First Observations of Gravity Wave Momentum Flux with Different Frequencies

Gopa Dutta
R & D Center, Vignana Bharathi Institute of Technology,
Aushapur (V), Ghatkesar (M), R.R. District-501301, Telangana, India
gopadutta@yahoo.com

Abstract- **It is now well established that internal gravity waves play a significant role in the momentum and thermal budget of the lower and middle atmosphere. This paper presents a comparison of the momentum fluxes carried by gravity waves in two period bands (< 2 h and 2-8 h). It is observed that the shorter period gravity waves transport higher momentum fluxes in the upper troposphere and lower stratosphere over Gadanki, a tropical Indian station. Oscillations between 60-100 min are found to be prominent and contribute significantly to the mean flux estimates. The wavelet transform momentum flux spectra displayed the temporal variability and discretization of the gravity wave momentum fluxes in frequency and time.**

Keywords- **Gravity waves, Momentum flux, Radar.**

I. INTRODUCTION

Both theoretical and observational studies have confirmed that internal gravity waves play a significant role in the momentum budget and thermal structure of the lower and middle atmosphere. Substantial momentum fluxes of gravity waves have been reported in the lower atmosphere due to mountain waves [1], convection (e.g. [2]-[4]) and topography (e.g. [5]). However, the frequency dependence of the flux has not been investigated in-depth and the measurements reported from the tropics are sparse.

Following the arguments of [6], [7] predicted that most of the momentum flux in the lower stratosphere should be contributed by high frequency gravity waves. But Momentum fluxes estimated using radar measurements in the stratosphere have shown larger contribution by waves of periods longer than 6 hours (e.g. [8]-[10]). These results were explained on the basis of synoptic scale disturbances due to mountain waves. Gravity waves of high frequencies (less than 1 hour period) are observed to contribute more than 70% of the total flux at mesospheric heights (e.g. [11]-[13]). But the report of [14] undermine the frequency dependence of the flux estimate. Using Jicamarca MST radar data, [7] made a detailed study of the momentum flux estimates in the stratosphere and mesosphere. They found that most of the flux was contributed by waves at periods $\geq$ 4 h in the stratosphere and $\geq$1 h in the mesosphere. At shorter periods, momentum flux spectra showed isotropic nature and contributed very little to the mean flux due to cancellation.

Reference [15] reviewed the causes and effects of variability of gravity wave forcing of the middle atmosphere and concluded that variability appeared to be greatest among gravity waves with smaller spatial scales and periods that account for the majority of energy and momentum transport, particularly at middle and higher latitudes. The scenario is not so clear for low latitudes. The primary goal of the present paper is to address the controversial topic of frequency dependence of momentum flux of gravity waves in two period bands (<2 h and 2-8 h) and to ascertain their contributions to the mean flux estimates in the troposphere and lower stratosphere over a tropical site, Gadanki.

II. RADAR DATA AND ANALYSIS PROCEDURES

The MST radar at Gadanki (13.5º N, 79.2º E) operates at a frequency of ~53 MHz in a coherent back scatter mode with an average power aperture product of ~$7X10^{8}\,Wm^{2}$ and provides an excellent opportunity to study mesoscale processes like gravity waves with a height resolution of 150 m in the troposphere and lower stratosphere. A detailed description of the system is available in work by [16]. Wind data obtained with the radar on four days (15-16 July, 2004; 18-19 April, 2005; 10-11 December, 2005; 12-13 February, 2006) continuously for ~ 24, 26, 32 and 32 hours respectively have been used for the present study. The data gaps on the corresponding days are ~ 2.5, 1.5, 3.5 and 2 min respectively. There were two small data gaps on 10-11 December, 2005 which have been spline interpolated to obtain a continuous data set. Outliers were removed by taking a mean wind in 1-hour section for each height and discarding values exceeding 1.7 times the standard deviations. The time series of radial velocities were detrended (subtracting the mean) and filtered appropriately using a fourth order Butterworth filter to retain wind oscillations with periods <2 h and between 2-8 h. The vertical fluxes of horizontal momentum were then estimated for each day using conjugate beam method developed by [17]. The momentum flux profiles were smoothed by taking a three-point running mean with weighted average and averaged over each day to obtain mean zonal and meridional momentum flux profiles which are illustrated in Fig. 1. Standard errors have been plotted at a few heights on each profile.

