A Study on Optimum Tilt Angle for Wind Estimation Using Indian MST Radar

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ABSTRACT

The effect of tilt angle on horizontal wind estimation is studied using Indian mesosphere–stratosphere–troposphere (MST) radar located at Gadanki (13.45°N, 79.18°E). It operates in Doppler beam swinging (DBS) mode with a beamwidth of 3°. Horizontal winds are computed for different tilt angles from 3° to 15° with an increment of 3° from a height range of 3.6–18 km. The effective beam pointing angle (θ_{eff}) is calculated to determine the effect of aspect sensitivity on the determination of horizontal wind components. For different tilt angles radar-derived winds are compared with simultaneous GPS sonde wind measurements, which were launched from a nearby site. The first method utilizes direct comparison of radar-derived winds with those of GPS sondes using the actual beam pointing angle; the second method uses the effective beam pointing angle derived from the ratios of two oblique beams. For this study a variety of statistics were explored in terms of standard deviation, correlation coefficient, and percentage error. From the results it is observed that in agreement with previous studies, the effective beam pointing angle deviates from the actual beam pointing angle, which results in the underestimation of horizontal wind components, and also when tilt angle is close to zenith and far from zenith, the estimation of horizontal winds is found to be far from true values at different heights. Radar wind estimation has better agreement with GPS sonde measurement when the off-zenith angle is around 10°. It is also found that correction to the actual beam pointing angle provides 3%–6% improved agreement between the radar and GPS wind measurements.

1. Introduction

VHF radars are widely used worldwide to measure atmospheric winds by the Doppler beam swinging (DBS) method. The quality of horizontal wind velocity estimation measured with VHF radars has been investigated through many kinds of experiments like in situ balloon observations, rocket sondes, and lidar observations (Fukao et al. 1982; Lawrence et al. 1986). Previously operational wind observations have depended on the tracking of weather balloons. It is therefore natural in assessing the performance of wind profiler systems to make a comparison with radiosonde measurements. Several such comparisons have been carried out at a range of latitudes; for example Strauch (1981), Fukao et al. (1982), Weber and Wuertz (1990), Astin and Thomas (1991), May (1993), Steinhagen et al. (1994), and Kishore et al. (2000) have made numerous comparisons with radiosondes. Apart from wind observations, for many years studies have been performed to unravel the back scattering mechanisms that generate the radar returns. A major process believed to contribute to VHF radar echoes from clear air is backscatter from small-scale turbulence. Turbulence in the atmosphere produces scatterers, which are elongated in the horizontal direction relative to their vertical extent. This means that when monostatic radar uses a beam directed in an off-zenith direction, the power backscattered to the receiver is diminished more as the tilt angle is moved farther from vertical. If narrow beam radar is used, the power diminishes as a function of zenith angle (Hocking 2001) according to

$$P(\theta) = P(0)\, e^{-\sin^2\theta/\sin^2\theta_s},$$

where θ is the tilt angle of the radar beam, $P(0)$ is the power received on the vertical beam, $P(\theta)$ is the power

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received on the off-vertical beam, and θ_s parameterizes the properties of the scatterers.

An essential property of the mesosphere–stratosphere–troposphere (MST) radar echoes operating at the lower VHF band is the dependence of the received power as a function of zenith angle. It was observed that echo power often strongly decreases as the radar beam is pointed away from zenith. This phenomenon is referred to as aspect sensitivity. Many studies have been made on aspect sensitivity since 1978 (Gage and Green 1978; Rottger and Liu 1978; Tsuda et al. 1986; Hocking et al. 1990; Hooper and Thomas 1995; Jain et al. 1997; Worthington et al. 1999, 2000). In spite of these investigations, the signatures of radar signals for different processes such as scattering from isotropic/anisotropic turbulence and Fresnel reflection/scattering from thin horizontally stratified and strong refractive index gradients are still not well understood, since it is difficult to distinguish the generation mechanisms. This difficulty has implications for studies directed toward turbulence intensities, Doppler wind measurements, and the nature of stable or turbulent layers. Thus the scattering process makes the backscattered echo aspect sensitive, which in turn influences the beam pointing angle and thereby determination of Doppler wind measurements. In the DBS system, radar can be directed in turn between vertical and several off-vertical beam directions. Beams tilted at larger angles are sensitive to weaker scatter compared to beams pointing overhead. Therefore, due to aspect sensitivity, the consequence is an underestimation of horizontal winds. This is because the effective radar beam pointing angle in the oblique direction is closer to the zenith rather than to the true beam direction (Hocking 1997). It has been reported in the literature that aspect sensitivity of radar echoes is a cause of underestimates of wind speeds by VHF radars (Hocking 1989; Hocking et al. 1990; Damle et al. 1994; Jain et al. 1997; Thomas et al. 1997; Kawano and Fukao 2001).

