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# Long-term mean vertical velocity measured by MST radar at Gadanki (13.5° N, 79.2° E)

**P. V. Rao**[1], **P. Vinay Kumar**[2], **M. C. Ajay Kumar**[3], **and G. Dutta**[2]

[1]Vasavi College of Engineering, Ibrahimbagh, Hyderabad – 500 031, India
[2]Anwarul-uloom College, New Mallepally, Hyderabad – 500 001, India
[3]Seethaiah Memorial Engineering College, Bandlaguda, Hyderabad – 500 005, India

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**Abstract.** MST radars are capable of measuring vertical motion along a vertically directed beam. We present 8 years (1995–2003) averaged profile of vertical velocity in the troposphere and the lower stratosphere over Gadanki (13.5° N, 79.2° E), a tropical station. A downward mid-tropospheric $\bar{w}$ is observed with a reversal of sign around 10 km and a further reversal can also be seen at ∼17 km. A significant diurnal and semidiurnal variation in vertical wind is observed for all heights with subsidence during the evening hours. Seasonal variability of vertical wind is also found to be quite appreciable. Vertical velocities have been derived using symmetric pairs of off-vertical beams and a comparison has been made with direct vertical beam measurements. Vertical components estimated from E-W and N-S radial velocities do not match and are also found to have discrepancy with direct measurements. Plausible causes of the discrepancy have been investigated with the help of some case studies. Vertical shear in horizontal wind, gradients in horizontal velocities and echo power imbalance may be some of the factors responsible for the observed discrepancy.

**Keywords.** Atmospheric composition and structure (Middle atmosphere – composition and chemistry) – Electromagnetics (Antenna arrays)

## 1 Introduction

Vertical velocity is an important dynamical parameter for various atmospheric processes like estimation of momentum fluxes which influence the success of numerical weather prediction models (Miller et al., 1989) and vertical transport between the troposphere and stratosphere (Balsley et al., 1988). However, direct measurements of this key parameter are sparse, particularly in the tropics. MST radars have the unique capability to make direct measurements of atmospheric vertical motions above the site. The long term mean value of the vertical wind velocity is very useful in studying the large-scale circulation pattern (Fritts, 1984) and wave transport phenomenon (Fritts, 1989). Nastrom and Gage (1984) studied climatology of vertical wind variability in the troposphere and stratosphere using the Poker Flat MST radar, Alaska. Measurements of vertical velocities by radar in the lower and middle atmosphere have proven to be valuable in defining the character and variability of the motion spectrum resulting from gravity wave and tidal motions (Hoppe and Fritts, 1995). Efforts have been made in the past to measure vertical velocity using VHF and UHF radars but were met with partial success. The accuracy of vertical velocity measurements have often been questioned, since tilting of reflecting layers could adversely affect the vertical velocities derived from MST radar observations (Röttger, 1980, 1981). Gage (1983) presented an overview of the measurements of atmospheric vertical motion using MST radar technique and observed consistency with the magnitudes of vertical motion obtained by other methods. Larsen and Röttger (1986) compared vertical velocity measurements with SOUSY VHF radar to the analyzed vertical velocities produced by the European Centre for Medium Range Weather Forecasting (ECMRWF) model for grid points near the radar site and observed very good agreement in both the overall magnitude and direction. Jagannadha Rao et al. (2003) made a comparison of the mean vertical velocities measured by radiosonde data using kinematic and adiabatic methods. They reported that the kinematically derived vertical velocities tend to approach the radar values as the spacing between the radiosonde stations decreases. The greater variability of the vertical velocities observed by the radar was attributed to propagating gravity waves. Measurements of vertical velocities directly by radars have yielded valuable information and

*Correspondence to:* G. Dutta
(gopadutta@yahoo.com)

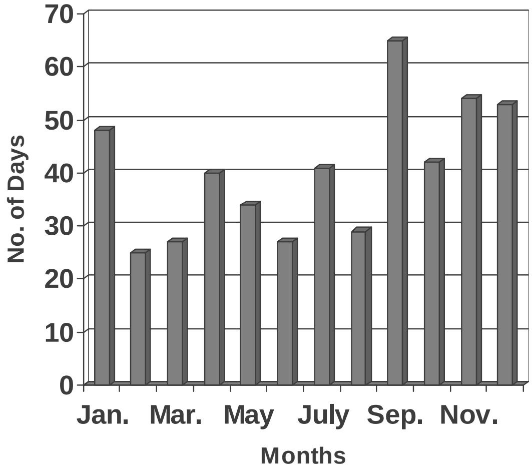


**Fig. 1.** A histogram representing days of data collection spread over a period of 8 years (1995–2003).

it is now well accepted that VHF radars do provide vertical velocity estimates to a useful precision.

The aim of this paper is to study the climatology of vertical velocity using wind data of 8 years obtained by VHF radar at Gadanki. Our paper is organized as follows: In Sect. 2 we outlined the system description and data used for the present study. Results and discussions are presented in Sect. 3. Finally the results are summarized in Sect. 4.