III. RESULTS AND DISCUSSION

A. Momentum Fluxes

Momentum flux being a product of velocity fluctuations is a small and inherently noisy quantity which demands an adequate averaging to get a meaningful estimate (e.g. [18], [7]). Reference [19] reported that an optimum beam angle between 9º - 12º and an integration of at least 15-16 hours are needed to minimize the error in momentum flux measurement to a

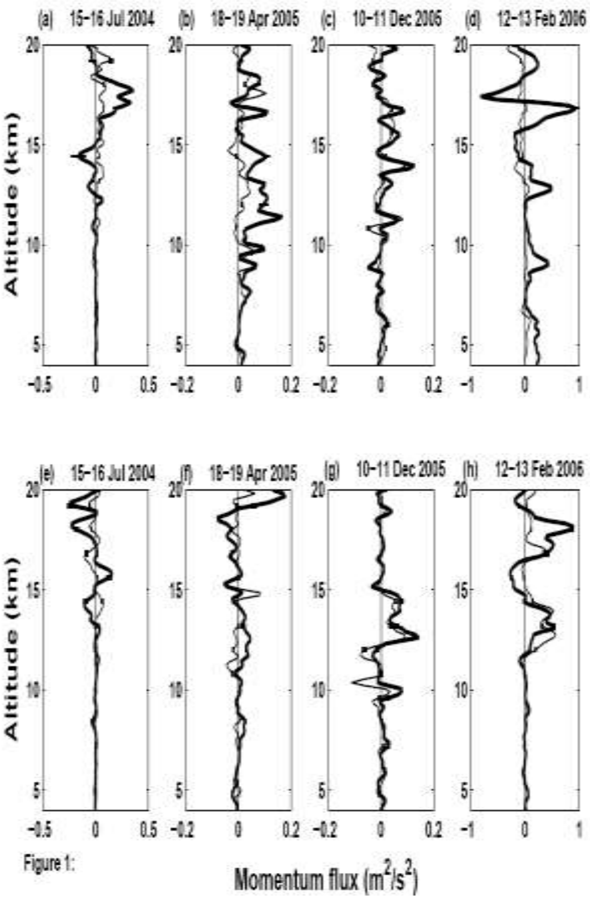

Fig. 1 Upper Panel: Comparison of zonal momentum flux profiles of < 2 h (thick line) and 2-8 h (thin line) for 15-16 July 2004 (a); 18-19 April 2005 (b); 10-11 December 2005 (c) and 12-13 February 2006 (d). Lower panel: Same as upper panel, but for meridional winds (e, f, g, h).

minimum, irreducible value. The MST radar at Gadanki operates at an optimum angle of 10º and the data length on each of the experimental days of the present study exceeds the minimum required time of averaging leading to reliable estimates of the fluxes. Mean zonal and meridional momentum flux profiles of all the days for <2 h and 2-8 h gravity waves are shown in the upper and lower panels of Fig. 1. Standard errors at a few heights are depicted by horizontal bars which are found to be an order smaller than the flux estimates enhancing our confidence in the measurements. Momentum flux of shorter period (<2 h) gravity waves is found to dominate in the upper troposphere and lower stratosphere on all the four days which agrees quite well with the estimate provided by [6] and the arguments given by [7] for the lower stratosphere. But the present results contradict the reports of several workers from mid-latitudes (e.g. [9],[10]). Fig. 1 shows significant variability of momentum flux on different days which is more prominent on 12-13 February when it is found to be a few times larger compared to other days despite comparable magnitudes of the velocities.

B. Momentum Flux Frequency Spectra

The frequency spectra of momentum flux on all the days were derived by subtracting the spectral densities obtained with the pair of east-west and north-south frequency spectra and dividing

