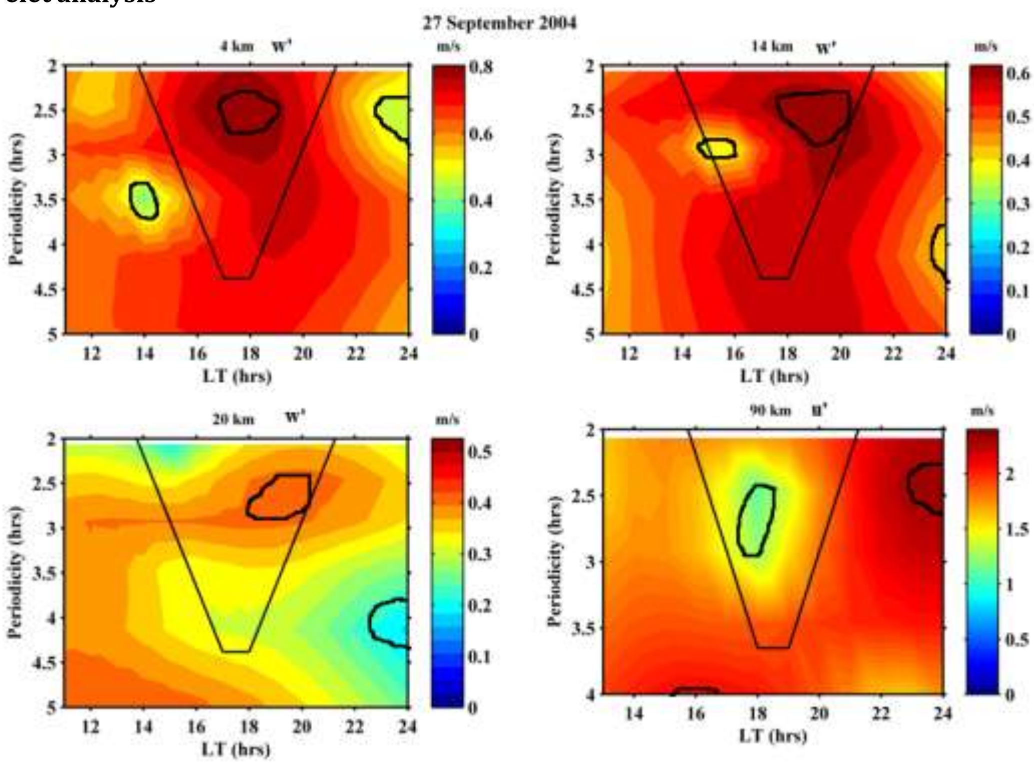

Figure 4a *WT of vertical wind (m/s) from Gadanki at 4 km, 14 km and 20 km, and zonalwind (m/s) at 90 km from Tirunelveli corresponding to 27 September 2004.*

