1
2 **Medium frequency gravity wave characteristics obtained using Weather Research and**
3 **Forecasting (WRF) model simulations**

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10 **Abstract**

11 Many studies have reported the characteristics of wide spectrum of Gravity Wave
12 (GW) using radiosonde, MST Radar, Lidar and other observations. In this study, we made an
13 attempt to obtain the characteristics of medium frequency GWs over a tropical station
14 Gadanki (13.5°N and 79.2°E) using the Weather Research and Forecasting (WRF) model
15 simulations for the period 2006-2017. Prior to GWs analysis, we have validated the model
16 outputs with radiosonde measurements over Gadanki to check the performance of the model
17 in capturing the realistic features as seen in the observations. Profiles of horizontal winds and
18 temperature are validated and the results of statistical analysis indicate that there is a good
19 correspondence between the WRF model simulations and the radiosonde measurements. The
20 FFT and wavelet analysis on the winds revealed the spectrum of waves. The band pass
21 filtered wind perturbations showed clear downward phase propagation with the dominant
22 periods 2-5 hours. The observed vertical and horizontal wave lengths are in the range of 6-8
23 km (3-8 km) and 100-200 km (100-500 km) in the troposphere (stratosphere), respectively.
24 These characteristics match well with those reported from the same location using MST radar
25 and radiosonde observations. Further, the long-term features like semi-annual oscillation,
26 annual oscillation and quasi-biannual oscillations are also simulated very well in the WRF
27 outputs. These results show the model's ability to simulate near realistic features as seen the

observations and can also be used to supplement the missing observations with errors limits as its uncertainty.

Key words: Gravity waves, WRF model simulations, long-period oscillations

1. Introduction

Gravity Waves (GWs) have occupied a crucial role in the current atmospheric research due to their myriad effects in atmospheric structure and dynamics. Impact of GWs on the middle atmospheric energy budget has become one of the most intriguing topics in the current scenario as they play a critical role in altering the thermo-dynamical structure of the middle-atmosphere (Fritts and Vincent, 1987; Wilson et al., 1990). Generally these waves are generated in the lower atmosphere due to mesoscale disturbances like convection, wind shear, orography, etc. They propagate to upper atmosphere and transport significant energy and momentum, which affect the general circulation of the coupled atmospheric regions (Holton, 1983; Krishna Murthy et al., 2002; Fritts and Alexander, 2003; Kim et al., 2003). Several studies reported that breaking of GWs in the middle atmosphere causes momentum flux deposition which induces mean flow acceleration/deceleration (Li et al., 2005; Antonita et al., 2007). Many studies (Dunkerton, 1997; Sato and Dunkerton, 1997; Baldwin et al., 2001) reveal that the GWs are one of the major contributors for driving and modifying large scale middle atmospheric variability such as semi-annual oscillation (SAO), annual oscillation (AO), quasi-biennial oscillation (QBO), etc.

Ground based instruments can provide measurements with very good temporal and vertical resolution, however, most of these measurements are limited to the a point, while satellite observations are useful for studying spatial distribution of GWs but the major constraint arise from its poor vertical and temporal resolutions. Construction of long-term climatological data of GWs and the analysis of these waves is extremely important to understand the persistent dynamical processes associated with GWs. Several observational

studies are made on the GW generation, their sources and its impact on the structure of the atmosphere (Kumar et al., 2006; 2007, Dhaka et al., 2002, Venkat Ratnam et al., 2008; Leena et al., 2012a,b; Pramitha et al., 2015; 2016) using long-term measurements over the Indian region particularly over Gadanki, though these studies have been constrained to over a single point because of the observational limitations. Studies have also shown that parameterization of GW drag is required in large scale numerical models for realistic simulations of the middle atmospheric circulation (Holton, 1983). For this parameterization, parameters related to wave characteristics are needed which can be determined from observations. Unfortunately, high resolution data of different temporal scales are very sparse particularly in the tropics. Thus, climatology of GWs including their complete spectrum is an important aspect in understanding their role in atmospheric phenomena in the tropics which remained as a constraint so far.

In recent times, numerical weather prediction (NWP) models have proven their skill in simulating the realistic features of the GWs and background atmosphere during passage of cyclone or thunderstorm/convection (Kuester et al., 2008; Chane Ming et al., 2014; Hima Bindu et al., 2016 etc). Many studies (Alexander and Rosenlof 2003; Kim et al., 2003; Preusse et al., 2014) showed the use of the global NWP models products for capturing the presence of GWs and analysis of the wave characteristics, though these models have inherent numerical stability constraints to damp the evolution of the GWs (Hedlin, and Drob, 2014). However, because the spatial and temporal scales of these atmospheric GWs are too small compared to the grid size of global model, the sub-grid scale processes such as the interaction of GWs are neither completely represented in the form of parameterization nor resolved fully in the global models. Several studies have reported that the Weather Research and Forecasting (WRF) mesoscale model was able to capture the GWs which compare well with the radar measurements (Valkonen et al., 2010; Udina et al., 2013; Kirkwood et al., 2010;

Ghosh et al., 2016). However, only a few studies exist on high or medium frequency GW characteristics from WRF model simulations (Evan et al., 2012; Rechou et al., 2013; Costantino et al., 2015; Kruse et al., 2016; Gisinger et al., 2017). In the present study, we show for the first time over Indian region that WRF model simulations can be used for the long term study of high and mid frequency GWs. The obtained periods and wave lengths of these GWs are compared with the previous studies made using radar, radiosonde and lidars. The present paper is organized in the following way: the data base and the model description used for the present study is provided in section 2 while section 3 details the validation of model results with observed data and the conclusions given in Section 4.

2. Data and Methodology

In this section, a brief description of the observational datasets is provided along with details of the WRF model configuration, model design and the simulation methodology.

2.1. WRF model and its configuration

A high-resolution regional climate reanalysis dataset has been generated for the Indian sub-continent from 2006-2017 using the Advanced WRF model. The model simulations are performed in consecutive integration method with daily initializations making use of WRF two-way nested domains configuration of 18 km and 6 km resolutions with 51 vertical levels. Figure 1 shows the model domains used in Advanced Weather Research and Forecasting (ARW) for the present simulation along with the terrain height. Location of Gadanki is also shown in this figure. Model physics used in the study are chosen based on the previous studies over Indian regions (Srinivas et al., 2013; Srinivas et al., 2015; Madala et al., 2016). For boundary layer processes, Yonsei University's non-local diffusion scheme (Hong et al., 2006) is used. The Kain-Fritsch scheme is used for cumulus convection (Kain and Fritsch, 1993). The WRF Single-Moment 3-class (WSM3) is used for microphysical processes. The Noah land surface scheme (Chen and Dudhia, 2001) for surface processes,

Rapid Radiation Transfer Model (RRTM) for long-wave radiation (Mlawer et al., 1997), and the Dudhia (1989) scheme for short-wave radiation. The initial and boundary conditions are obtained from ECMWF ERA-Interim 6-hourly data. To improve the land-sea contrast and simulation of wind over coastal regions, we have replaced the coarse-resolution sea surface temperature (SST) obtained from ERA-Interim data with time-varying high-resolution SST obtained from the Real-Time Global High-Resolution (RTG-HR) (Gemmill et al., 2007).