## 2 Radar system and data description

The Indian MST radar at Gadanki (13.5° N, 79.2° E) is a high power VHF radar operating at ∼53 MHz in coherent backscatter mode with an average power aperture product of $\sim 7\times10^{8}$ W m$^2$ with a peak power of 2.5 MW. The phase antenna array consists of 1024 (32×32) three-element Yagi antennas occupying an area of 130 m$^2$. A detailed description of the radar has been given by Rao et al. (1995). The standard operation of Indian MST radar is carried out in two modes. In one mode, it is operated daily in the evening for half an hour to 45 min around 17:00 LT (12:00 GMT). In the second mode, the radar is operated for about 15 min in each hour in a 24 h cycle (diurnal cycle) twice in a month. The available evening and diurnal cycle wind data over 8 years between 1995 and 2003 have been used to study the climatology of vertical wind. The histogram of the data used is presented in Fig. 1. In the year 1998, the radar was operated every alternate hour for one day in each month only in the vertical mode. The vertical wind data collected during these special experiments have also been used to find the structure of mean measured vertical wind profile. Case studies have been taken up using wind data collected during some special experiments conducted between (9–13) May and 15–16 July 2004. The details of the data and Experimental Specification Files (ESF) used for these experiments are given in Table 1. Spectral data collected by the radar have been processed both on-line and off-line (Dutta et al., 1999; Sasi et al., 1998) to obtain radial velocities. Outliers have been removed by taking mean wind in 45 min to 1 h section for evening and continuous data respectively for each height and discarding values exceeding 1.7 times the standard deviation. Similar procedure has been followed for diurnal cycle but by taking mean wind in a 3 h section. Data gaps, if any with respect to height are filled up by linear interpolation.

**Table 1.** Experimental specifications.

| Specifications | 15–16 July 2004 | (9–13) May 2004 |
|---|---|---|
| Data length | 24 h | 6 h |
| Time gap | 2.5 min | 4 min 40 s |
| No. of range bins | 150 | 150 |
| No. of FFT points | 256 | 512 |
| No. of coherent integrations. | 64 | 64 |
| No. of incoherent. integrations. | 1 | 1 |
| IPP | 1000 | 1000 |
| Pulse width | 16 $\mu$s | 16 $\mu$s |
| No. of beams | 5 (E,W,N,S,Zy) | 6 (E,W,N,S,Zy $Z_X$) |
| Beam angle | 10° | 10° |

## 3 Results and discussion

### 3.1 Mean vertical wind profile

Vertical wind profiles measured by the vertically directed radar beam for 8 years in the common mode have been averaged separately for evening and diurnal cycle data. Evening data of each day has been used to compute mean vertical velocity profile of each month. Monthly profiles have then been split into three seasons: summer (May, June, July, August), equinox (March, April, September, October) and winter (November, December, January, February) and the mean profiles of vertical wind for each season have been obtained. The evening data could be contaminated by the diurnal and semi-diurnal variation of the wind. The diurnal cycle data of vertical winds were harmonically analyzed to obtain diurnal and semi-diurnal components and averaged for three seasons as mentioned before. The values of diurnal and semi-diurnal components for the evening (16:00 LT) time were then reconstructed using the amplitudes and phases obtained by harmonic analysis. The sum of the two components are then subtracted from the monthly averages of vertical wind profiles belonging to different seasons appropriately and the corrected monthly profiles of vertical winds are obtained. The diurnal cycle data of vertical wind is averaged over each day. The mean of the corrected monthly profiles of evening data and diurnal cycle (each day's average) vertical wind profiles is then calculated and considered as the mean vertical velocity profile over this tropical site and is shown in Fig. 2.

The standard error has been calculated as $\frac{\sigma}{\sqrt{N}}$ where $\sigma$ is the standard deviation of the wind values at each height and $N$ is the number of observations. The error so calculated has been plotted at a few heights as mean estimate ±std error. The solid line is a sixth order polynomial fit through the data points which shows a smooth variation of vertical velocity with height.

The structure of vertical velocity profile over Gadanki shows a wave like structure with downward motion in the mid-troposphere with a reversal of sign below the tropopause. A further reversal can be seen at ~17 km. The observed structure matches with the vertical wind profile model reported in Worthington et al. (2001) (Fig. 1c) and can be explained by model 5 of his paper. This model considers a real residual mountain wave component since the phase of mountain waves above the radar is not completely random (Worthington, 1999). The Indian MST radar, located at Gadanki, is surrounded by hills with a maximum height of 500–1000 m above the mean sea level. So, the local topography is complex, with a number of small hills and there is some scope for gravity waves and mountain waves to develop, since hills of 100-m height are also capable of generating mountain waves (Worthington et al., 2001). Huff et al. (1975) reported that the small hills of 120-m heights around southern Illinois did affect the atmosphere and caused more rainfall.

Mean values of vertical velocity $\overline{w}$ obtained in the present study are found to lie between $\pm 1.5\,\mathrm{cms}^{-1}$. Using three years data (1995–1998), Jagannadha Rao et al. (2002) reported vertical velocity ranging between ~3 to $20\,\mathrm{cms}^{-1}$ for the same site. Huaman and Balsley (1996) compared the vertical wind profiles of three tropical stations Piura, Pohnpei and Christmas Island. They observed that all profiles (mean of 2–3 years) exhibited a small but measurable subsidence of the order of $1\,\mathrm{cms}^{-1}$, which was well in line with the mean vertical wind profile deduced independently by a convergence technique for the tropical pacific region under clear air condition (Reed and Recker, 1971). Nastrom and VanZandt (1994) reported that the mean vertical motion observed using the VHF radar at Flatland and at Liberal are downward in the troposphere ranging in magnitude from about 3 to $7\,\mathrm{cms}^{-1}$. They go to zero near the tropopause and are often slightly positive in the lower stratosphere regardless of weather, time of the day or season. The authors suggest that the dominant effect causing non-zero $\overline{w}$ is small changes in the refractive index induced by vertically propagating gravity waves. The $\overline{w}$ measurements for June 1990 to December 1999 by the Aberystwyth (52.42° N, 4.00° W) MST radar had been reported by Worthington (1999). The mean vertical wind is found to be as much as $3\,\mathrm{cms}^{-1}$ downward in the troposphere and more weakly upward in the stratosphere. Using Chung-Li VHF radar (24.9° N) data collected between 1995–2001, Chen (2006) reported wave like structures in vertical velocities which had similar features as observed in the tropics.