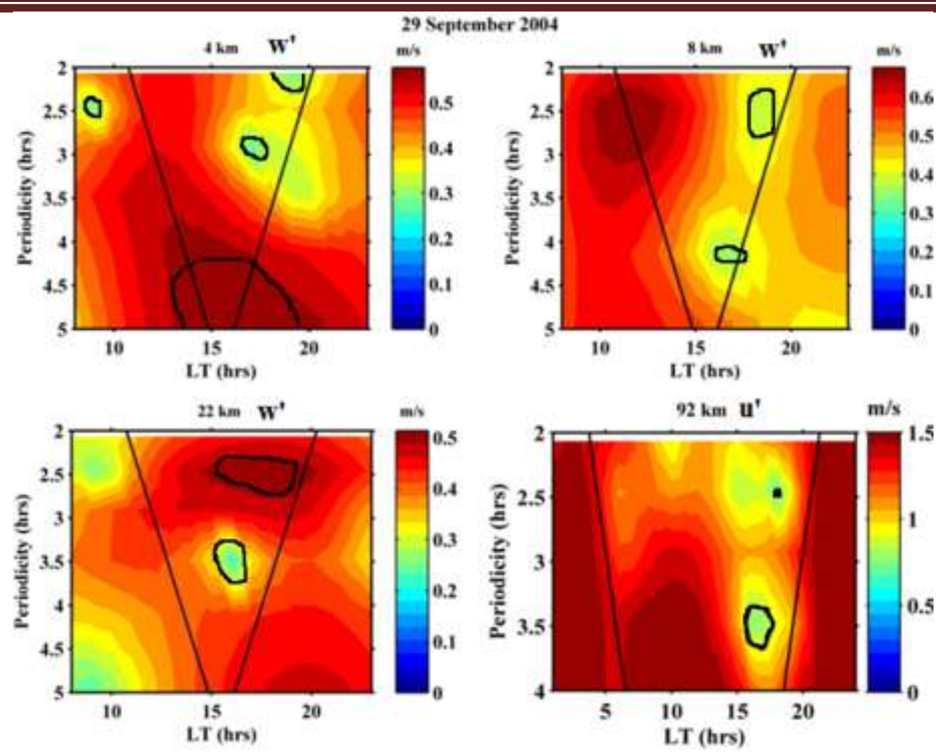

Figure 4b *WT of vertical wind (m/s) from Gadanki at 4 km, 8 km and 22 km, and zonal wind (m/s) at 92 km from Tirunelveli corresponding to 29 September 2004.*

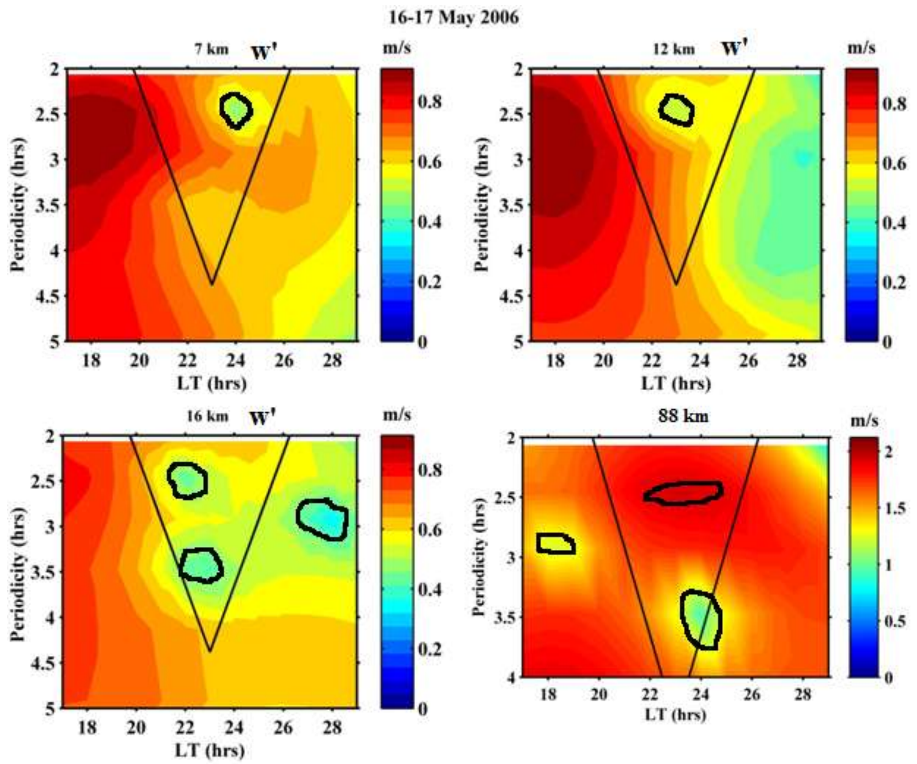

Figure 4c *WT of vertical wind (m/s) from Gadanki at 7 km, 12 km and 16 km, and zonal wind (m/s) at 88 km from Tirunelveli corresponding to 16-17 May 2006.*

In order to localize important modes of oscillation, Wavelet Transform (WT) analysis is employed in restricted intervals of the data series as in *Arunachalam et al.* (2014). Morlet wavelet is used as a mother wavelet to obtain dominant spectral components from the vertical wind fluctuations from MST Radar for the UTLS region and zonal wind fluctuation from MF radar for MLT region.