For the present study, the WRF model is initialized on daily basis at 12 UTC using ECMWF ERA-Interim, and integrated for the complete 24-hour period. Note that the model datasets from 2006 to 2017 are only used for the present study based on the availability of GPS radiosonde data. To find out whether the mesoscale weather models are able to simulate realistic profiles of the atmosphere, the profile information from the GPS radiosonde data over Gadanki has been considered during 2006 and 2017 as benchmark observations to validate the high-resolution climate reanalysis dataset generated using ARW model.

2.2. GPS Radiosonde Observations

High resolution GPS Radiosondes (Väisälä RS-80 (April 2006 to March 2007), RS-92 (July to August 2006), Meisei RD-06G (May 2007 to January 2014), Meisei RD-11G (February 2014 to December 2015), Meisei RS-11G (January 2016 to December 2016) and Meisei iMS-100 (January 2017 to December 2017) were launched daily around 1730 IST (IST = UT+0530h) at Gadanki. Note that there is not much difference in the quality of the radiosonde instruments of different makes/agencies. However, there is a difference in the sampling time and altitude resolutions. For Väisälä RS-80 it is 25-30 m (sampled at 5-s intervals) whereas for the other two radiosondes it is 10 m (sampled at 1-s intervals). The radiosonde data set spans over the 12 years and there are minor gaps in the years 2006, 2007, and 2013 which do not affect the present study. The average ascent rate of these sondes is about 5 m/s and they attained at an altitude of 28 km. These data are interpolated to 100 m

vertical sampling so as to remove outliers that are occurring due to random motions of the balloon. The radiosonde ascent rate of ~ 5 m/s with 100 m altitude resolution is equivalent to 20 s in time. Details of this radiosonde system, data base and quality checks applied to the data are reported in Mehta et al. (2011) and Venkat Ratnam et al. (2014).

3. Results

3.1. Comparison of background atmospheric conditions

For the present study, seasons are divided as Pre-monsoon (March, April and May, MAM), monsoon (June, July and August, JJA), Post-monsoon (September, October and November, SON) and winter (December, January and February) based on the background conditions of the atmosphere prevailing over the Indian region. The meteorological parameters from the GPS radiosonde observations and WRF model are used to compute monthly means, seasonal, annual, and inter-annual variations.

The time height profiles of monthly mean zonal wind, meridional wind and temperature obtained from both WRF and radiosonde over Gadanki are shown in Figure 2. During monsoon season (JJA), both the data sets show the easterly winds with a magnitude of 30 m/s in the height region of 16-22 km and westerly with a magnitude of 7-8 m/s below 8 km indicating the presence of easterly jet and westerly winds of Indian Summer Monsoon origin as discussed by Venkat Ratnam et al. (2008). The zonal wind is easterly from surface up to height of 5-6 km, westerly in between the heights of 10-20 during the winter and pre-monsoon seasons with the wind speeds in the range of 12-14 m/s indicating the prevalence of north-easterly winds as well as sub-tropical westerly jet in winter months. Also the easterly winds in winter monsoon season are stronger than the westerly winds during summer monsoon since the study region partly comes under rain shadow regions of south-west monsoon.

The strengths of meridional winds are smaller than zonal winds and are northerly with a magnitude of ~ 7 m/s around 13-15 km during the monsoon season and southerly during the winter with a peak velocity of ~ 9 m/s. The sensitivity of temperature with respect to the season is clearly visible in the boundary layer region (< 3 km) with peak temperature observed from April to June. However, temperatures do not show any significant variations at upper level with season. Hence, these observed features of the radiosonde are well captured by model suggesting that WRF model could able to simulate the background atmospheric parameters. In addition, the time-height profiles of winds by both radiosonde and WRF model during 2006 to 2017 shows strong intra-seasonal and inter-annual variability in the lower and upper troposphere.

In Figure 3, the difference between the monthly means of radiosonde observations and WRF model outputs are shown. The differences between the observed and model simulated monthly mean of horizontal winds (Figures 3 a & b) are found to be 5 m/s in the height region of 15-20 km altitude and difference in the temperature (Figure 3 c) is in the range of 2-3 K. Neglecting the variations in wind due to the drift of radiosonde, the WRF model results at Gadanki underestimates the intensity of easterly jet and overestimates the winds of subtropical westerly jet between the heights 12 and 20-km.

Temperatures are underestimated (< 2 K) during summer and overestimated during winter. Surface winds are overestimated in the model simulation. The slight overestimation of winds at surface has been reported by Srinivas et al. (2013) and attributed to the model tendency to simulate higher differences between the heat low and Mascarene high, resulting in higher gradients in pressure and winds. At rest of the altitudes, particularly in the troposphere, the differences are too small, suggesting that the WRF model is able to simulate the realistic features of the background meteorological parameters of the atmosphere.

The seasonal mean root mean square error (RMSE) computed for the daily profiles of temperature, zonal and meridional wind over Gadanki between the radiosonde and WRF model simulations during 2006 to 2017 are shown in Figure 4. The RMSE profiles over Gadanki clearly suggest that the model exhibits different skills based on the season, found to be high at surface as well the jet regions of easterly and westerlies during monsoon and post-monsoon seasons. During the pre-monsoon season, the RMSE in the zonal wind shows an error of 1-2 m/s from the surface to 30 km altitude, whereas in the meridional wind the RMSE of 1-2 m/s is found except near the tropopause where it is ~ 3 m/s. The RMSE in the zonal wind during the monsoon is found to be 1-3 m/s which reach ~ 6 m/s in the lower stratosphere (LS) region. These variations could be both due to the overestimation of simulated wind in the low level and upper tropospheric jets as well due to the model differences in simulating the actual height of jet. During monsoon, meridional wind exhibits an error of 0.5-1.5 m/s except near the tropopause and LS region where it reaches 3 m/s. During the post-monsoon season, the horizontal winds show 1-3 m/s error and during winter the RMSE in zonal (meridional) wind shows 1-2 m/s (1-3 m/s). Over all, the RMSE in the zonal and meridional winds climatologically vary between 1 and 3 m/s. During all the seasons, the RMSE in the temperature varies in the range of 0.5-2.5 K. It is found to be maximum at surface and core jet regions of easterly and westerlies. The climatological mean RMSE for the simulated temperature shows ± 0.75 K which is very small, suggesting model exhibits good skill in reproducing the seasonal variation of temperature. In general, maximum RMSE in the zonal and meridional winds (temperature) of 3 m/s (0.5 K) is found which confirms that the WRF model produces near realistic features of the atmosphere over Gadanki.