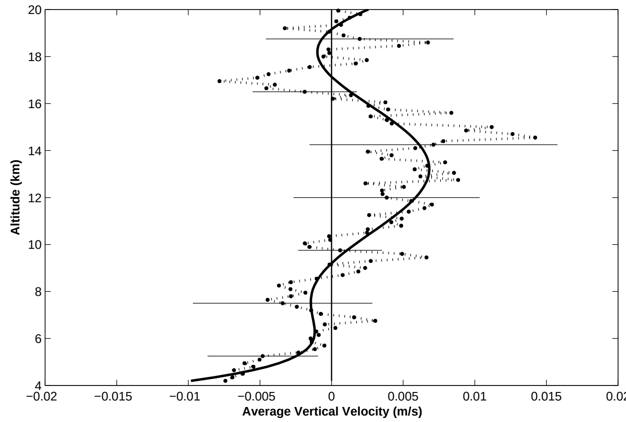


**Fig. 2.** Height profile of mean vertical wind W measured by the VHF radar at Gadanki (solid line represents polynomial fit of 6th order; dotted line represents actual profile).

The largest negative vertical velocities observed by him vary between $-0.4$ to $60\,\mathrm{cms}^{-1}$.

### 3.2 Diurnal and seasonal variations of vertical wind

The diurnal cycle of vertical velocity from profiler measurements can be determined by stratifying the vertical velocity measurements by time of a day. The variation of vertical motions and their variability in the tropical atmosphere are topics of considerable interests among the meteorologists. Furthermore, since diurnal cycles are unlikely to be influenced by any instrumental bias, they can also help with the interpretation of the profiler-observed mean vertical motion in the tropics (Gage et al., 1992). It has long been recognized that there are important diurnal variations in tropical cloudiness and precipitation (Brier and Simpson, 1969).

The hourly averaged diurnal cycle vertical wind data of 33 days are plotted with local time for three altitude blocks (4–9.75) km, (9.9–15) km and (15.15–20) km and are shown in Fig. 3. Polynomial fits of fourth order have been given to the data points (solid lines) which show the presence of semi-diurnal components. When the data is split into seasonal and monthly averages a diurnal component can also be seen (figure not shown). Gage et al. (1992) also reported a diurnal cycle in the generally downward tropospheric motion at Christmas Island which is an equatorial station. But the 10 years averaged $\overline{w}$ for a mid-latitude station, Aberystwyth, did not show clear diurnal effect.

The monthly mean profiles of vertical winds have been grouped and averaged for three seasons – summer, equinox and winter, as explained earlier in Sect. 3.1. Height variations of vertical winds for different seasons are depicted in Fig. 4, which shows higher negative values in mid-troposphere (5 km to 10 km) during summer months. Wave-like structures are seen in all the three seasons. Negative Values observed in the mid-troposphere and lower stratosphere range