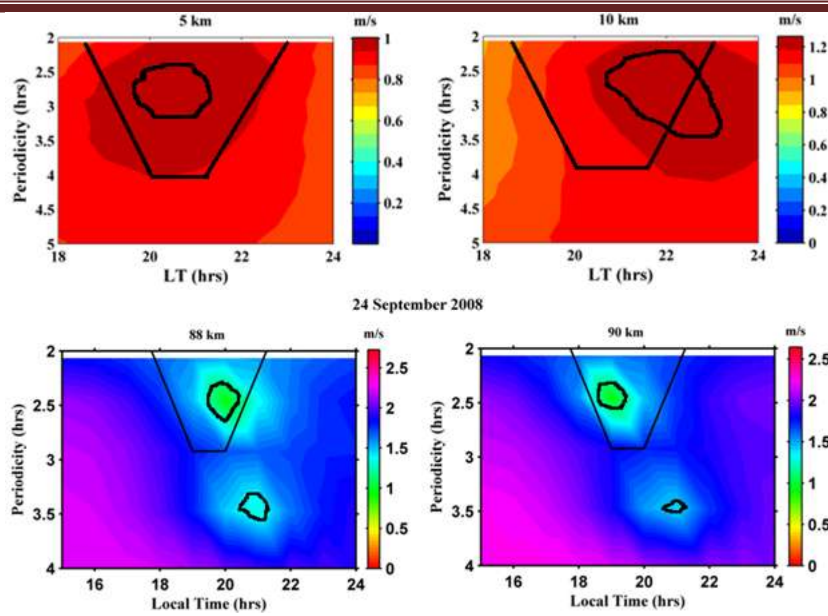

Figure 4d *WT of vertical wind (m/s) from Gadanki at 5 km and 10 km, and zonal wind (m/s) at 88 km and 90 km from Tirunelveli corresponding to 24 September 2008.*

Both the fluctuations show that there exists dominant 2-3 hr periodic oscillations both in UTLS as well as in the MLT region as shown in **Figure 4a-4d**, which means that, short-period gravity waves generated in the lower atmosphere are propagating into the middle and upper atmospheric altitudes with increase in phase speed and vertical wavelength (*Fritts and Alexander*, 2003).