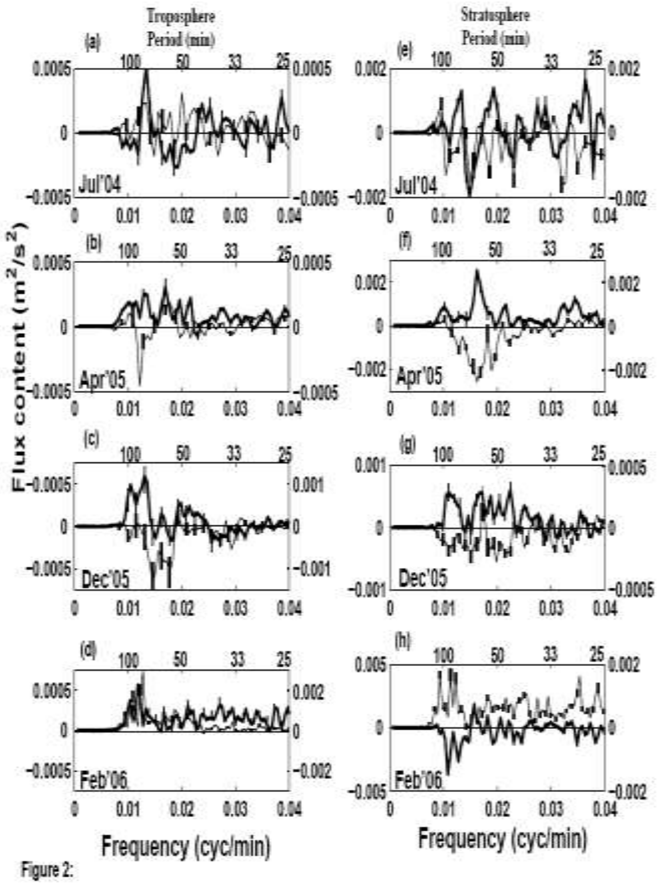

Fig. 2 Left panel: Frequency spectra of short period (<2 h) zonal (thick line, left hand ordinate) and meridional (thin line, right hand ordinate) momentum fluxes in flux content form for 15-16 July 2004 (a); 18-19 April 2005 (b) ; 10-11 December 2005 (c) and 12-13 February 2006 (d) in the troposphere. Right panel: Same as left panel but for stratosphere (e, f, g and h).

the resultant spectral density by $2\sin 2\theta$, where θ is the beam pointing angle [13]. The momentum flux frequency spectra were then averaged over the altitudes between 4-15 km and 17-20 km and are shown in Fig. 2 and Fig. 3 for <2 h and 2-8 h gravity waves respectively. Error bars plotted on the spectra indicate 95% confidence level of spectral stability. Zonal and meridional spectra, in general, display similar nature for both the period bands with higher values for the zonal component. The zonal

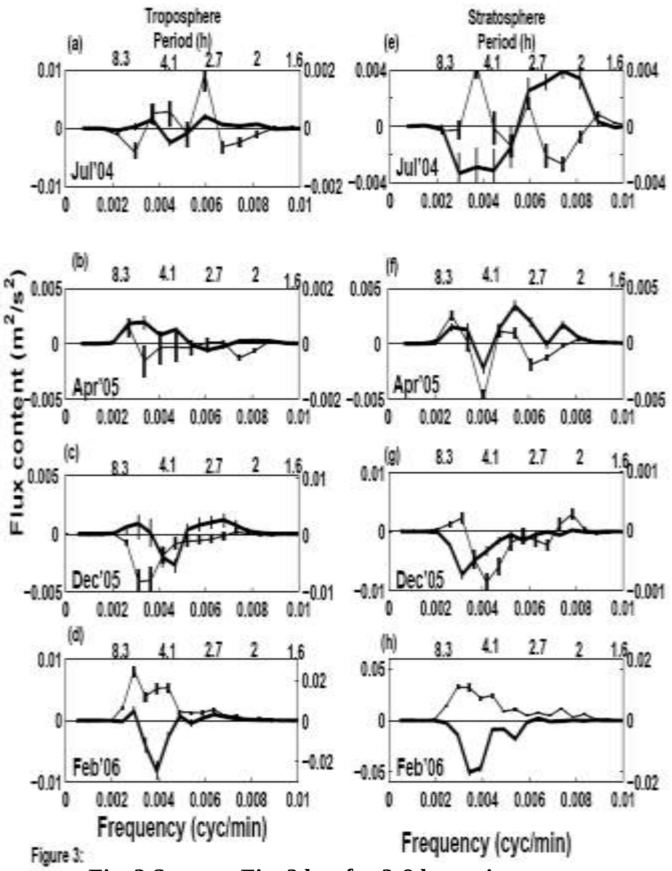

Fig. 3 Same as Fig. 2 but for 2-8 h gravity wave.

wind over Gadanki is mostly westward during the months of May-October in the middle and upper troposphere which slowly changes its sign above ~20km. It is eastward in the same altitude region between November and April. Easterly jets prevail below the tropopause during the Indian summer monsoon (June, July, August) with strong wind shear which contributes to the enhancement of gravity wave momentum flux. The momentum flux spectra of 15 July, 2004 in the stratosphere are found to be more isotropic in nature. Correlation between momentum flux and wind shear in the stratosphere is found to be quite appreciable in this case.