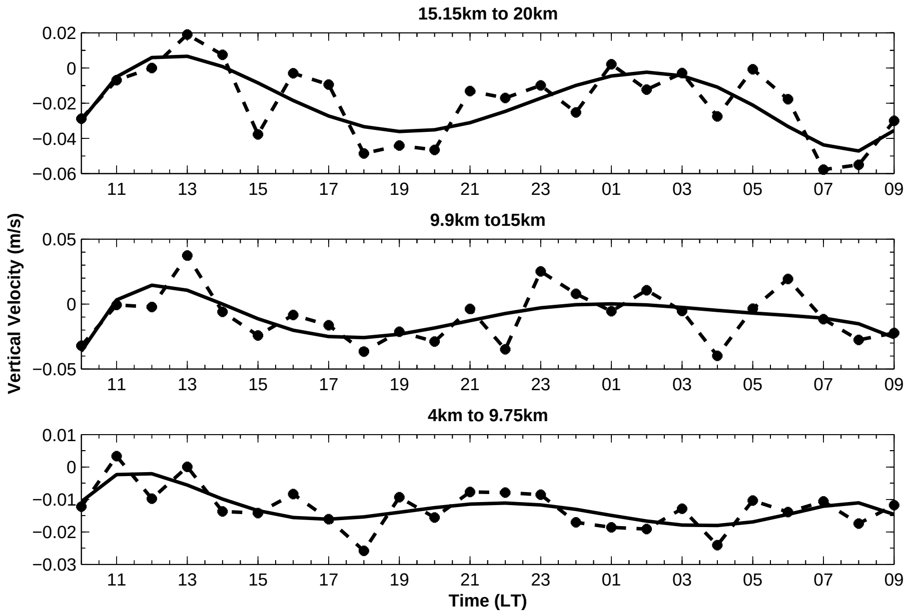


**Fig. 3.** Diurnal variation of mean vertical velocity in three different height blocks.

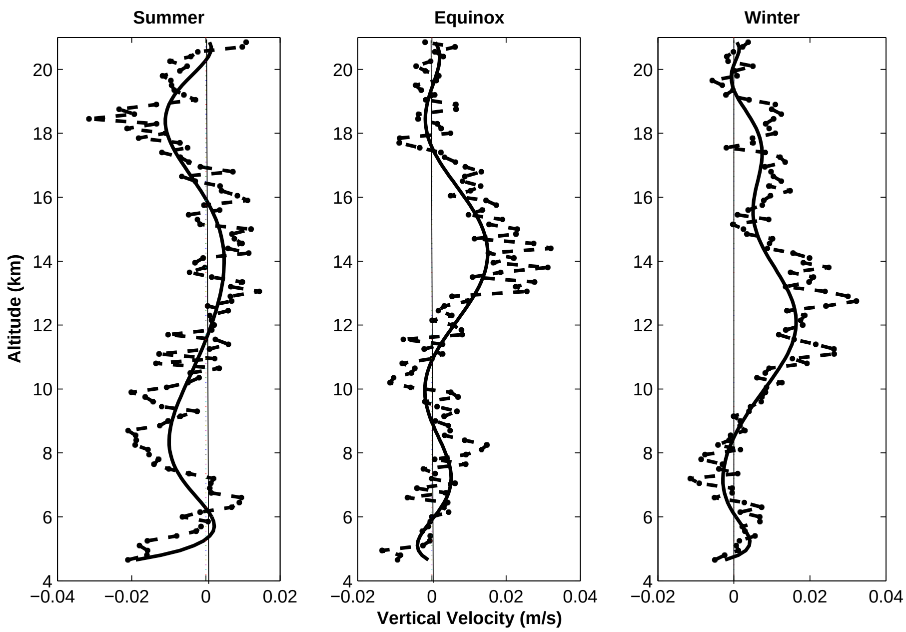


**Fig. 4.** Seasonal variation of mean vertical velocity (Solid line represents the polynomial fit and dashed line represents the actual profile).

between $-3$ to $+1\,\mathrm{cms}^{-1}$ for summer season. Positive values with higher magnitudes ($-1$ to $3\,\mathrm{cms}^{-1}$) are found in the upper troposphere for equinox and winter. Jagannadha Rao et al. (2002) observed large negative velocities $\sim 20\,\mathrm{cms}^{-1}$ in the lower troposphere during monsoon and also found variation of mean vertical velocity from season to season. The large downward motion was attributed to the presence of gravity waves. Gravity wave activity at this tropical station is reported to be high (Dutta et al., 1999; Nagpal et al., 1994; Revathy et al., 1994).

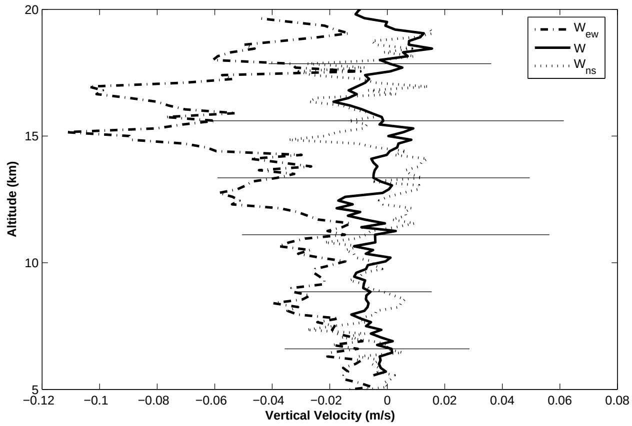


**Fig. 5.** Average profiles of measured and derived vertical velocities using E-W ($W_{ew}$) and N-S ($W_{ns}$) radial beams. Error bars are plotted on mean measured vertical velocity.

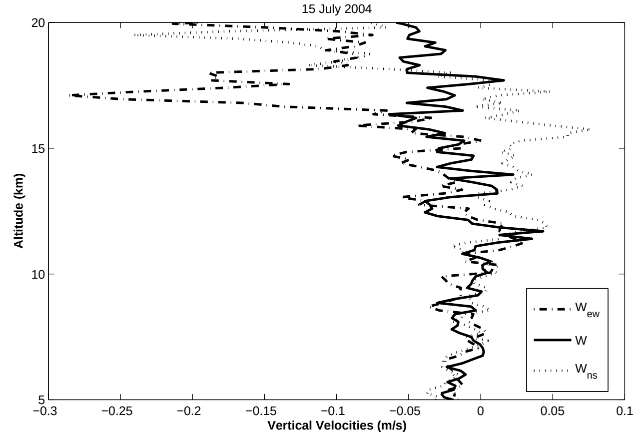


**Fig. 6.** Comparison of derived vertical velocities ($W_{ew}$ and $W_{ns}$) with direct measurements.

### 3.3 Comparison of derived and measured vertical velocities

The vertical winds can be derived from oblique beam radial velocities:

$$W_{ew} = \frac{v_E + v_W}{2\cos\theta} \quad W_{ns} = \frac{v_N + v_S}{2\cos\theta} \tag{1}$$

where $v_E$, $v_W$, $v_N$ and $v_S$ represent the radial velocities in the east, west, north and south directions respectively. The vertical winds derived from E-W and N-S radial winds averaged over 8 years are shown in Fig. 5 along with direct vertical wind measurement for comparison. It can be seen that the two derived vertical wind profiles do not match with each other and also found to have discrepancy with direct measurements. The derived vertical velocity from N-S radial winds agree quite well with the measured vertical wind whereas the one derived from E-W radial velocities show some discrepancy, particularly near the tropopause and in the lower stratosphere. It has been pointed out earlier that the structure of the mean measured vertical velocity profile over Gadanki can be explained by mountain wave model. But for a real, residual mountain wave component the derived vertical velocities from symmetric beam pairs should be similar, if the horizontal beam separation is small compared to the horizontal wavelength of gravity waves and aspect sensitivity is negligible (Worthington et al., 2001). The present observations differ in this respect. Case studies have been taken up to find the plausible causes of the discrepancy.