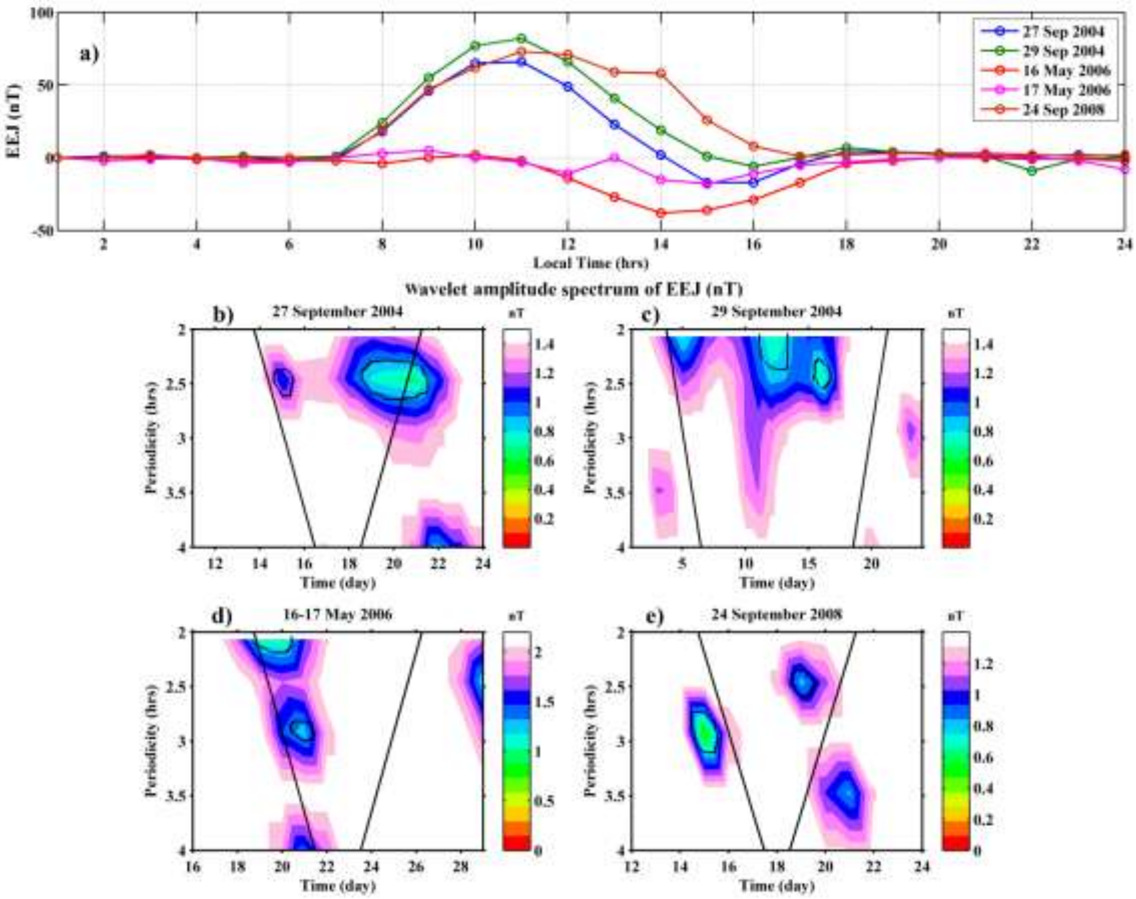

Figure 5 *(a) EEJ (nT) time series from Tirunelveli (top panel) and (b-e) correspondsto WT of EEJ (nT) for 27 September 2004, 29 September 2004, 16-17 May 2006and 24 September 2008.*

In addition to WT of vertical and zonal wind fluctuations, an attempt has been made to find the dominant oscillations in the ionospheric altitudes with the help of EEJ data. **Figure 5a** shows the hourly EEJ (nT) from Tirunelveli for all the case studies, among which 27 and 29 September 2004 has shown maximum EEJ strength between 9-12 Local Time (LT in hrs), 24 September 2008 has shown maximum EEJ strength between 9-14 LT, but for 16 and 17 May 2006 there is no maximum EEJ strength rather minimum is observed between 12-17 LT. The minimum EEJ strength of -38 nT observed on 16 May 2006 might be due to type I counter electro jet (CEJ) event and -18 nT observed on 17 September 2008 might be due to type II CEJ event. In their study during CEJ event *Somayajulu et al.* (1994) observed type II spectra with CEJ event intensity at about −10 nT in the presence of blanketing Es layers and type I spectra with CEJ event intensity between −35 and −40 nT in the absence of blanketing Es layers. The altitude of the echoing region was 95–100 km (in the presence of blanketing Es layers) during the observations of type II spectra and ranged from 100 to 108 km when type I waves were observed. WT of EEJ (**Figure 5b-5e**) for all the events show that ~2-3 hr periodic oscillations are also dominant in the ionospheric altitudes, which means that the short-period gravity waves generated in the lower atmosphere (source region) are propagating vertically up into the atmosphere.

3.3 2D FFT of Rayleigh Lidar Temperatures

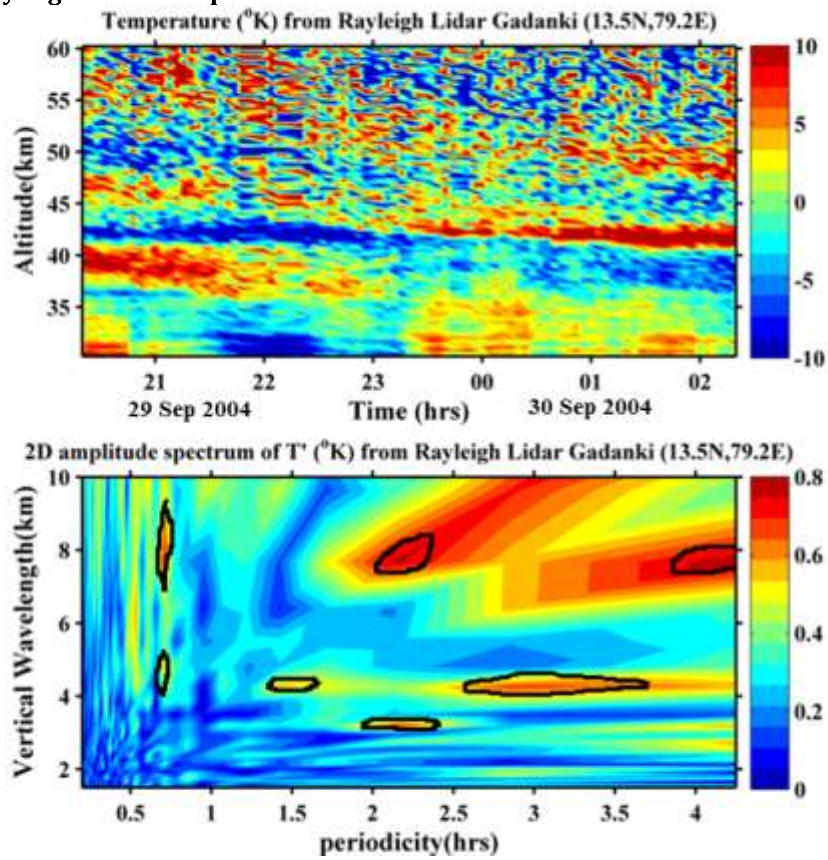

Figure 6 *Rayleigh Lidar temperature fluctuations (top) and corresponding 2D FFT (bottom) for periodicity (hrs) vs. vertical wavelength (km) on 29 September 2004.*