Convection is also a major source of gravity wave activity in this tropical station and its characteristics are very different. The ground temperature in the month of April is found to be very high with lager values of storm height [20]. Localized convection is found to be intense with large raindrop size distribution [21] and becomes an important source of gravity wave in this month. The zonal/meridional spectra on 18-19 April 2005 are predominantly eastward/southward. The convective activity develops in to a more organized system in the months of July-August. Shorter periods (50-75 min and 2-4 h) are found to be more prominent in the months of July and April when convection is intense.

Topography is also supposed to be an important source of gravity waves with horizontal wavelengths of tens to hundreds of kilometers. The north-east surface winds of ~ 4-5 ms $^{-1}$ magnitude crosses sharp ridges of ~ 1000 m altitude on the north-east side of Gadanki during the months of November, December, January and are likely to give rise to gravity waves

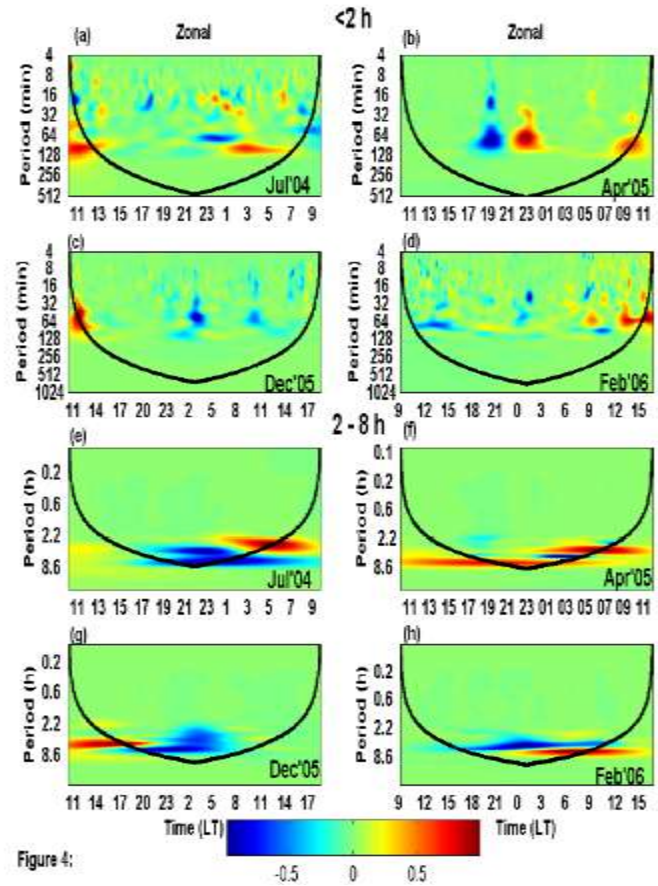

Fig. 4 Upper panels: Momentum flux wavelet transforms for the altitude region between 17-20 km for 15-16 July 2004 (a); 18-19 April 2005 (b) ; 10-11 December 2005 (c) and 12-13 February 2006 (d) for <2 h gravity wave. The momentum fluxes are normalized to the maximum magnitude and the scale includes positive and negative values. Lower panels: Same as upper panels but for 2-8 h (e, f, g, h) gravity wave.

[20]. The stratospheric momentum flux spectra of December and February show the prominence of little longer period (60-90 min and 5-6 h) gravity waves suggesting possibly a greater contribution due to topography. So the sources of gravity waves appear to be different for different seasons.

In general structures are found to be similar for both <2 h and 2-8 h gravity waves. Oscillations in the 60-100 min period band dominate over the very short period (<1 h) spectra which are observed to be more isotropic. Reference [7] also reported that wave packets with periods less than an hour may individually carry significant momentum but contribute little to the integrated spectrum in the stratosphere. But their observations that most of the momentum flux is carried by waves at periods ≥ 4 h in the stratosphere does not agree with our findings. Jicamarca is a tropical site in the southern hemisphere and hemispheric asymmetry could be responsible for this discrepancy. Periods between 2.5 to 6 h are found to be prominent in the 2-8 h gravity wave band (Fig. 3) which show both positive and negative peaks leading to lesser values of flux estimates in the mean profiles compared to the <2 h fluxes. Background wind profiles (figure not shown) are found to be directed mostly opposite to the momentum flux particularly in the stratospheric region which can be considered as the propagating region. In general gravity waves are known to propagate upward when they move against the background wind.