#### 3.3.1 Case study – I

Vertical velocities derived from E-W and N-S radial beams of 24 h continuous wind measurements (15–16 July 2004) are shown in Fig. 6 along with the direct measurements of $\overline{w}$. Lot of discrepancy can be observed in the lower stratosphere particularly for the vertical wind derived from E-W radial beams. The SNR values near the tropopause and in the lower stratosphere are poor. So one of the reasons of the discrepancy in this altitude region could be due to degradation of data quality. July, being one of the months of S-W monsoon, a strong easterly jet $\sim$42 $\mathrm{ms}^{-1}$ was present during the observations at an altitude of $\sim$16 km. Zonal wind shear at the corresponding heights was also very high. Figure 7 shows height variation of the difference between measured vertical wind and derived vertical velocity from E-W radial beams (upper left panel), height variation of zonal shear (upper right panel) and corresponding variations for N-S beams and meridional shear (lower panels). A good correlation is quite apparent in zonal wind case. The cross-correlation coefficients obtained for zonal wind case is 0.6. Meridional shear does not show good correlation. Correlation between the difference of two derived vertical velocities and wind shear in total horizontal wind is also quite appreciable (0.5). The results of the case studies have been tested for all available days. A good positive correlation is observed in 65% cases. Muschinski (1996) has shown that the "KHI bias" in vertical velocity observed by a vertically pointed VHF radar is upward in the shear zone above the horizontal jet speed maximum and downward below. But the present case study with VHF radar at Gadanki does not support this theory.

The difference between the derived vertical velocities using symmetric beam pair could be due to the gradient in horizontal velocity. This effect has been studied following the equations of Reid (1987)

$$W_{ew} = \frac{v_E + v_W}{2\cos\theta} = \overline{w} + \frac{\partial\overline{u}}{\partial x} z \tan^2\theta \tag{2}$$

$$W_{ns} = \frac{v_N + v_S}{2\cos\theta} = \overline{w} + \frac{\partial\overline{v}}{\partial y} z \tan^2\theta \tag{3}$$

where $W_{ew}$ and $W_{ns}$ are the two derived vertical winds from E-W and N-S beams, respectively, $\overline{w}$ is the true vertical wind,

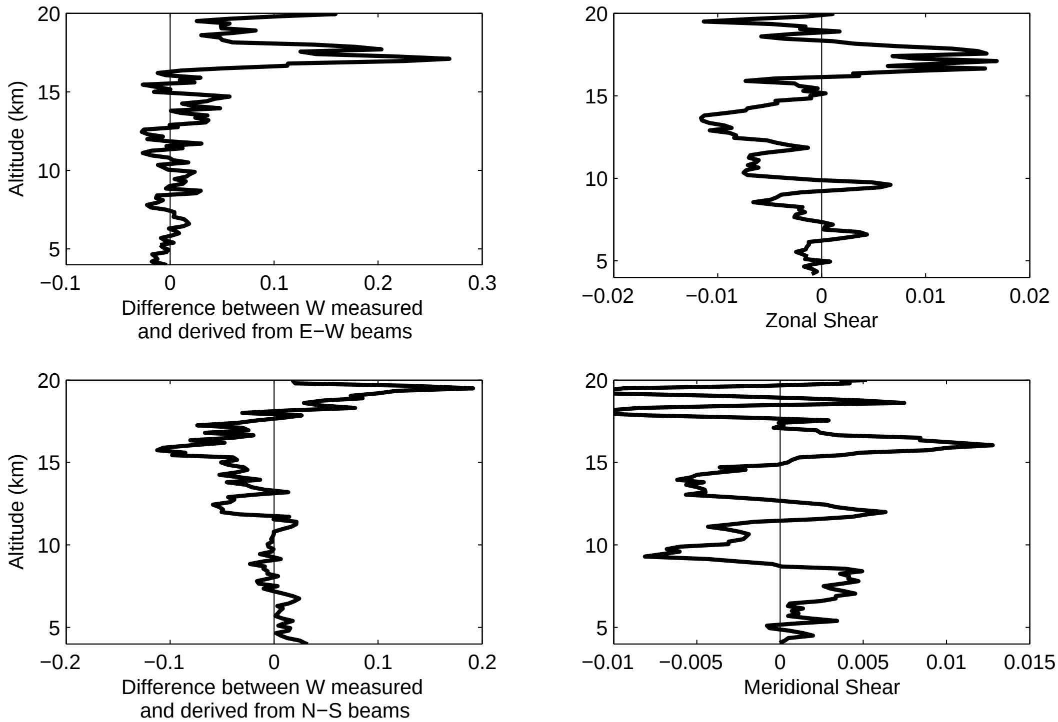


**Fig. 7.** Height variation of difference between measured vertical wind and derived from E-W radial beams (upper left panel), height variation of zonal shear (upper right panel) and similar variations but for N-S beams and meridional shear ( lower panels).