To find the presence of dominant oscillations corresponding to dominant vertical wavelength in the stratospheric region, high resolution (4 min. temporal and 300 m vertical resolution) temperature profiles in the stratospheric region (between 35 km to 65 km) for 29 September 2004 from Rayleigh Lidar located at Gadanki is subjected to two-dimensional Fast Fourier Transform analysis. From the **Figure 6**, it is clear that short-period gravity waves with periodicities 0.5-1 hr corresponding to vertical wavelengths of 4.2 km and 8 km, 1.5 hr periodicity with vertical wavelength of 4.2 km, 2-2.5 hr periodicities corresponding to vertical wavelengths of 3.2 km and 7.8 km, and 2.5-3.5 hr periodicity corresponding to 4.2 km vertical wavelength are found to be dominant showing 95% significance (black contours).

4 Summary and Conclusions

Using high resolution Indian MST radar, MF radar, and Lidar based observations, characteristics of vertically propagating convectively generated short period gravity waves associated with strong vertical velocities have been studied for the first time. Among all the convective events 16-17 May 2006 is found to be deep with TBB of ~185 K, with maximum (updraft) vertical velocity of 16 m/s and 24 September 2008 is also equivalently deep with TBB value of ~205 K, with maximum vertical updrafts and downdrafts of ~ ±10 m/s. In all the case studies, there exists strong vertical wind associated with WERs in SNR in the tropospheric region which results in the entrainment of the ambient air into the convective system, which lowers the mixing ratio as well as the temperature. The entrainment will be effective as long as the updrafts are intense. Thus, the present observations have shown that the strong updrafts in the convective systems are mainly responsible for the WERs (*Kumar et al.*, 2005). Also, all the events are double pause structures in stratopause and mesopause altitudes, which mean that there is a strong diffusion or momentum transport within the atmosphere at the pause regions.

WT analysis of vertical and zonal wind fluctuations clearly depicts that 2-3 hr short period gravity waves are dominant both in the UTLS and MLT region. 2D FFT of Rayleigh Lidar temperature fluctuations also show similar kind of oscillations with vertical wavelengths of ~ 4.2 km and ~7.6 km in the stratospheric region. Even though there exist short period oscillations other than 2-3 hr, in the present observation it is found that they are found to be limited to the stratospheric altitudes. During all the convective events, the EEJ strength is positive except for 16-17 May 2006, where it is negative, with 16 May 2006 corresponding to type-I CEJ event and 17 May 2006 corresponding to type-II CEJ event. Plausible reasons behind these CEJ events could be due to the presence of a negative electron density gradient during such events, which occur in the presence of blanketing Es layers and strong local shears in the E-region wind structures (*Somayajulu and Viswanathan*, 1987). From the WT of EEJ it is emphasized that ~ 2-3 hr periodic oscillations are also exist in the ionospheric altitudes. Hence, short period (2-3 hr) gravity waves generated in the lower atmosphere (troposphere) due to deep convective events are noticed to be propagating into the middle (stratosphere and mesosphere) and upper atmospheric (ionosphere) altitudes with an increase in phase speed and vertical wavelength thereby transporting energy (momentum) from (to) lower to (from) middle and upper atmospheric regions. For all the case studies the phase propagation is found to be downward leading to upward wave energy propagation.

It is now well known that gravity waves contribute significantly to the large-scale atmospheric circulation, especially in the mesosphere and lower thermosphere (MLT), because of the wave dissipation and the accompanying momentum flux divergence. So far, many studies have been reported the horizontal characteristics of the MLT gravity waves (such as wavelength, phase speed, and propagation direction) based on long-term radar and airglow observations at various latitudes (*e.g.,Suzuki et al.*, 2011; *Taori et al.*, 2012). The horizontal propagation structure of gravity waves in the airglow images sometimes give a useful hint to identify their wave sources, e.g., gravity waves observed as concentric rings that were generated by strong convective plumes located at the center of the rings in the troposphere (*Taylor and Hapgood*, 1988, *Suzuki et al.*, 2007a, *Yue et al.*, 2009). Similar cases, however, are not common. Generally, it is difficult to obtain a clear one-to-one correspondence between the wave sources in the lower atmosphere and the gravity waves in the MLT region.

