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Meteor radar estimation of Gravity Wave Variances and Momentum Fluxes in the mesosphere lower thermosphere: Evaluation of different methods using simulations and observations over three tropical locations

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Abstract

Meteor Radar is widely used to study Gravity wave (GW) variances and their Momentum Fluxes (MFs) at mesospheric altitudes. However, the accuracy of meteor radar observations of GWMF should be evaluated before they can be used for research applications. In this regard, the present study evaluates the meteor radar observations of GWMF obtained from Thumba [8.5°N, 77°E (2006-2015)], Kototabang [0.2°S, 100.3°E (2002-2017)] and Tirupati [13.63°N, 79.4°E (2013-2018)]. These radars provide hourly zonal and meridional wind observations round the clock in 80-100 km height domain known as mesosphere lower thermosphere region. Three methods are employed to evaluate the meteor radar performance in estimating the simulated GWMFs, Viz., 1) Day by day analysis, which is traditional Hocking method 2) Composite day analysis and 3) Modified Composite day analysis. After evaluating these methods by employing GW simulations, it is found that modified composite day analysis shows good agreement and the same is used for constructing the GWMF climatologies over the observational locations. The significance of the present study lies in evaluating the three different methods for estimating GWMF by employing GW simulations and meteor radar observations.

1. Introduction

Gravity waves can alter the structure, energetics and dynamics of the middle atmosphere by transferring energy and momentum from troposphere (source region) to the mesosphere (where it dissipates) [1,2,3]. Departure of Radiative equilibrium in the middle atmosphere is attributed to the mean meridional circulation with rising motion in the summer hemisphere and sinking motion in the winter hemisphere, and these meridional circulation sustains due to the momentum transferred by the gravity waves. Studying GW activity at middle atmosphere is essential for the explanations of mean meridional circulation at mesosphere, cold summer mesopause, warm winter mesopause, equatorial semi-annual and quasi-biennial oscillations and wind reversal in lower thermosphere [2,4]. Instruments like LIDAR, RADAR, Satellite and Airglow Imager are used extensively to study GWs in the mesospheric region. Comparing to other instruments, RADARs operating and VHF can continuously monitor variation of winds and GW activity independent of weather conditions. The central objective of the present study is to evaluate how well meteor radars employed in present study can estimate the GW momentum fluxes using GW simulations. These are the first such simulations carried out over the Indian region to quantify the accuracies of meteor radars in estimating GWMF. In present study observations from three Meteor Radars located at Thumba [8.5°N, 77°E (2006-2015)], Kototabang [0.2°S, 100.3°E (2002-2017)] and Tirupati [13.63°N, 79.4°E (2013-2018)] are extensively used. These three radar operate at 35.25 (40 kW), 37.7(12 kW) and 35.25(40 kW) MHz frequency (peak power), respectively.

2. Methodology

Meteor Radars located at three tropical stations as mentioned earlier are employed for estimating the GWMF using Hocking method [5]. By following [6,7,8] an attempt is made to evaluate how well these Radars can estimate the GW variances and MFs using simulation studies. Hocking method is a generalized dual beam method by considering the perturbation in radial velocity obtained after the removal of background winds, which are purely due to GWs and these methods are widely used to get GWMF from Meteor radar. [8] has pointed out that these perturbations can contains the contributions from tides and quasi 2day waves over the tropical region. In the present study three different approaches have been employed to estimate GW parameters, *Viz.,* 1) Day by Day analysis 2) Composite day analysis and 3) Modified Composite day analysis (MCD).

Day by day analysis is traditional Hocking method in which the meteor counts in each time height bin greater than 30 is taken for the analysis and the estimated parameters are averaged over a month to get reliable results. In composite day analysis, radial velocity perturbation obtained for one month is arranged in a single day time height bin so that each time height bin will have enough meteors for the calculation of MFs and Variances. Using this perturbation along with Hocking method GWMF and variances are estimated. It is known that observed zonal (U) and meridional (V) winds are superposition of mean winds, diurnal, semi diurnal, ter diurnal tides, quasi 2 day wave and gravity waves. In order to get the wind perturbation due GWs alone, contributions from all above mentioned waves other than GWs should be removed from the observed radial velocity. In the present study, amplitude and phase of tides and planetary waves are estimated using least square method. Radial velocities are then estimated using the amplitude and phase of tides and planetary waves. This radial velocity is subtracted from the meteor radar observed radial velocity to obtain the perturbation due to GWs alone. Considering this as perturbation in radial velocity, the GWMF is estimated by employing the composite day analysis. This procedure is known as Modified Composite Day (MCD) analysis.