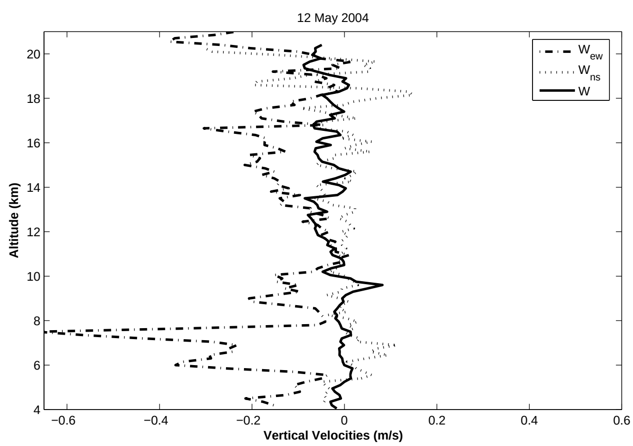


**Fig. 8.** Same as Fig. 6, but for a different day (12 May 2004).

$\frac{\partial \overline{u}}{\partial x}$ and $\frac{\partial \overline{v}}{\partial y}$ are the horizontal gradient in zonal and meridional velocities, $z$ is the corresponding altitude and $\theta$ is the beam separation angle. These two equations indicate that if a gradient exists in the mean horizontal wind, then the vertical component cannot be calculated from the two off-vertical coplanar beams. The author also showed that horizontal gradients of about 0.1 $\mathrm{ms^{-1}\,km^{-1}}$ will make a significant contribution to the derived vertical velocity in the height range of 80–96 km. We have investigated the discrepancy between the two derived vertical winds in the light of gradients in horizontal wind. We have chosen 16.65 km as the altitude where the discrepancy is significant. The zonal ($u_1$, $u_2$) and meridional ($v_1$, $v_2$) velocities can be derived at the height of interest using the measurements made by the two oblique beam pairs E-W and N-S following the equations:

$$u_1(v_1) = \frac{v_E(v_N) - w\cos\theta}{\sin\theta} \tag{4}$$

$$-u_2(-v_2) = \frac{v_W(v_S) - w\cos\theta}{\sin\theta} \tag{5}$$

Here, the direct measurement of $w$ has been accepted as an independent estimate. The differences of wind velocities at this height are found to 1.2 $\mathrm{ms^{-1}}$ for zonal component and 0.2 $\mathrm{ms^{-1}}$ for meridional component for a horizontal beam separation of 6 km and this leads to the gradients of 0.2 $\mathrm{ms^{-1}\,km^{-1}}$ and 0.03 $\mathrm{ms^{-1}\,km^{-1}}$, respectively. This shows that the larger deviation of the vertical wind from direct measurement using E-W radial beams could partially be due to the larger gradient of horizontal wind in the E-W direction, which is an order higher than the gradient in N-S direction.

### 3.3.2 Case study – II

Another case study of the discrepancy is shown in Fig. 8 for 12 May 2004 where the difference in derived (E-W) and