Various numerical simulations of the generation and propagation of the gravity waves have been developed (e.g., *Piani et al.*, 2000; *Vadas and Fritts,* 2004; *Kimet al.*,2009). These simulations reproduced the existing results in which convectively triggered gravity waves in the troposphere reach the upper stratosphere and the MLT region. On the other hand, vertical gravity wave signatures up to the stratosphere were investigated using radiosonde and lidar observations (*e.g., Schoch et al.*, 2004; *Sato* and *Yoshiki*, 2008; *Yamashita et al.*, 2009). *Sato et al.* (1995) reported the stratospheric wind disturbances associated with gravity waves generated by cumulus convection using the middle and upper atmosphere (MU) radar observations. In their study they concluded that the gravity waves having short periods from a few minutes to a few hours associated with cumulus convection are considered to be important for transport of momentum and substances across the tropopause and emphasized the importance of short-period gravity waves in the tropical region where convective activity is strong. *Dhaka et al.* (2002) and *Kumar* (2006) have reported direct intrusions of tropospheric air into the lower stratosphere during gravity wave activity associated with convection.

Vertically propagating gravity waves are indeed the origin of the zonal drag (*Fritts,* 1989). Hence, it is essential to include the effects of gravity wave drag in models of middle atmospheric circulation. Gravity wave drag is particularly crucial in understanding the summer mesopause. However, observations of the vertical propagation of waves from the lower atmosphere into the MLT region are more limited. Even though, it is difficult to get both wind and temperature information simultaneously during the deep convective events from lower to middle and upper atmospheric altitudes, the present study is unique to explain about vertical propagation of gravity waves with the help of MST radar, MF radar, Rayleigh Lidar and EEJ datasets.

Acknowledgements

Author is very much thankful to Director, National Atmospheric Research Laboratory (NARL), Gadanki, India, Prof. S. Gurubaran, Equitorial Geomagnetic Research Laboratory (EGRL), Tirunelveli and Dr. S. Sridharan, NARL, Gadanki for providing necessary datasets to carry out the present work. Author is also thankful to UGC for providing SRF under UGC-BSR RFSMS.