3. Results

3.1 Mesosphere lower thermospheric wind simulations

To evaluate the three different methods to estimate the GWMF, the wind field is generated using known inputs of mean winds, tides, gravity and planetary wave amplitudes using equation (1), (2) & (3).

$$\begin{aligned} U(x,y,z,t) &= U_M + U_{2D}(t)\sin\big(2\pi(t-\delta_{U2D})/T_{2D}\big) \\ &+ U_D(z,t)\sin\big(2\pi(t-\delta_{UD})/T_D\big) \\ &+ U_{SD}(z,t)\sin\big(2\pi(t-\delta_{USD})/T_{SD}\big) \qquad (1) \\ &+ U_{TD}(z,t)\sin\big(2\pi(t-\delta_{UTD})/T_{TD}\big) \\ &U_{GW1}(x,y,z,t)\sin(k_1x+l_1y+m_1z-2\pi t/T_{GW1}) \\ &+U_{GW2}(x,y,z,t)\sin(k_2x+l_2y+m_2z-2\pi t/T_{GW2}) \\ &+U_{GW3}(x,y,z,t)\sin(k_3x+l_3y+m_3z-2\pi t/T_{GW3}) \\ &+U_{GW4}(x,y,z,t)\sin(k_4x+l_4y+m_4z|-2\pi t/T_{GW4}) \end{aligned}$$

$$\begin{aligned} V(x,y,z,t) &= V_M + V_{2D}(t)\sin\big(2\pi(t-\delta_{V2D})/T_{2D}\big) + \\ &+ V_D(z,t)\sin\big(2\pi(t-\delta_{VD})/T_D\big) + \\ &+ V_{SD}(z,t)\sin\big(2\pi(t-\delta_{VSD})/T_{SD}\big) + \qquad (2) \\ &+ V_{TD}(z,t)\sin\big(2\pi(t-\delta_{VTD})/T_{TD}\big) + \\ &+V_{GW1}(x,y,z,t)\sin(k_1x+l_1y+m_1z-2\pi t/T_{GW1}) \\ &+V_{GW2}(x,y,z,t)\sin(k_2x+l_2y+m_2z-2\pi t/T_{GW2}) \\ &+V_{GW3}(x,y,z,t)\sin(k_3x+l_3y+m_3z-2\pi t/T_{GW3}) \\ &+V_{GW4}(x,y,z,t)\sin(k_4x+l_4y+m_4z|-2\pi t/T_{GW4}) \end{aligned}$$

$$\begin{aligned} W &= W_{GW1}(x,y,z,t)\sin(k_1x+l_1y+m_1z-2\pi t/T_{GW1}) \\ &+W_{GW2}(x,y,z,t)\sin(k_2x+l_2y+m_2z-2\pi t/T_{GW2}) \quad (3) \\ &+W_{GW3}(x,y,z,t)\sin(k_3x+l_3y+m_3z-2\pi t/T_{GW3}) \\ &+W_{GW4}(x,y,z,t)\sin(k_4x+l_4y+m_4z|-2\pi t/T_{GW4}) \end{aligned}$$

---- U_M, V_M represents zonal and meridional mean winds

---- U_{2D}, V_{2D} represents zonal and meridional component of 2day wave amplitude.

---- δ_{U2D}, δ_{V2D} represents zonal and meridional component of 2day wave phase.

---- (U_D, V_D), (U_{SD}, V_{SD}), (U_{TD}, V_{TD}) represents zonal and meridional components of diurnal, semidiurnal and terdiurnal tidal amplitude.

---- (δ_{UD}, δ_{VD}), (δ_{USD}, δ_{VSD}), ((δ_{UTD}, δ_{VTD}) represents zonal and meridional components of diurnal, semidiurnal and terdiurnal tidal Phase.

-----T_{2D},T_D, T_{SD},T_{TD} are the wave period 48h,24h,12h,8h respectively.

The wind filed represented by equations 1, 2 and 43 are generated and the same is used to evaluate the proposed methods. Various terms in the equations are given in table 1 for the four cases by varying the background conditions.

Table1: Mean, Tidal and GW parameters used for wind field simulations for four test cases