C. Wavelet Transform Momentum Flux Spectra

The wavelet transform is ideally suited to look into the temporal localization of the forcing and the corresponding dominant periods. The wavelet transform momentum flux spectra were obtained by subtracting the wavelet transforms of the radial velocity variances of two symmetric beams using Morlet wavelet and then normalizing them to a peak value of ±1 at the highest variances. Fig. 4 displays the wavelet transforms of the stratospheric zonal momentum fluxes in two period bands (<2 h and 2-8 h) for all the four days. Short period (<2 h) fluxes are observed to be confined mostly within the cone of influence whereas the estimates of 2-8 h band show stronger fluxes to be out of the cone thereby reducing its significance. Significant variability with time can be seen on each day which cannot be appreciated form the mean profiles and frequency spectra of momentum flux. The diagrams of Fig. 4 can be compared with the corresponding stratospheric zonal spectra of Fig. 2 and Fig. 3 (e, f, g, h) to derive some meaningful insight of the variability. Fig. 4a shows numerous positive and negative estimates for <2 h gravity waves with time for periods between 10- 90 minutes which can also be seen in Fig. 2e. The Fig. 4b depicts discrete packets of momentum flux estimates only in the time interval between 18- 09 h (LT) with an average flux which is positive for a wave period at ~ 60 – 64 min (Fig. 2f). Fig. 4e and Fig. 4d also show variation of positive and negative fluxes of high frequency gravity waves with time leading to an average positive (eastward) flux (Fig. 2g and Fig. 2h). A similar comparison can be carried out for Fig. 4(e, f, g, h) with corresponding Fig. 3(e, f, g, h) which reveal that only a few events seem to contribute significantly to mean momentum fluxes and dominate the averages. A similar observation was made by [15]. The wavelet transforms of meridional momentum fluxes also show similar features (Figure not shown).

IV. SUMMARY

This paper addresses an important issue of comparison of momentum fluxes carried by gravity waves in two period bands (<2 h and 2-8 h) and is the first of its kind using radar data of a tropical Indian site in the northern hemisphere. The long data sets used in the present study has led to meaningful estimates of the flux which are found to be an order higher than the corresponding errors. Gravity waves of <2 h period are observed to carry higher momentum fluxes compared to 2-8 h periodicity in upper troposphere and lower stratosphere. Oscillations between 60-100 minutes are found to be stronger and carry most of the flux estimates whereas for periods <1 h, the flux is more isotropic and contribute little to the mean momentum fluxes. In the longer period band, prominent oscillations between 2.5 - 6 h are found to be isotropic in nature leading to lesser mean flux estimates in the stratosphere. Wavelet transforms show significant variability and localization of the estimates with time. The dominant gravity wave momentum fluxes are found to arise from discrete and localized wave packets in frequency and time.

ACKNOWLEDGEMENTS

The Indian MST radar Project was funded jointly by DOE, DOS, DOEn, DST, DRDO and CSIR with DOS as the nodal agency. The author is grateful to Indian Space Research Organization (RESPOND), Government of India, for providing financial assistance to run the project. The authors are grateful to Director, NARL, India for providing raw data for the research. The program (Atmospheric Data Processing) provided by V. K. Anandan is gratefully acknowledged. The authors thank the anonymous reviewer for his constructive comments which substantially improved the quality of the paper.

REFERENCES

[1] Peltier, W. R., and T. L. Clark (1979), The evolution and stability of finite-amplitude mountain waves. Part II: Surface wave drag and severe downslope windstorms. *J. Atmos. Sci., 39,* 1498-1529.

[2] Dutta, G., M. C. Ajay Kumar, P. Vinay Kumar, M. Venkat Ratnam, M. Chandrashekar, Y. Shibagaki, Md. Salauddin, and H. A. Basha (2009), Characteristics of high frequency gravity waves generated by tropical deep convection: Case studies, *J. Geophys. Res., 114,* D18109, doi: 10.1029/2008JD011332.

[3] McLandress, C., M. J. Alexander, and D. L. Wu (2000), Microwave Limb Sounder observations of gravity waves in the stratosphere: A climatology and interpretation, *J. Geophys. Res., 105,* 11,947-11,967.

[4] Alexander, M. J., J. H. Beres, and L. Pfister (2000), Tropical stratospheric gravity wave activity and relationship to clouds, *J. Geophys. Res.*, *105*, 22,299-22,309.

[5] Nastrom, G. D., and D. C. Fritts (1992), Sources of Mesoscale Variability of Gravity waves, Part I, Topographic excitation, *J. Atmos. Sci., 49,* 101-110.

[6] Fritts, D. C., (1984a), Gravity wave saturation in the middle atmosphere: A review of theory and observations, *Rev. Geophys., 22,* 275-308.