References

1. Alexander, M. J., 1995: The gravity wave response above deep convection in a squall line
2. Simulation, *J. Atmos. Sci.*, 52, 2212–2226.
3. Alexander, M. J., 1996: A simulated spectrum of convectively generated gravity waves:
4. Propagation from the troposphere to the mesopause and effects on the middle atmosphere, *J. Geophys. Res.*, 101, 1571-1588.
5. Alexander, M. J. and Ortland, D. A., 2010: Equatorial waves in High Resolution
6. Dynamics Limb Sounder (HIRDLS) data, *J. Geophys. Res.*, 115, D24111.
7. Alexander, M. J. and K. H. Rosenlof, 2003: Gravity wave forcing in the stratosphere:
8. Observational constraints from the Upper Atmosphere Research Satellite and implications for parameterization in global models, *J. Geophys. Res.,*108.doi: 10.1029/2003JD003373.
9. Arkin, P. A. and Meisner, B. N., 1987: The relationship between large-scale convective
10. rainfall and cold cloud over the western hemisphere during 1982-1984, *Mon. Weather Rev.*, 115, 51-74.
11. Arunachalam Srinivasan, M., S. V. B. Rao, and R. Suresh, 2014: Investigation of convectively generated gravity wave characteristics and generation mechanisms during the passage of thunderstorm and squall line over Gadanki (13.5° N, 79.2° E), *Ann. Geophys.,* Vol. 32. No. 1. Copernicus GmbH.
12. Björn, L., 1984: The cold summer mesopause, *Adv. Space Res.*, 4, 145–151.
13. Butchart, and Coauthors, 2010: Chemistry-climate model simulations of 21st century
14. stratospheric climate and circulation changes, *J. Climate*, 23, 5349-5374.
15. Chen, S.S., R. A. Houze Jr., and B. E. Mapes, 1996: Multiscale variability of deep
16. convection in relation to large-scale circulation in TOGA COARE, *J. Atmos. Sci.*, 53, 1380-1409.
17. Dunkerton, T. J., 1997: The role of gravity waves in the quasi-biennial oscillation,
18. *J. Geophys. Res.*, 102, 26053–26076.
19. Dutta, G., T. Tsuda, P. V. Kumar, M. C. A. Kumar, S. P. Alexander and T. Kozu, 2008:
20. Seasonal variation of short-period (<2 h) gravity wave activity over Gadanki, India (13.5N, 79.2E), *J. Geophys. Res.*, 113, D14103, doi:10.1029/2007JD009178.
21. Dhaka, S. K., Choudhary, R. K., Malik, S., Shibagaki, Y., Yamanaka, M. D., Fukao, S.,
22. 2002: Observable signatures of a convectively generated wave field over the tropics using Indian MST radar at Gadanki (13.5°N, 79.2°E), *Geophys. Res. Lett.*, 29, 1872.
23. Ern, M., Ploeger, F., Preusse, P., Gille, J. C., Gray, L. J., Kalisch, S., Mlynczak, M. G.,
24. Russell III, J. M., and Riese, M., 2014: Interaction of gravity waves with the QBO: A satellite perspective, *J. Geophys. Res.*, 119, 2329–2355.
25. Ern, M. and Preusse, P., 2009: Wave fluxes of equatorial Kelvin waves and QBO zonal wind forcing derived from SABER and ECMWF temperature space-time spectra, *Atmos. Chem. Phys.*, 9, 3957–3986.
26. Ern, M., Preusse, P., Kalisch, S., Kaufmann, M., and Riese, M., 2013: Role of gravity waves in the forcing of quasi two-day waves in the mesosphere: An observational study, *J. Geophys. Res.-Atmos.*, 118, 3467–3485.
27. Evan, S., Alexander, M. J., and Dudhia, J., 2012: WRF simulations of convectively generated gravity waves in opposite QBO phases, *J. Geophys. Res.*, 117, D12117.
28. Fritts, D. C., Alexander, M. J., 2003: Gravity wave dynamics and effects in the middle
29. Atmosphere, *Rev. of Geophy.*, 41(1), 1003.
30. Fritts, D. C. and Vincent, R. A., 1987: Mesospheric momentum flux studies at Adelaide, Australia: observations and a gravity wave-tidal interaction model, *J. Atmos. Sci.*, 44, 605–619.
31. Fritts, D. C., 1989: A review of gravity wave saturation processes, effects, and variability
32. in the middle atmosphere, *Pure Appl.Geophys.*, 130, 343–371.
33. Garcia, R. R., and W. J. Randel, 2008: Acceleration of the Brewer–Dobson circulation due to increases in greenhouse gases, *J. Atmos. Sci.*, 65, 2731–2739.
34. Green, J., 1999: Atmospheric Dynamics, *Cambridge Atmospheric and Space Science*
35. *Series*, Cambridge University Press, 17 pg and 90 pg.
36. Kim, S.-Y., Chun, H.-Y., Wu, D. L., 2009: A study on stratospheric gravity waves generated by Typhoon Ewiniar: numerical simulations and satellite observations, *J. Geophys. Res.*, 114, D22104, http://dx.doi.org/10.1029/2009JD011971.
37. Kumar, K. K., J. Joseph, A. R. Jain, and D. N. Rao, 2005: VHF radar observations of weak echo regions in tropical