Parameter	Case0	Case1	Case2	Case3
U_M,V_M	10,5	10,5	10,5	40,-20
U_D,V_D	40,40	40,40	40,40	50,50
λ_D	25km	25km	25km	25km
U_{SD},V_{SD}	10,10	10,10	10,10	$20+2(z-80)\sin^2(\pi t/T_M)$
λ_{SD}	50km	50km	50km	-
U_{2D},V_{2D}	$20+5R_0$, $30+5R_0$	0,0	0,0	0,0
U_{GW1},V_{GW1}, W_{GW1}	10,0,5	10,0,5	10,0,5	20abs $[\sin(2\pi t/T_M)]\sin(2\pi t/T_{SD})$,0, -10abs $[\sin(2\pi t/T_M)]\sin(2\pi t/T_{SD})$
k_1,l_1,m_1	2π/30,0,0	2π/30,0,0	2π/30,0,0	2π/30,0,0
T_{GW1}	20min	20min	20min	20min
U_{GW2},V_{GW2}, W_{GW2}	0,20,2	0,20,2	0,20,2	0,20abs $[\sin(2\pi t/T_M)]\cos(2\pi t/T_{SD})$, 5abs $[\sin(2\pi t/T_M)]\cos(2\pi t/T_{SD})$
k_2,l_2,m_2	0,2π/50,0	0,2π/50,0	0,2π/50,0	0,2π/50, 0
T_{GW2}	30min	30min	30min	30min
U_{GW3},V_{GW3}, W_{GW3}	0,0,0	0,0,0	20,0,-10	20,0,-10
k_3,l_3,m_3	0,0,0	0,0,0	2π/60,0,0	2π/60,0,0
T_{GW3}	inf	inf	2.5h	2.5h
U_{GW4},V_{GW4}, W_{GW4}	0,0,0	0,0,0	0,10,2	0,10,2
k_4,l_4,m_4	0,0,0	0,0,0	0,0,2π/80,0	0,0,2π/80,0
T_{GW4}	inf	inf	3h	3h
$\langle u'w' \rangle_{mean}$	25	25	-75	-100
$\langle v'w' \rangle_{mean}$	20	20	30	10

3.2 Evaluation of meteor radar capabilities to measure simulated GW parameters

After simulating the wind files d in the mesosphere lower thermosphere region with known amplitudes of tides, gravity and planter waves as provided in table 1, the GWMFs are estimated using proposed three methods. For this purpose, the real time and space distribution of meteors obtained during August 2011 for Thumba, August 2004 for Kototabang and August 2017 for Tirupati are employed. In case0 tides have both temporal and vertical variation, with vertical wavelength of 25 km for diurnal tide and 50 km for semi diurnal tide. Quasi 2day waves have amplitude 20 and 30 ms^{-1} in zonal and meridional winds, respectively. In case 1, many of the parameters are same as case 0 but without quasi 2 day wave contribution. Cases 2 and 3 represent more realistic scenario in which four different GW parameters are used. In case3, semi diurnal tide has a 10-day amplitude modulation with amplitude increasing with altitude. Using these four cases, the radial velocities are estimated, which are then used to estimate GWMF using three different methods as discussed earlier. As the GWMF are known from the simulations, the radar estimated GWMF are compared. It is noted that GWMF estimated from radars at Thumba and Tirupati using MCD analysis show better agreement with the simulations as shown in figure 1 for case 2.

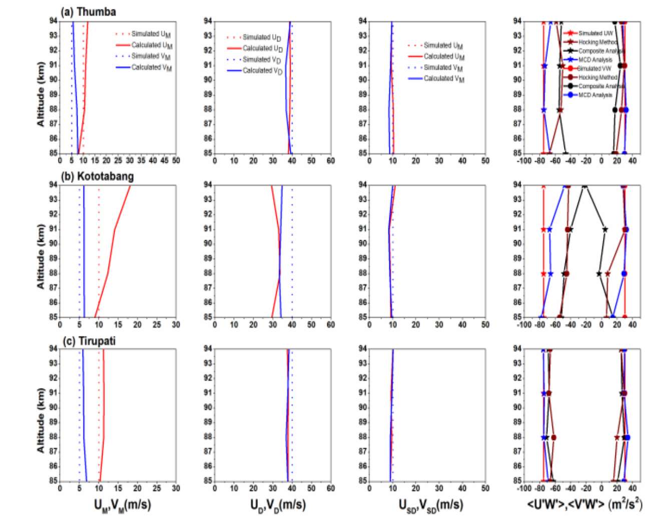

Figure 1. Monthly mean winds, diurnal tides, Semi diurnal tides and GW momentum fluxes at a) Thumba, b) Kototabang and c) Tirupati. These results correspond to GW simulations for case 2 in Table 1