[7] Riggin, D. M., D. C. Fritts, C. D. Fawcett, E. Kudeki, and M. H. Hitchman (1997), Radar observations of gravity waves over Jicamarca,

Peru during the CADRE campaign, *J. Geophys. Res., 102,* D22, 26,263-26,281.

[8] McAfee, J. R., B. B. Balsley, and K. S. Gage (1989), Momentum flux measurements over mountains: Problems associated with the symmetric two-beam radar technique, *J. Atmos. Oceanic Technol., 6,* 500-508.

[9] Fukao, S., T. Sato, T. Tsuda, S. Kato, M. Inaba, and I. Kimura (1988), VHF Doppler radar determination of the momentum flux in the upper troposphere and lower stratosphere: Comparison between the 3- and four-beam methods, *J. Atmos. Oceanic Technol., 5,* 57-69.

[10] Fritts, D.C., T. Tsuda, T. E. VanZandt, S. A. Smith, T. Sato, S. Fukao, and S. Kato (1990b), Studies of velocity fluctuations in the lower atmosphere using the MU radar, II, Momentum fluxes and energy densities, *J. Atmos. Sci., 47,* 51-66.

[11] Fritts, D. C., and R. A. Vincent (1987), Mesospheric momentum flux studies at Adelaide, Australia: Observations and a gravity wave/tidal interaction model, *J. Atmos. Sci., 44,* 605-619.

[12] Reid, I. M., and R. A. Vincent (1987), Measurements of mesospheric gravity wave momentum fluxes and mean flow accelerations at Adelaide, Australia, *J. Atmos. Terr. Phys., 49,* 4433-4460.

[13] Nakamura, T., T. Tsuda, M. Yamamoto, S. Fukao, and S. Kato (1993c), Characteristics of gravity waves in the mesosphere observed with the middle and upper atmosphere radar, 1. Momentum flux, *J. Geophys. Res., 98,* D5, 8899-8910.

[14] Murphy, D. A., and R. A. Vincent (1993), Estimates of momentum flux in the mesosphere and lower thermosphere over Adelaide, Australia, from March 1985 to February 1986, *J. Geophys. Res., 98,* 18,617-18,638.

[15] Fritts, D. C., D. Janches, D. M. Riggin, R. G. Stockwell, M. P. Sulzer, and S. Gonzalez (2006), Gravity waves and momentum fluxes in the mesosphere and lower thermosphere using 430MHz dual-beam measurements at Arecibo: 2. Frequency spectra, momentum fluxes, and variability, *J. Geophys. Res., 111,* D18108, doi: 10.1029/2005JD006883.

[16] Rao, P. B., A. R. Jain, P. Kishore, P. Balamuralidhar, S. H. Damle, and G. Vishwanathan (1995), Indian MST radar: 1. System description and sample vector wind measurements in ST mode, *Radio Sci., 30,* 1125-1138, doi: 10.1029/95RS00787.

[17] Vincent, R. A., and I. M. Reid (1983), HF Doppler measurements of mesospheric gravity wave momentum fluxes, *J. Atmos. Sci., 40,* 1321-1333.

[18] Dutta, G., P. V. Rao, M. C. Ajay Kumar, P. Vinay Kumar, H. Aleem Basha, V. K. Anandan, and A. K. Ghosh (2005), On the optimum time of integration for estimation of momentum flux from VHF radar data, *Geophys. Res. Lett., 32,* L15811, doi: 10.1029/2005GL023777.

[19] Dutta, G., P. Vinay Kumar, P. V. Rao, M. C. Ajay Kumar, K. S. Mukarram, V. Harshavardhan, and P. B. Rao (2007), On the optimal radar beam angle to minimize statistical estimation error of momentum flux using conjugate beam technique, *Geophys. Res. Lett., 34,* L22802, doi: 10.1029/2007GL030652.

[20] Dutta, G., T. Tsuda, P. V. Kumar, M. C. Ajay Kumar, S. P. Alexander, and T. Kozu (2008), Seasonal variation of short –period (<2 h) gravity wave activity over Gadanki, India (13.5 º N, 79.2 º E), *J. Geophys. Res., 114,* doi: 10.1029/2007/JD009178.

[21] Kozu, T., K. K. Reddy, S. Mori, M. Thurai, J. t. Ong, D. N. Rao, and T. Shimomai (2006), Seasonal and diurnal variations of raindrop size distribution in Asian monsoon region, *J. Meteorol. Soc. Jpn., 84A,* 195-209.