mesoscale convective systems, *Geophys. Res. Lett.*, 32, L10804, doi:10.1029/2004GL022238.
38. Kumar, K. K., 2006: VHF radar observations of convectively generated gravity waves:
39. Some new insights, *Geophys. Res. Lett.*, 33, L01815.
40. Li, F., J. Austin, and R. J. Wilson, 2008: The strength of the Brewer–Dobson circulation
41. in a changing climate: Coupled chemistry–climate model simulations, *J. Climate*, 21, 40–57.
42. Lindzen, R. S., 1981: Turbulence and Stress Owing to Gravity Wave and Tidal Breakdown,
43. *J. Geophys. Res.*, 86, 9707–9714.
44. Matsuno, T., 1982: A quasi one-dimensional model of the middle atmosphere circulation interacting with internal gravity waves, *J. Meteorol.Soc. Jpn.*, 60, 215–226.
45. McLandress, C., and T. G. Shepherd, 2009: Simulated anthropogenic changes in the Brewer–Dobson circulation, including its extension to high latitudes, *J. Climate*, 22, 1516–1540.
46. Piani, C., Durran, D., Alexander, M. J., Holton, J. R., 2000: A numerical study of three-
47. dimensional gravity waves triggered by deep tropical convection and their role in the dynamics of the QBO, *J. Atmos. Sci.*, 57, 3689–3702.
48. Plougonven, R., and F. Zhang, 2014: Internal gravity waves from atmospheric jets and
49. fronts, *Rev. Geophys.*, 52.
50. Radhakrishna, B.C.V., T. N. Rao, D. N. Rao, N. P. Rao, K. Nakamura, and A. K.
51. Sharma, 2009: Spatial and seasonal variability of raindrop size distributions in southeast India, *J. Geophys. Res.*, 114, D04203.
52. Sato, K., H. Hashiguchi, and S. Fukao, 1995: Gravity waves and turbulence associated
53. with cumulus convection observed with the UHF/VHF clear-air Doppler radars, *J. Geophys. Res.*, 100, 7111–7119
54. Sato, K., and Yoshiki, M., 2008: Gravity wave generation around the polar vortex in the
55. stratosphere revealed by 3-hourly radiosonde observations at Syowa Station, *J. Atmos. Sci.,* 65, 3719–3735.
56. Schoch, A., Baumgarten, G., Fritts, D.C., Hoffmann, P., Serafimovich, A., Wang, L.,
57. Dalin, P., Mullemann, A., Schmidlin, F.J., 2004: Gravity waves in the troposphere and stratosphere during the MaCWAVE/MIDAS summer rocket program, *Geophys. Res. Lett.*,31, L24S04, http://dx.doi.org/10.1029/2004GL019837.
58. Somayajulu, V. V. and Viswanathan, K. S., 1987: VHF Radar Observations During Equatorial Counter Electrojet Events, *Indian J. Radio Space Phys.*, 16, 380–383.
59. Somayajulu, V. V., Selvamurugan, R., Devasia, C. V., and Cherian, L., 1994: VHF Backscatter Radar Observations of Type-I Waves During a Counter Electrojet Event, *Geophys. Res. Lett.*, 21(18), 2047–2050.
60. Suzuki, S., Shiokawa, K., Otsuka, Y., Ogawa, T., Nakamura, K., Nakamura, T., 2007a: A concentric gravity wave structure in the mesospheric airglow images, *J. Geophys. Res.,* 112, D02102, http://dx.doi.org/10.1029/2005JD006558.
61. Suzuki, S., Tsutsumi, M., Palo, S.E., Ebihara, Y., Taguchi, M., Ejiri, M., 2011: Shortperiod gravity waves and ripples in the South Pole mesosphere, *J. Geophys. Res.*, 116, D19109, http://dx.doi.org/10.1029/2011JD015882.
62. Taori, A., Raizada, S., Ratnam, M. V., Tepley, C. A., Nath, D., and Jayaraman, A., 2012: Role of tropical convective cells in the observed middle atmospheric gravity wave properties from two distant low latitude stations. *Earth Sci. Res.*, 1(1), p87.
63. Taylor, M.J., Hapgood, M.A., 1988: Identification of a thunderstorm as a source of short period gravity waves in the upper atmospheric nightglow emissions, *Planetary Space Science*, 36, 975–985.
64. Vadas, S.L., and Fritts, D.C., 2004: Thermospheric responses to gravity waves arising
65. from mesoscale convective complexes. *J. Atmos. Sol. Terr. Phys.*, 66, 781–804.
66. Yamashita, C., Chu, X., Liu, H.-L., Espy, P.J., Nott, G.J., Huang, W., 2009: Stratospheric
67. gravity wave characteristics and seasonal variations observed by lidar at the South Pole and Rothera, Antarctica, *J. Geophys. Res.*, 114, D12101.
68. http://dx.doi.org/10.1029/2008JD011472.
69. Yigit, E., and Medvedev, A. S. 2014: Internal wave coupling processes in Earth's
70. Atmosphere, *Adv. Space Res.,* 55, 983–1003.
71. Yue, J., Vadas, S.L., She, C.-Y., Nakamura, T., Reising, S.C., Liu, H.-L., Stamus, P., Krueger, D.A., Lyons, W., Li, T., 2009: Concentric gravity waves in the mesosphere generated by deep convective plumes in the lower atmosphere near Fort Collins, Colorado, *J. Geophys. Res.,* 114, D06104, http://dx.doi.org/10.1029/2008JD011244.