3.2. Long-term oscillations in the WRF model simulations and observations

In the lower atmosphere, both the zonal and meridional winds exhibit the variations at annual and inter annual time scales. However, the oscillations observed in the middle atmosphere such as Annual Oscillation (AO) and Quasi-biennial Oscillation (QBO) which have the time period of 12 and 24 months, respectively. As far QBO is concerned, it is an east-west oscillation of the equatorial zonal wind in the stratosphere characterized by an irregular period of 28 to 29 months (it can vary from 24 to 36 months). Figure 5 shows the Lomb Scargle Periodogram (LSP) (Vanderplas et al., 2017) analysis of monthly mean data of zonal wind, meridional wind and temperature for the complete time series (2006-2017) for the radiosonde observations and WRF model simulations at 15 km and 24 km altitudes. Horizontal lines indicate 90% confidence level. The periodogram of zonal wind shows the first dominant periodicity at ~1 year i.e., AO and the second dominant peak found at about ~2 year 4 months (QBO) at 24 km altitude. Both the LSPs for the radiosonde and WRF model simulations show similar variability. LSP for meridional wind and temperature shows the dominant AO though the amplitude in the WRF model is larger in the meridional wind. In the temperature, both WRF and radiosonde observations are again well matched. Similar analysis is made for all altitudes such as 10, 12, 16, 18, 20, 22 km and similar significant features are observed (figures not shown). In general, very good agreement is observed between these two independent data sets suggesting that the WRF model simulated outputs are accurate enough to study the broad spectrum of wave/oscillations in the atmosphere.

Figure 6 (a & b) shows the time-height section of FFT analysis of monthly mean zonal wind and meridional wind applied to the radiosonde observations obtained over Gadanki during 2006-2017. Zonal wind shows the dominant AO and QBO oscillation with the magnitude of 10 m/s in the lower stratosphere with the mean period of 28-29 months. Dominant AO is observed in the meridional wind component with the maximum amplitude

of about 2 m/s. SAO is also observed in both the zonal and meridional wind components but is less significant in the zonal wind when compared to the meridional wind.

Similarly, the monthly mean wind profiles from WRF model simulations are subjected to the FFT analysis to find out the dominant oscillations (Figure 6 c & d). The FFT analysis of zonal wind suggests that the dominant AO from the surface to lower stratospheric region with maximum amplitude of 10 m/s and QBO with a mean period of 28 to 29 months in the tropical lower stratosphere over Gadanki. SAO is also observed in the zonal wind with a small magnitude. The time series of FFT for meridional wind shows the AO with maximum amplitude of 2 m/s, whereas temperature does not show any significant variation. Signature of SAO is also observed in the meridional wind. Thus, the general features of WRF model matches well with the in-situ radiosonde observations (Figure 6) over Gadanki and it is clear that the model could able to produce the long period features such as SAO, AO and QBO, which plays a crucial role in driving the middle atmospheric dynamics.

To get further insight on the short period GWs as they are having periods from few minutes to few hours, the hourly data of the simulated parameters such as zonal, meridional, vertical winds and temperature from the WRF model simulations are subjected to the FFT analysis. Figure 7(a) shows the time-height section of the FFT analysis of vertical wind obtained from WRF model simulations over Gadanki during 01-05 January 2006 (i.e., first 120 hours of this FFT spectrum to show the short period waves). The vertical wind shows dominant short period waves ranging from an hour to 5 hours with 0.01 m/s amplitude in the Upper Troposphere and Lower Stratosphere (UTLS) region. The results also confirm the earlier findings that vertical wind is a best observational parameter to extract GWs from the WRF model simulations (Choi et al., 2006; Hima Bindu et al., 2016). Apart from the GWs, tidal components are also clearly observed in all the three wind components (figure not

shown) which again confirm the model ability in simulating both the small scale wave features and tidal oscillations.

3.3. Wavelet spectra of winds in WRF model

In order to investigate the dominant periods that are associated with short period waves, the time evolution of power spectra and Morlet wavelet analysis (Torrence and Compo, 1998) have been carried for the zonal, meridional and vertical wind velocity fluctuations at 24 km during the study period (2006-2017). However the wavelet analysis of vertical wind is only shown in Figure 7(b). The thick red coloured contours represent 95% confidence level which is statistically significant.

The vertical wind perturbations clearly show the existence of high frequency waves with the period starting from an hour. It is observed that most of the dominant periods of waves are observed during monsoon with maximum amplitudes in each year. Similar significant wave features are observed at other altitudes also (figures not shown). Tides and planetary waves also can be clearly observed from the figure. The low frequency wave activity is observed at lower altitudes and when it comes to the higher altitudes they might be filtered by the background wind. From the Figure 7 (a & b), it is clear that WRF model simulations can observe the dominant short period waves in the UTLS region.

3.4. High/medium frequency gravity wave characteristics from the WRF simulation

To obtain the characteristics of the short period waves over Gadanki, the time series of all the three wind perturbation components from the WRF model are subjected to the band pass filter for the entire study period (i.e., 2006-2017). The minimum and maximum limits kept for the filter are 2 and 5 hours, respectively. Figure 8 shows the time-height section of band pass filtered zonal wind, meridional wind and vertical wind perturbations over Gadanki during 2006-2017. Alternative positive and negative perturbations of amplitudes of about ± 2 m/s and ± 0.1 m/s are observed in horizontal and vertical winds, respectively, in the

275 troposphere and lower stratosphere, especially in the vertical wind component. The band pass
276 filtered wind perturbations showed clear downward phase propagation (upward propagating
277 waves especially in the vertical wind component) with the dominant periods 2-5 hours in the
278 UTLS region. The zoomed portion in-region with the small subset of data has been shown
279 taken for on 04th July 2007 in for Figure 8c to show the phase propagation of these GWs.
280 Strong seasonal variation is also simulated in these waves with maximum during monsoon
281 season.

282 In order to obtain the other characteristics of these high frequency waves from the
283 WRF model, the 2-5 hours band pass filtered zonal, meridional and vertical wind parameters
284 are subjected to FFT analysis in vertical to obtain dominant vertical wavelengths. The
285 obtained range of vertical wavelengths is shown with the box plot for all the three wind
286 velocities in Figure 9. The vertical wavelengths range from the 0.5 to 16 km altitude
287 (troposphere). The dominant vertical wavelengths ranging from 6-8 km (3-8 km) can be
288 noticed in the troposphere (stratosphere) from Figure 9. Horizontal wavelengths are obtained
289 from the dispersion relation. They range from 100-200 km (100-500 km) in the troposphere
290 (lower stratosphere). The above obtained wave parameters show good agreement with the
291 earlier study on the high frequency GWs over the present study region made by Leena et al.
292 (2012a) ('vertical wavelengths ranging from 6-12 km (3-7 km) and horizontal wavelengths
293 ranging from 100-300 km (100-500 km) in the troposphere and (lower stratosphere)
294 respectively '). Note that the height resolution in the troposphere and stratosphere for the
295 present study is 0.5 km and 1 km, respectively. The other parameters like direction of
296 propagation, energy and momentum flux, etc of these waves needs to be addressed as
297 previous studies (Wagner et al., 2017 and Kruse et al., 2017). Thus, WRF model outputs can
298 simulate the high/medium frequency GW characteristics and these wave characteristics agree

well with the previous studies performed with radiosonde and MST radar observations over Gadanki.