In figure 1 first row represents results from Thumba, second Kototabang and third Tirupati, respectively. First column in each panel represents means zonal and meridional winds, in blue and red color, respectively. Where dashed lines represent simulated and thick lines are estimated values. Second column represents diurnal tidal amplitude and third one is semi diurnal tidal amplitude. Fourth column represents the zonal and meridional GW momentum fluxes, where red one is the simulated value, blue is MCD, wine color is Day by day analysis and black is composite day analysis, where star symbol is for u'w' and circle is for v'w'. From figure 1, it is clear that simulated and estimated winds and tides agree very well except at Kototabang where winds and tides have large variation from simulated ones. This can be directly attributed to less number of meteor echoes detected by this radar owing to relatively less peak power as compared other two radars. GW MF variation is 1% and 3% at maximum echo height over Tirupati and which is 2% and 3% over Thumba and 10% and 6% over Kototabang at maximum echo height for zonal and meridional components, respectively. Over all height variation is within 12% over Thumba and Tirupati. Kototabang variation is above 80% in different cases. So for the further analysis we have avoided observations from Kototabang for GWMF estimations. From all these simulation it is found that MCD is reliable as compared to other two methods in estimating the GWMF. Further analysis is thus carried out using MCD method. It is very interesting to note that both Thumba and Tirupati radar with peak power of 40 kW are suitable for estimating the GWMF, which is a valuable parameter to study the mesosphere lower thermosphere dynamics.

Using MCD analysis GWMF and variances are estimated over Thumba 2006-2015 and Tirupati 2013-2018. Results show prominent interannual variations in GWMFs with values ranging from -30 to 30 m^2/s^2. Mean annual cycles of GWMF are shown in figure 2 and figure3 for Thumba and Tirupati, respectively. In annual variation it is noted that there is a 4month oscillation in zonal momentum fluxes over Thumba and semiannual oscillation in meridional momentum fluxes over Tirupati. A semiannual oscillation at 88km in zonal momentum fluxes is noted over Thumba also. Using Lomb Scargle Periodogram it is found that 12 month,8 month oscillations are also significant in the GWMF. Further studies are aimed at estimating the GW induced accelerations over the two radar locations.

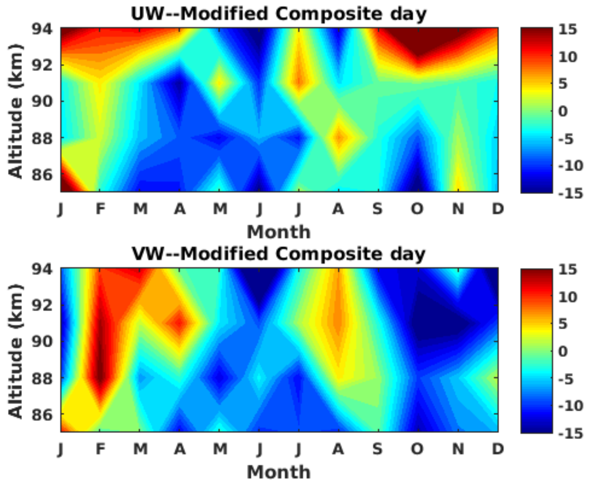

Figure 2. Annual variation of zonal and meridional GWMF over Thumba using MCD analysis.

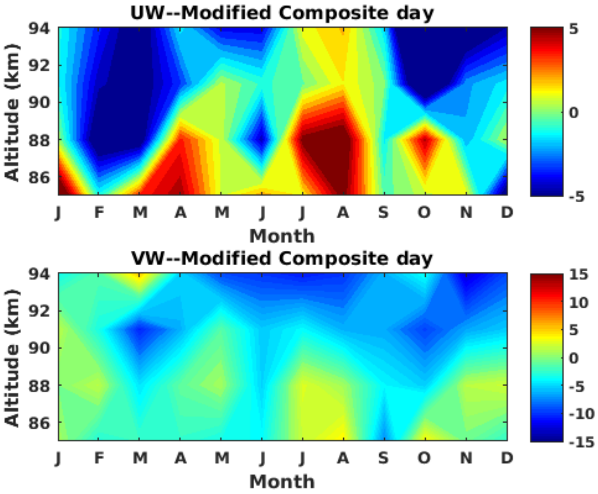

Figure 3. Annual variation of zonal and meridional MF over Tirupati using MCD analysis.

4. Summary

A study is carried out to evaluate how well meteor radars operating at three tropical locations can estimate the GW momentum fluxes by simulating mesosphere lower thermosphere wind fields. The known characteristics of tides, gravity and planetary waves are used to simulate the realistic wind fields and the same are sampled by mimicking the meteor radar observations. Three widely used methods viz., 1) Day by day analysis, which is traditional Hocking method 2) Composite day analysis and 3) Modified Composite day analysis, are evaluated using these simulations. Four test cases with different background scenarios as well as GW activity are used for the present study. The GWMF estimated from the radar are then compared with the simulations. The results show that radar operating at Thumba and Tirupati perform better as compared to Kototabang, which transmit relatively less peak power among the three radars. It is also noted that MCD method perform better that other two methods. After evaluating the three methods, annual cycle of GWMF are estimated over Thumba and Tirupati. These are the first such simulations carried out over the Indian region to quantify the accuracies of meteor radars in estimating GWMF.

5. Acknowledgements

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6. References

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