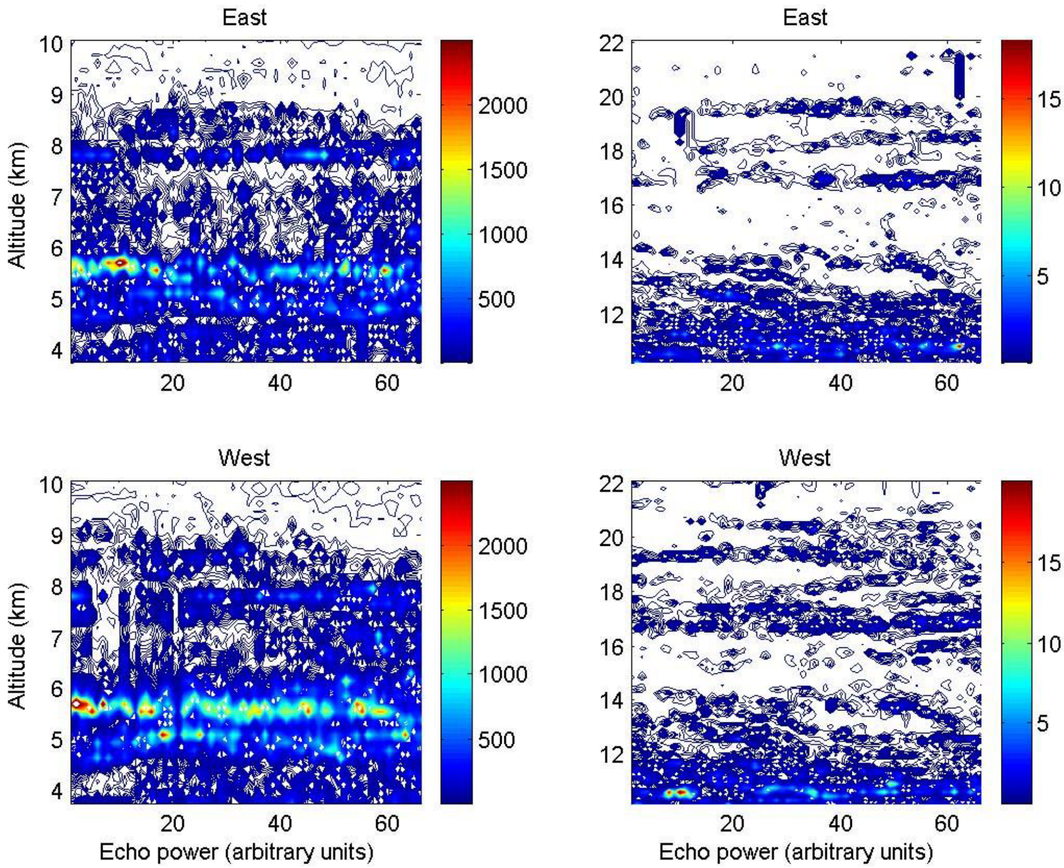


**Fig. 9.** Contours of echo power for radial velocities (12 May 2004) in two altitude ranges 4–10 km (left panel) and 10–20 km (right panel). Corresponding contour intervals are 5 ms$^{-1}$ and 0.5 ms$^{-1}$.

measured vertical wind is observed in the lower troposphere where SNR condition is good. The derived vertical wind using meridional components shows a very good agreement with vertical beam measurement. Wind shear and wind gradient are supposed to be quite insignificant at this altitude range. An inspection of the echo power contours (Fig. 9) of east and west beams showed appreciable difference in the height range of 5–8 km where the discrepancy is pronounced. Echo powers of north and south beams show almost identical powers. So the difference between $W_{ew}$ (Eq. 1) and measured vertical velocity could partially be attributed to the difference in echo powers of the symmetric radial beams. The measurements in the two radial beams may be affected due to random measurement errors and outliers. Any failure to remove the outlier will allow large errors in the measurements for one beam and thereby introduce a significant error in the derived vertical velocity. There is also a risk of differing levels of random measurement error in the two time series of radial velocities at each height, especially in the low SNR conditions near the top of the radar height range where the data quality for one beam may degrade more rapidly than the other (Worthington and Thomas, 1996). Hocking et al. (1986) mentioned the effect of VHF noise contributed by astrophysical sources in reducing the SNR in one of the pair of beams. Disagreement between direct and indirect estimates of vertical velocity were also noted by Yoe et al. (1994) who attributed it to the tilting of anisotropic scattering layers.

## 4 Summary

We have presented the climatology of vertical wind, one of the most important dynamical parameters of the atmosphere, over a tropical station Gadanki. Tropics are highly active regions but the available data are very sparse. The long time average (8 years) of vertical wind profile is found to have wave like structure with negative velocity in the mid-troposphere with a reversal around 17 km. The mean magnitude of the vertical wind is found to vary between $\pm 1.5$ cms$^{-1}$ and agrees quite well with other reported measurements. The structure can be explained with the mountain wave model proposed by Worthington et al. (2001). Gadanki is surrounded by hills of 500–1000 m heights which are capable of producing some mountain wave activity in conducive atmospheric conditions. A prominent diurnal and semidiurnal variation in vertical wind is observed for all heights with larger subsidence during the evening hours. The diurnal variation is reasonably consistent with the hypothesis that the vertical motion is radiatively determined by the balance of diabatic and adiabatic processes. Seasonal variation of vertical wind shows larger negative values during monsoon (summer) and positive values during equinox and winter.

The vertical winds have also been derived using horizontal radial beam measurements. A discrepancy is observed between the two vertical winds derived from E-W and N-S beams and also between the derived and directly measured vertical velocity with vertical beam. An attempt has been made to investigate the plausible causes of this discrepancy. The difference between the direct measurement and the one derived using N-S symmetric beams is less compared to that of the E–W derived one. Vertical shear in horizontal wind, gradients in horizontal wind velocities and echo power imbalance seem to contribute to the observed inconsistencies. Worthington (1999) observed reasonable agreement between the derived and measured vertical winds for a beam angle of 6°. It is felt that for lower beam angles like 6°, the contribution of vertical wind in the horizontal wind measurement is more and hence the derived vertical wind may have better agreement with the measured one. Of course, we have to remember that the discrepancy is significant near the tropopause and in the lower stratosphere where SNR conditions are poor degrading the reliability of the measurements.

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## References

Balsley, B. B., Ecklund, W. L., Carter, D. A., Riddle, A. C., and Gage, K. S.: Average Vertical Motions in the Tropical Atmosphere observed by a radar wind profiler on Pohnpei (7° N, 157° E), J. Atmos. Sci., 45, 396–405, 1988.

Brier, G. W. and Simpson, J. S.: Tropical cloudiness and precipitation related to pressure and tidal variations, Q. J. Roy. Meteorol. Soc., 5, 120–147, 1969.

Chen, J. S.: Long-Term Mean Vertical Wind observed by the Chung-Li VHF Radar, Terr. Atmos. Ocean. Sci., 17, 317–327, 2006.

Dutta, G., Bapiraju, B., Balasubrahmanyam, P., and Basha, H. A.: VHF radar observations of gravity waves at a low latitude, Ann. Geophys., 17, 1012–1019, 1999, http://www.ann-geophys.net/17/1012/1999/.

Fritts, D. C.: Gravity wave saturation in the middle atmosphere: A review of theory and observations, Rev. Geophys. Space Phys., 22, 275–308, 1984.

Fritts, D. C.: A review of gravity wave saturation process, effects and variability in the middle atmosphere, Pure Appl. Geophys., 130, 343–371, 1989.

Gage, K. S., McAfee, J. R., and Reid, G. C.: Diurnal variation in vertical motion over the central equatorial Pacific from VHF wind-profiling Doppler radar observations at Christmas Island (2° N, 157° W), Geophys. Res. Lett., 19, 1827–1830, 1992.