A high-resolution 2-km regional climate reanalysis dataset has been generated for the Indian sub-continent from 1980-2017 using the Advanced Weather Research Forecasting (WRF) model to show the long term variation of high/medium frequency GWs. 2- 5 hrs bandpass filtered vertical wind variance at 15km altitude along with 13-point running mean is shown in Figure 10a. After smoothening, the vertical wind shows the clear increase in the amplitude during monsoon season every year. Monthly mean variance averaged during 1980 to 2017 shown in Figure 10b further confirmed its enhancement in monsoon season and there exists large inter-annual variation (standard deviations).

4. Summary and Conclusions

WRF model simulated outputs are validated with the independent radiosonde observations over a tropical station Gadanki (13.5°N and 79.2°E) for the first time to check whether WRF model is able to simulate the observed features or not. The model simulations are performed with two-way nested domains with horizontal resolutions of 18 km and 6 km and initial and boundary conditions obtained from ECMWF ERA-Interim 6-hourly data. The model outputs are obtained with hourly temporal resolution. These outputs are validated using independent radiosonde observations which have not gone into any of the reanalysis data sets. From the detailed validation, it is confirmed that the WRF model is able to simulate the realistic features of the background meteorological conditions over Gadanki. Seasonal and climatological RMSE in the horizontal winds and temperature shows the maximum error of 3 m/s and 0.5°K, respectively, which indicates that WRF model simulation could able to simulate the near realistic features over Gadanki. The WRF model is also able to simulate the long-period oscillations like semi-annual oscillation (SAO), annual oscillation (AO) in both zonal and meridional winds and are in good agreement with the radiosonde observations.

Quasi biennial oscillation (QBO) in the zonal component is also well reproduced in both the observations and model simulations. With this analysis, it is clear that WRF model simulation is proved to be a useful numerical model for obtaining the atmospheric background conditions.

GWs are major contributors to these long term oscillations. Wavelet spectra of winds especially vertical winds revealed a prominent oscillation in the period of an hour to 7 hours in the UTLS region. Hourly winds from the WRF model especially vertical wind velocity show dominant 2-5 hours of medium frequency GWs in UTLS region. Strong seasonal variation is also observed in these GWs with maximum during monsoon season. The dominant vertical and horizontal wavelengths ranging from 6-8 km (3-8 km) and 100-200 (100-500) km in the troposphere (stratosphere), respectively. Long term variation of 2-5 hrs filtered high/medium frequency GWs from the long term regional climate reanalysis data set (1980-2017) also shows the strong seasonal variation with maximum during monsoon season.

There are many observational studies which have shown the seasonal behaviour of GWs over Gadanki from short period to inertial period (Antonita et al., 2007, Debashis Nath et al., 2009, Guharay et al., 2011, Leena et al., 2012a and b, Pramitha et al., 2016, and references therein) using Gadanki radiosonde, lidar, MST Radar observations. However, the comparison of WRF model simulated output results with the radiosonde observations and validation of these results with the previous published results are quite unique and they show the model's capability to simulate the near real features of the background atmosphere. In conclusion, WRF model simulations can be effectively used for the study of medium frequency GWs, and these obtained GW parameters made a good agreement with the earlier study on the high and medium frequency GWs over the present study region made by Leena et al. (2012a). Thus, characteristics of medium frequency GWs obtained using WRF model simulated output can be used in absence of observations.

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Figures

Figure 1. Model domains used in ARW for the present simulation. The shading gives the terrain height in meters. Inner star (red colored) shows the location of Gadanki.

Figure 3. Time-height variation of monthly mean difference in the (a) zonal wind, (b) meridional wind, and (c) temperature between WRF model simulation and Gadanki radiosonde observations during 2006-2017.

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543 **Figure 4.** Root mean square error (RMSE) observed between the daily radiosonde
 544 observations and WRF simulations during different seasons in the (a) zonal wind, (b)
 545 meridional wind and (c) temperature during 2006-2017 over Gadanki.

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550 **Figure 5.** Lomb Scargle Periodogram (LSP) analysis of monthly mean (a & b) zonal wind,
551 (c & d) meridional wind and (e & f) temperature for the complete time series (2006-2017,
552 12 years) for radiosonde observations (red line) and WRF model simulations (blue line) at
553 15 and 24 km altitude respectively. Horizontal lines indicate 90% confidence level.

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Figure 6. Time-height section of FFT spectral analysis of monthly mean (a & c) zonal wind, (b & d) Meridional wind obtained from radiosonde observations (top two panels) and WRF simulations (bottom two panels) respectively over Gadanki during 2006-2017.

Figure 7. (a) Time-height section of FFT spectral analysis of vertical wind over Gadanki during 01-05 January 2006 and (b) Wavelet spectra of vertical wind perturbations at 24km altitude over Gadanki during 2006-2017 obtained from the WRF model simulations.

Figure 8. Time-height section of 2-5 hours band pass filtered (a) zonal wind, (b) meridional wind and (c) vertical wind over Gadanki obtained from the WRF simulation during 2006-2017. (d) The Zoomed portion observed on 4 July 2017 in region is shown for in the vertical wind perturbations (e).

Figure 9. Box plot showing the dominant vertical wavelengths in the troposphere (0.5 to 16km) and stratosphere (16-27km) obtained from the WRF model. (a& d), (b & e) and (c & f) are zonal, meridional and vertical winds in the troposphere and stratosphere, respectively. Top and bottom x is the 99% and 1% confidence levels, whiskers show maximum and minimum values and solid box is the mean value.

Figure 10. (a) Monthly mean variation of 2 -5 hrs bandpass filtered vertical wind at 15km altitude. A 13-point running mean is also shown (black line) from 1980 to 2017. (b)

599 Monthly mean 2-5 hrs bandpass filtered variance in the vertical wind averaged during
600 1980 to 2017. Vertical bars show the standard deviation.
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Medium frequency gravity wave characteristics obtained using Weather Research and Forecasting (WRF) model simulations

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Highlights

- An attempt is made to obtain the characteristics of medium frequency GWs using the WRF model simulations for the period 2006-2017.
- Validated the model outputs with radiosonde measurements to check the performance of the model in capturing the realistic features.
- The band pass filtered wind perturbations showed clear downward phase propagation with the dominant periods 2-5 hours.
- Observed that the model is able to simulate near realistic features and can be used at times observations are not available.

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2 **Medium frequency gravity wave characteristics obtained using Weather Research and**
3 **Forecasting (WRF) model simulations**

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9

10 **Abstract**

11 Many studies have reported the characteristics of wide spectrum of Gravity Wave
12 (GW) using radiosonde, MST Radar, Lidar and other observations. In this study, we made an
13 attempt to obtain the characteristics of medium frequency GWs over a tropical station
14 Gadanki (13.5°N and 79.2°E) using the Weather Research and Forecasting (WRF) model
15 simulations for the period 2006-2017. Prior to GWs analysis, we have validated the model
16 outputs with radiosonde measurements over Gadanki to check the performance of the model
17 in capturing the realistic features as seen in the observations. Profiles of horizontal winds and
18 temperature are validated and the results of statistical analysis indicate that there is a good
19 correspondence between the WRF model simulations and the radiosonde measurements. The
20 FFT and wavelet analysis on the winds revealed the spectrum of waves. The band pass
21 filtered wind perturbations showed clear downward phase propagation with the dominant
22 periods 2-5 hours. The observed vertical and horizontal wave lengths are in the range of 6-8
23 km (3-8 km) and 100-200 km (100-500 km) in the troposphere (stratosphere), respectively.
24 These characteristics match well with those reported from the same location using MST radar
25 and radiosonde observations. Further, the long-term features like semi-annual oscillation,
26 annual oscillation and quasi-biannual oscillations are also simulated very well in the WRF
27 outputs. These results show the model's ability to simulate near realistic features as seen the

observations and can also be used to supplement the missing observations with errors limits as its uncertainty.

Key words: Gravity waves, WRF model simulations, long-period oscillations

1. Introduction

Gravity Waves (GWs) have occupied a crucial role in the current atmospheric research due to their myriad effects in atmospheric structure and dynamics. Impact of GWs on the middle atmospheric energy budget has become one of the most intriguing topics in the current scenario as they play a critical role in altering the thermo-dynamical structure of the middle-atmosphere (Fritts and Vincent, 1987; Wilson et al., 1990). Generally these waves are generated in the lower atmosphere due to mesoscale disturbances like convection, wind shear, orography, etc. They propagate to upper atmosphere and transport significant energy and momentum, which affect the general circulation of the coupled atmospheric regions (Holton, 1983; Krishna Murthy et al., 2002; Fritts and Alexander, 2003; Kim et al., 2003). Several studies reported that breaking of GWs in the middle atmosphere causes momentum flux deposition which induces mean flow acceleration/deceleration (Li et al., 2005; Antonita et al., 2007). Many studies (Dunkerton, 1997; Sato and Dunkerton, 1997; Baldwin et al., 2001) reveal that the GWs are one of the major contributors for driving and modifying large scale middle atmospheric variability such as semi-annual oscillation (SAO), annual oscillation (AO), quasi-biennial oscillation (QBO), etc.

Ground based instruments can provide measurements with very good temporal and vertical resolution, however, most of these measurements are limited to the a point, while satellite observations are useful for studying spatial distribution of GWs but the major constraint arise from its poor vertical and temporal resolutions. Construction of long-term climatological data of GWs and the analysis of these waves is extremely important to understand the persistent dynamical processes associated with GWs. Several observational

studies are made on the GW generation, their sources and its impact on the structure of the atmosphere (Kumar et al., 2006; 2007, Dhaka et al., 2002, Venkat Ratnam et al., 2008; Leena et al., 2012a,b; Pramitha et al., 2015; 2016) using long-term measurements over the Indian region particularly over Gadanki, though these studies have been constrained to over a single point because of the observational limitations. Studies have also shown that parameterization of GW drag is required in large scale numerical models for realistic simulations of the middle atmospheric circulation (Holton, 1983). For this parameterization, parameters related to wave characteristics are needed which can be determined from observations. Unfortunately, high resolution data of different temporal scales are very sparse particularly in the tropics. Thus, climatology of GWs including their complete spectrum is an important aspect in understanding their role in atmospheric phenomena in the tropics which remained as a constraint so far.

In recent times, numerical weather prediction (NWP) models have proven their skill in simulating the realistic features of the GWs and background atmosphere during passage of cyclone or thunderstorm/convection (Kuester et al., 2008; Chane Ming et al., 2014; Hima Bindu et al., 2016 etc). Many studies (Alexander and Rosenlof 2003; Kim et al., 2003; Preusse et al., 2014) showed the use of the global NWP models products for capturing the presence of GWs and analysis of the wave characteristics, though these models have inherent numerical stability constraints to damp the evolution of the GWs (Hedlin, and Drob, 2014). However, because the spatial and temporal scales of these atmospheric GWs are too small compared to the grid size of global model, the sub-grid scale processes such as the interaction of GWs are neither completely represented in the form of parameterization nor resolved fully in the global models. Several studies have reported that the Weather Research and Forecasting (WRF) mesoscale model was able to capture the GWs which compare well with the radar measurements (Valkonen et al., 2010; Udina et al., 2013; Kirkwood et al., 2010;

Ghosh et al., 2016). However, only a few studies exist on high or medium frequency GW characteristics from WRF model simulations (Evan et al., 2012; Rechou et al., 2013; Costantino et al., 2015; Kruse et al., 2016; Gisinger et al., 2017). In the present study, we show for the first time over Indian region that WRF model simulations can be used for the long term study of high and mid frequency GWs. The obtained periods and wave lengths of these GWs are compared with the previous studies made using radar, radiosonde and lidars. The present paper is organized in the following way: the data base and the model description used for the present study is provided in section 2 while section 3 details the validation of model results with observed data and the conclusions given in Section 4.

2. Data and Methodology

In this section, a brief description of the observational datasets is provided along with details of the WRF model configuration, model design and the simulation methodology.

2.1. WRF model and its configuration

A high-resolution regional climate reanalysis dataset has been generated for the Indian sub-continent from 2006-2017 using the Advanced WRF model. The model simulations are performed in consecutive integration method with daily initializations making use of WRF two-way nested domains configuration of 18 km and 6 km resolutions with 51 vertical levels. Figure 1 shows the model domains used in Advanced Weather Research and Forecasting (ARW) for the present simulation along with the terrain height. Location of Gadanki is also shown in this figure. Model physics used in the study are chosen based on the previous studies over Indian regions (Srinivas et al., 2013; Srinivas et al., 2015; Madala et al., 2016). For boundary layer processes, Yonsei University's non-local diffusion scheme (Hong et al., 2006) is used. The Kain-Fritsch scheme is used for cumulus convection (Kain and Fritsch, 1993). The WRF Single-Moment 3-class (WSM3) is used for microphysical processes. The Noah land surface scheme (Chen and Dudhia, 2001) for surface processes,

Rapid Radiation Transfer Model (RRTM) for long-wave radiation (Mlawer et al., 1997), and the Dudhia (1989) scheme for short-wave radiation. The initial and boundary conditions are obtained from ECMWF ERA-Interim 6-hourly data. To improve the land-sea contrast and simulation of wind over coastal regions, we have replaced the coarse-resolution sea surface temperature (SST) obtained from ERA-Interim data with time-varying high-resolution SST obtained from the Real-Time Global High-Resolution (RTG-HR) (Gemmill et al., 2007).