Gage, K. S.: On the measurement of vertical velocity by MST radar, in: Handbook for MAP, vol. 9, edited by: Bowhill, S. A. and Edwards, B., pp 215–226, SCOSTEP. Secr. Urbana, III, 1983.

Hocking, W. K., Ruster, R., and Czechowski, P.: Absolute reflectivities and aspect sensitivities of VHF radio wave scatterers measured with the SOUSY radar J. Atmos. Terr. Phys., 48, 131–144, 1986.

Hoppe, U. P. and Fritts, D. C.: On the downward bias in vertical velocity measurements by VHF radars, Geophys. Res. Lett., 22, 619–622, 1995.

Huaman, M. M. and Balsley, B. B.: Long term average vertical motions observed by VHF wind profilers: The effect of slight antenna-pointing inaccuracies, J. Atmos. Oceanic Technol., 13, 560–569, 1996.

Huff, F. A., Changnon, S. A., and Jones, D. M. A.: Precipitation increases in the low hills of southern Illinois. Part I: Climatic and network studies, Mon. Weather Rev., 103, 823–829, 1975.

Jagannadha Rao, V. V. M., Venkat Ratnam, M., and Narayana Rao, D.: Study of mean vertical motions over Gadanki (13.5° N, 79.2° E), a tropical station, using Indian MST radar, Radio. Sci., 37, 1108, doi:10:1029/2001RS002505, 2002.

Jagannadha Rao, V. V. M., Narayana Rao, D., Venkat Ratnam, M., Mohan, K., and Vijay Bhaskar, S.: Mean vertical velocities measured by Indian MST radar and comparison with indirectly computed values, J. Appl. Meteorol., 42, 541–552, 2003.

Larsen, M. F. and Rottger, J.: A comparison of thunderstorm reflectivities measured at VHF and UHF. J. Atmos. Oceanic Technol., 4, 151–159, 1986.

Miller, M. J., Palmer, T. N., and Swinbank, R.: Parmameterization and influence of subgridscale orography in general circulation and numerical weather prediction models, Meteorol. Atmos. Phys., 40, 84–109, 1989.

Muschinski, A.: Possible effect of Kelvin-Helmholtz instability on VHF radar observations of the mean vertical wind, J. Appl. Meteorol., 35, 2210–2217, 1996.

Nagpal, O., Praveen Kumar, P. D., and Dhaka, S. K.: Characteristics of tropospheric gravity waves by the Indian MST radar: ST mode operation, Indian J. Radio Space Phys., 23, 6–11, 1994.

Nastrom, G. D. and Gage, K. S.: A brief climatology of vertical wind variability in the troposphere and stratosphere as seen by the Poker Flat, Alaska, MST radar, J. Clim. Appl. Meteorol., 23, 453–460, 1984.

Nastrom, G. D. and VanZandt, T. E.: Mean vertical motions seen by radar wind profilers, J. Appl. Meteorol., 33, 984–994, 1994.

Rao, P. B., Jain, A. R., Kishore, P., Balamuralidhar, P., Damle, S. H., and Viswanathan, G.: Indian MST radar 1, System description and sample vector wind measurements in ST mode, Radio Sci., 30, 1125–1138, 1995.

Reed, R. J. and Recker, E. E.: Structure and properties of synopticscale wave disturbances in the equatorial western pacific, J. Atmos. Sci., 28, 1117–1133, 1971.

Revathy, K., Praseedom, M., and Prabhakaran Nayar, S. R.: Short-period fluctuations at low latitude tropospheric heights using MST radar, Indian J. Radio Space Phys., 23, 12–20, 1994.

Ried, I. M.: Some aspects of Doppler radar measurements of the mean and fluctuating components of the wind field in the upper middle atmosphere, J. Atmos. Terr. Phys., 49, 467–484, 1987.

Röttger, J.: Reflection and scattering of VHF radar signals from atmospheric refractivity structures, Radio Sci., 15, 259–276, 1980.

Röttger, J.: Wind variability in the stratosphere deduced from spaced antenna VHF radar measurements, Proc. 20th Conference on Radar Meteorology, American Meteorological Society, 22–29, 1981.

Sasi, M. N., Ramkumar, G., and Deepa, V.: Non migrating diurnal tides in the troposphere and lower stratosphere over Gadanki (13.5° N, 79.2° E), J. Geophys. Res., 103, 19 485–19 494, 1998.

Worthington, R. M.: Calculating the azimuth of mountain waves, using the effect of tilted fine-scale stable layers on VHF radar echoes, Ann. Geophys., 17, 257–272, 1999, http://www.ann-geophys.net/17/257/1999/.

Worthington, R. M., Muschinski, A., and Balsley, B. B.: Bias in mean vertical wind measured by VHF radars: Significance of radar location relative to mountains, J. Atmos. Sci., 58, 707–723, 2001.

Worthington, R. M. and Thomas, L.: The measurement of gravity wave momentum flux in the lower atmosphere using VHF radar, Radio Sci., 31, 1501–1517, 1996.

Yoe, J. G., Gzechowsky, P., Ruster, R., and Schmidt, G.: Spatial variability of the aspect sensitivity of VHF radar echoes in the troposphere and lower stratosphere during jet stream passages, Ann. Geophys., 12, 733–745, 1994, http://www.ann-geophys.net/12/733/1994/.