For the present study, the WRF model is initialized on daily basis at 12 UTC using ECMWF ERA-Interim, and integrated for the complete 24-hour period. Note that the model datasets from 2006 to 2017 are only used for the present study based on the availability of GPS radiosonde data. To find out whether the mesoscale weather models are able to simulate realistic profiles of the atmosphere, the profile information from the GPS radiosonde data over Gadanki has been considered during 2006 and 2017 as benchmark observations to validate the high-resolution climate reanalysis dataset generated using ARW model.

2.2. GPS Radiosonde Observations

High resolution GPS Radiosondes (Väisälä RS-80 (April 2006 to March 2007), RS-92 (July to August 2006), Meisei RD-06G (May 2007 to January 2014), Meisei RD-11G (February 2014 to December 2015), Meisei RS-11G (January 2016 to December 2016) and Meisei iMS-100 (January 2017 to December 2017) were launched daily around 1730 IST (IST = UT+0530h) at Gadanki. Note that there is not much difference in the quality of the radiosonde instruments of different makes/agencies. However, there is a difference in the sampling time and altitude resolutions. For Väisälä RS-80 it is 25-30 m (sampled at 5-s intervals) whereas for the other two radiosondes it is 10 m (sampled at 1-s intervals). The radiosonde data set spans over the 12 years and there are minor gaps in the years 2006, 2007, and 2013 which do not affect the present study. The average ascent rate of these sondes is about 5 m/s and they attained at an altitude of 28 km. These data are interpolated to 100 m

vertical sampling so as to remove outliers that are occurring due to random motions of the balloon. The radiosonde ascent rate of ~ 5 m/s with 100 m altitude resolution is equivalent to 20 s in time. Details of this radiosonde system, data base and quality checks applied to the data are reported in Mehta et al. (2011) and Venkat Ratnam et al. (2014).

3. Results

3.1. Comparison of background atmospheric conditions

For the present study, seasons are divided as Pre-monsoon (March, April and May, MAM), monsoon (June, July and August, JJA), Post-monsoon (September, October and November, SON) and winter (December, January and February) based on the background conditions of the atmosphere prevailing over the Indian region. The meteorological parameters from the GPS radiosonde observations and WRF model are used to compute monthly means, seasonal, annual, and inter-annual variations.

The time height profiles of monthly mean zonal wind, meridional wind and temperature obtained from both WRF and radiosonde over Gadanki are shown in Figure 2. During monsoon season (JJA), both the data sets show the easterly winds with a magnitude of 30 m/s in the height region of 16-22 km and westerly with a magnitude of 7-8 m/s below 8 km indicating the presence of easterly jet and westerly winds of Indian Summer Monsoon origin as discussed by Venkat Ratnam et al. (2008). The zonal wind is easterly from surface up to height of 5-6 km, westerly in between the heights of 10-20 during the winter and pre-monsoon seasons with the wind speeds in the range of 12-14 m/s indicating the prevalence of north-easterly winds as well as sub-tropical westerly jet in winter months. Also the easterly winds in winter monsoon season are stronger than the westerly winds during summer monsoon since the study region partly comes under rain shadow regions of south-west monsoon.

The strengths of meridional winds are smaller than zonal winds and are northerly with a magnitude of ~ 7 m/s around 13-15 km during the monsoon season and southerly during the winter with a peak velocity of ~ 9 m/s. The sensitivity of temperature with respect to the season is clearly visible in the boundary layer region (< 3 km) with peak temperature observed from April to June. However, temperatures do not show any significant variations at upper level with season. Hence, these observed features of the radiosonde are well captured by model suggesting that WRF model could able to simulate the background atmospheric parameters. In addition, the time-height profiles of winds by both radiosonde and WRF model during 2006 to 2017 shows strong intra-seasonal and inter-annual variability in the lower and upper troposphere.

In Figure 3, the difference between the monthly means of radiosonde observations and WRF model outputs are shown. The differences between the observed and model simulated monthly mean of horizontal winds (Figures 3 a & b) are found to be 5 m/s in the height region of 15-20 km altitude and difference in the temperature (Figure 3 c) is in the range of 2-3 K. Neglecting the variations in wind due to the drift of radiosonde, the WRF model results at Gadanki underestimates the intensity of easterly jet and overestimates the winds of subtropical westerly jet between the heights 12 and 20-km.

Temperatures are underestimated (< 2 K) during summer and overestimated during winter. Surface winds are overestimated in the model simulation. The slight overestimation of winds at surface has been reported by Srinivas et al. (2013) and attributed to the model tendency to simulate higher differences between the heat low and Mascarene high, resulting in higher gradients in pressure and winds. At rest of the altitudes, particularly in the troposphere, the differences are too small, suggesting that the WRF model is able to simulate the realistic features of the background meteorological parameters of the atmosphere.

The seasonal mean root mean square error (RMSE) computed for the daily profiles of temperature, zonal and meridional wind over Gadanki between the radiosonde and WRF model simulations during 2006 to 2017 are shown in Figure 4. The RMSE profiles over Gadanki clearly suggest that the model exhibits different skills based on the season, found to be high at surface as well the jet regions of easterly and westerlies during monsoon and post-monsoon seasons. During the pre-monsoon season, the RMSE in the zonal wind shows an error of 1-2 m/s from the surface to 30 km altitude, whereas in the meridional wind the RMSE of 1-2 m/s is found except near the tropopause where it is ~ 3 m/s. The RMSE in the zonal wind during the monsoon is found to be 1-3 m/s which reach ~ 6 m/s in the lower stratosphere (LS) region. These variations could be both due to the overestimation of simulated wind in the low level and upper tropospheric jets as well due to the model differences in simulating the actual height of jet. During monsoon, meridional wind exhibits an error of 0.5-1.5 m/s except near the tropopause and LS region where it reaches 3 m/s. During the post-monsoon season, the horizontal winds show 1-3 m/s error and during winter the RMSE in zonal (meridional) wind shows 1-2 m/s (1-3 m/s). Over all, the RMSE in the zonal and meridional winds climatologically vary between 1 and 3 m/s. During all the seasons, the RMSE in the temperature varies in the range of 0.5-2.5 K. It is found to be maximum at surface and core jet regions of easterly and westerlies. The climatological mean RMSE for the simulated temperature shows ± 0.75 K which is very small, suggesting model exhibits good skill in reproducing the seasonal variation of temperature. In general, maximum RMSE in the zonal and meridional winds (temperature) of 3 m/s (0.5 K) is found which confirms that the WRF model produces near realistic features of the atmosphere over Gadanki.

3.2. Long-term oscillations in the WRF model simulations and observations

In the lower atmosphere, both the zonal and meridional winds exhibit the variations at annual and inter annual time scales. However, the oscillations observed in the middle atmosphere such as Annual Oscillation (AO) and Quasi-biennial Oscillation (QBO) which have the time period of 12 and 24 months, respectively. As far QBO is concerned, it is an east-west oscillation of the equatorial zonal wind in the stratosphere characterized by an irregular period of 28 to 29 months (it can vary from 24 to 36 months). Figure 5 shows the Lomb Scargle Periodogram (LSP) (Vanderplas et al., 2017) analysis of monthly mean data of zonal wind, meridional wind and temperature for the complete time series (2006-2017) for the radiosonde observations and WRF model simulations at 15 km and 24 km altitudes. Horizontal lines indicate 90% confidence level. The periodogram of zonal wind shows the first dominant periodicity at ~1 year i.e., AO and the second dominant peak found at about ~2 year 4 months (QBO) at 24 km altitude. Both the LSPs for the radiosonde and WRF model simulations show similar variability. LSP for meridional wind and temperature shows the dominant AO though the amplitude in the WRF model is larger in the meridional wind. In the temperature, both WRF and radiosonde observations are again well matched. Similar analysis is made for all altitudes such as 10, 12, 16, 18, 20, 22 km and similar significant features are observed (figures not shown). In general, very good agreement is observed between these two independent data sets suggesting that the WRF model simulated outputs are accurate enough to study the broad spectrum of wave/oscillations in the atmosphere.

Figure 6 (a & b) shows the time-height section of FFT analysis of monthly mean zonal wind and meridional wind applied to the radiosonde observations obtained over Gadanki during 2006-2017. Zonal wind shows the dominant AO and QBO oscillation with the magnitude of 10 m/s in the lower stratosphere with the mean period of 28-29 months. Dominant AO is observed in the meridional wind component with the maximum amplitude

of about 2 m/s. SAO is also observed in both the zonal and meridional wind components but is less significant in the zonal wind when compared to the meridional wind.

Similarly, the monthly mean wind profiles from WRF model simulations are subjected to the FFT analysis to find out the dominant oscillations (Figure 6 c & d). The FFT analysis of zonal wind suggests that the dominant AO from the surface to lower stratospheric region with maximum amplitude of 10 m/s and QBO with a mean period of 28 to 29 months in the tropical lower stratosphere over Gadanki. SAO is also observed in the zonal wind with a small magnitude. The time series of FFT for meridional wind shows the AO with maximum amplitude of 2 m/s, whereas temperature does not show any significant variation. Signature of SAO is also observed in the meridional wind. Thus, the general features of WRF model matches well with the in-situ radiosonde observations (Figure 6) over Gadanki and it is clear that the model could able to produce the long period features such as SAO, AO and QBO, which plays a crucial role in driving the middle atmospheric dynamics.

To get further insight on the short period GWs as they are having periods from few minutes to few hours, the hourly data of the simulated parameters such as zonal, meridional, vertical winds and temperature from the WRF model simulations are subjected to the FFT analysis. Figure 7(a) shows the time-height section of the FFT analysis of vertical wind obtained from WRF model simulations over Gadanki during 01-05 January 2006 (i.e., first 120 hours of this FFT spectrum to show the short period waves). The vertical wind shows dominant short period waves ranging from an hour to 5 hours with 0.01 m/s amplitude in the Upper Troposphere and Lower Stratosphere (UTLS) region. The results also confirm the earlier findings that vertical wind is a best observational parameter to extract GWs from the WRF model simulations (Choi et al., 2006; Hima Bindu et al., 2016). Apart from the GWs, tidal components are also clearly observed in all the three wind components (figure not

shown) which again confirm the model ability in simulating both the small scale wave features and tidal oscillations.

3.3. Wavelet spectra of winds in WRF model

In order to investigate the dominant periods that are associated with short period waves, the time evolution of power spectra and Morlet wavelet analysis (Torrence and Compo, 1998) have been carried for the zonal, meridional and vertical wind velocity fluctuations at 24 km during the study period (2006-2017). However the wavelet analysis of vertical wind is only shown in Figure 7(b). The thick red coloured contours represent 95% confidence level which is statistically significant.

The vertical wind perturbations clearly show the existence of high frequency waves with the period starting from an hour. It is observed that most of the dominant periods of waves are observed during monsoon with maximum amplitudes in each year. Similar significant wave features are observed at other altitudes also (figures not shown). Tides and planetary waves also can be clearly observed from the figure. The low frequency wave activity is observed at lower altitudes and when it comes to the higher altitudes they might be filtered by the background wind. From the Figure 7 (a & b), it is clear that WRF model simulations can observe the dominant short period waves in the UTLS region.

3.4. High/medium frequency gravity wave characteristics from the WRF simulation

To obtain the characteristics of the short period waves over Gadanki, the time series of all the three wind perturbation components from the WRF model are subjected to the band pass filter for the entire study period (i.e., 2006-2017). The minimum and maximum limits kept for the filter are 2 and 5 hours, respectively. Figure 8 shows the time-height section of band pass filtered zonal wind, meridional wind and vertical wind perturbations over Gadanki during 2006-2017. Alternative positive and negative perturbations of amplitudes of about ± 2 m/s and ± 0.1 m/s are observed in horizontal and vertical winds, respectively, in the

275 troposphere and lower stratosphere, especially in the vertical wind component. The band pass
276 filtered wind perturbations showed clear downward phase propagation (upward propagating
277 waves especially in the vertical wind component) with the dominant periods 2-5 hours in the
278 UTLS region. The zoomed portion with the small subset of data has been shown for 04th July
279 2007 in Figure 8c to show the phase propagation of these GWs. Strong seasonal variation is
280 also simulated in these waves with maximum during monsoon season.

281 In order to obtain the other characteristics of these high frequency waves from the
282 WRF model, the 2-5 hours band pass filtered zonal, meridional and vertical wind parameters
283 are subjected to FFT analysis in vertical to obtain dominant vertical wavelengths. The
284 obtained range of vertical wavelengths is shown with the box plot for all the three wind
285 velocities in Figure 9. The vertical wavelengths range from the 0.5 to 16 km altitude
286 (troposphere). The dominant vertical wavelengths ranging from 6-8 km (3-8 km) can be
287 noticed in the troposphere (stratosphere) from Figure 9. Horizontal wavelengths are obtained
288 from the dispersion relation. They range from 100-200 km (100-500 km) in the troposphere
289 (lower stratosphere). The above obtained wave parameters show good agreement with the
290 earlier study on the high frequency GWs over the present study region made by Leena et al.
291 (2012a) ('vertical wavelengths ranging from 6-12 km (3-7 km) and horizontal wavelengths
292 ranging from 100-300 km (100-500 km) in the troposphere and (lower stratosphere)
293 respectively '). Note that the height resolution in the troposphere and stratosphere for the
294 present study is 0.5 km and 1 km, respectively. The other parameters like direction of
295 propagation, energy and momentum flux, etc of these waves needs to be addressed as
296 previous studies (Wagner et al., 2017 and Kruse et al., 2017). Thus, WRF model outputs can
297 simulate the high/medium frequency GW characteristics and these wave characteristics agree
298 well with the previous studies performed with radiosonde and MST radar observations over
299 Gadanki.

A high-resolution 2-km regional climate reanalysis dataset has been generated for the Indian sub-continent from 1980-2017 using the Advanced Weather Research Forecasting (WRF) model to show the long term variation of high/medium frequency GWs. 2- 5 hrs bandpass filtered vertical wind variance at 15km altitude along with 13-point running mean is shown in Figure 10a. After smoothening, the vertical wind shows the clear increase in the amplitude during monsoon season every year. Monthly mean variance averaged during 1980 to 2017 shown in Figure 10b further confirmed its enhancement in monsoon season and there exists large inter-annual variation (standard deviations).

4. Summary and Conclusions

WRF model simulated outputs are validated with the independent radiosonde observations over a tropical station Gadanki (13.5°N and 79.2°E) for the first time to check whether WRF model is able to simulate the observed features or not. The model simulations are performed with two-way nested domains with horizontal resolutions of 18 km and 6 km and initial and boundary conditions obtained from ECMWF ERA-Interim 6-hourly data. The model outputs are obtained with hourly temporal resolution. These outputs are validated using independent radiosonde observations which have not gone into any of the reanalysis data sets. From the detailed validation, it is confirmed that the WRF model is able to simulate the realistic features of the background meteorological conditions over Gadanki. Seasonal and climatological RMSE in the horizontal winds and temperature shows the maximum error of 3 m/s and 0.5°K, respectively, which indicates that WRF model simulation could able to simulate the near realistic features over Gadanki. The WRF model is also able to simulate the long-period oscillations like semi-annual oscillation (SAO), annual oscillation (AO) in both zonal and meridional winds and are in good agreement with the radiosonde observations. Quasi biennial oscillation (QBO) in the zonal component is also well reproduced in both the observations and model simulations. With this analysis, it is clear that WRF model simulation

is proved to be a useful numerical model for obtaining the atmospheric background conditions.

GWs are major contributors to these long term oscillations. Wavelet spectra of winds especially vertical winds revealed a prominent oscillation in the period of an hour to 7 hours in the UTLS region. Hourly winds from the WRF model especially vertical wind velocity show dominant 2-5 hours of medium frequency GWs in UTLS region. Strong seasonal variation is also observed in these GWs with maximum during monsoon season. The dominant vertical and horizontal wavelengths ranging from 6-8 km (3-8 km) and 100-200 (100-500) km in the troposphere (stratosphere), respectively. Long term variation of 2-5 hrs filtered high/medium frequency GWs from the long term regional climate reanalysis data set (1980-2017) also shows the strong seasonal variation with maximum during monsoon season.

There are many observational studies which have shown the seasonal behaviour of GWs over Gadanki from short period to inertial period (Antonita et al., 2007, Debashis Nath et al., 2009, Guharay et al., 2011, Leena et al., 2012a and b, Pramitha et al., 2016, and references therein) using Gadanki radiosonde, lidar, MST Radar observations. However, the comparison of WRF model simulated output results with the radiosonde observations and validation of these results with the previous published results are quite unique and they show the model's capability to simulate the near real features of the background atmosphere. In conclusion, WRF model simulations can be effectively used for the study of medium frequency GWs, and these obtained GW parameters made a good agreement with the earlier study on the high and medium frequency GWs over the present study region made by Leena et al. (2012a). Thus, characteristics of medium frequency GWs obtained using WRF model simulated output can be used in absence of observations.

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Figures

Figure 1. Model domains used in ARW for the present simulation. The shading gives the terrain height in meters. Inner star (red colored) shows the location of Gadanki.

Figure 2. Monthly mean time-height section of (a) zonal wind, (b) meridional wind and (c) temperature obtained from radiosonde observations over Gadanki during 2006 - 2017. (d)-(f) Same as (a)-(c) but obtained from WRF model simulation over Gadanki.

Figure 4. Root mean square error (RMSE) observed between the daily radiosonde observations and WRF simulations during different seasons in the (a) zonal wind, (b) meridional wind and (c) temperature during 2006-2017 over Gadanki.

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549 **Figure 5.** Lomb Scargle Periodogram (LSP) analysis of monthly mean (a & b) zonal wind,
550 (c & d) meridional wind and (e & f) temperature for the complete time series (2006-2017,
551 12 years) for radiosonde observations (red line) and WRF model simulations (blue line) at
552 15 and 24 km altitude respectively. Horizontal lines indicate 90% confidence level.

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Figure 6. Time-height section of FFT spectral analysis of monthly mean (a & c) zonal wind, (b & d) Meridional wind obtained from radiosonde observations (top two panels) and WRF simulations (bottom two panels) respectively over Gadanki during 2006-2017.

Figure 7. (a) Time-height section of FFT spectral analysis of vertical wind over Gadanki during 01-05 January 2006 and (b) Wavelet spectra of vertical wind perturbations at 24km altitude over Gadanki during 2006-2017 obtained from the WRF model simulations.

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Figure 8. Time-height section of 2-5 hours band pass filtered (a) zonal wind, (b) meridional wind and (c) vertical wind over Gadanki obtained from the WRF simulation during 2006-2017. (d) Zoomed portion observed on 4 July 2017 in the vertical wind perturbations.

Figure 9. Box plot showing the dominant vertical wavelengths in the troposphere (0.5 to 16km) and stratosphere (16-27km) obtained from the WRF model. (a& d), (b & e) and (c & f) are zonal, meridional and vertical winds in the troposphere and stratosphere, respectively. Top and bottom x is the 99% and 1% confidence levels, whiskers show maximum and minimum values and solid box is the mean value.

Figure 10. (a) Monthly mean variation of 2 -5 hrs bandpass filtered vertical wind at 15km altitude. A 13-point running mean is also shown (black line) from 1980 to 2017. (b) Monthly mean 2-5 hrs bandpass filtered variance in the vertical wind averaged during 1980 to 2017. Vertical bars show the standard deviation.