The purpose of the present study is to examine the effect of tilt angle on horizontal wind measurements from the observations of Indian MST radar. A quantitative study has been made for horizontal wind velocities using different tilt angles in two methods. Results have been compared with GPS sonde measurements. In the first method horizontal winds are computed for tilt angles of 3°, 6°, 9°, 10°, 12°, and 15° in the height range of 3.6–18 km. Radar-derived winds for the above zenith angles were compared with corresponding GPS sonde wind measurements and various statistics were explored. In the second method horizontal winds are computed using an effective beam pointing angle that is derived from the ratios of powers at two zenith angles of 6° and 12° in the east–west direction and then again compared with GPS sonde measurements. In the comparisons some random differences are expected between the two sets of measurements due to the spatial and temporal resolution of sampling used by the two different techniques.

TABLE 1. Radar parameters used for the experiment.

Parameter	Value
No. of beam positions	36
Pulse width	16 μs (complementary code with 1-μs baud)
Interpulse period	1000 μs
No. of range gates	150
No. of coherent integrations	64
No. of FFT points	256
No. of incoherent integrations	1
Range resolution	150 m
Observation window	24–174 μs (3.6–25.95 km)
Data type	Doppler power spectrum

2. System description and data analysis

The Indian MST radar is located at Gadanki (13.45°N, 79.18°E)—a tropical station surrounded by hills around 200-m height. The Indian MST radar is a highly sensitive VHF phased array radar operating at a frequency of 53 MHz with a peak power aperture product of 3×10^{10} W m^2. The complete phased array consists of 1024 crossed three-element Yagi antennas occupying an area of 130 m × 130 m. It generates a radiation pattern with a 3-dB beamwidth of 3°, which corresponds to a two-way beamwidth (θ_o) of 1.8°. The radar beam can be positioned at any look angle within ±20° off zenith in two major planes (east–west, north–south) with a 1° interval. Details of the system description are given by Rao et al. (1995). In the present study, the experiment was conducted using six beams for different zenith angles starting from 3° to 15° with an increment of 3° with a beam sequence north, south, zenith, east, west, and zenith. After completion of this set, measurements were also made with a 10° tilt angle with the same beam sequence. The received echo signal is sampled at intervals of 150 m in the height range of 3.6–25.95 km. The details of the experiment are shown in Table 1. The atmospheric signals were identified by using the adaptive moments estimation technique (Anandan et al. 2005) and first three lower-order moments were estimated using the expressions given by Woodman (1985). This adaptive technique is based on certain criteria, set up for the Doppler window, signal-to-noise ratio (SNR), and wind shear parameters, which are used to adaptively track the signal in the range Doppler spectral frame. Adaptive moments estimation

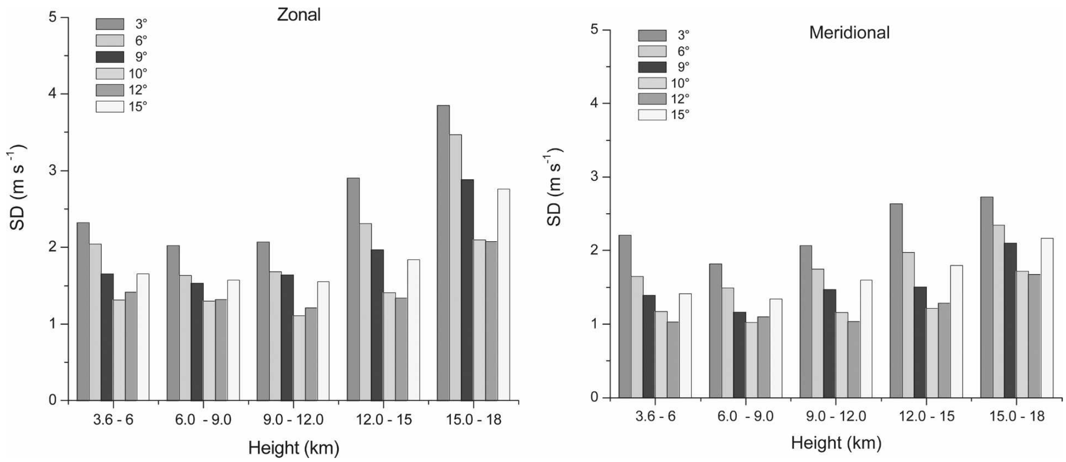

FIG. 1. SD differences in wind velocities between the GPS sonde and the radar observations for different tilt angles.

algorithm has significant advantage in terms of better height coverage compared to the conventional single peak detection method. Though the experiment was designed to cover a height range of up to 25.95 km, the wind information above 18 km was not considered because of poor SNR.

To know the accuracy of wind measurements for different tilt angles, radar-measured winds are compared with simultaneous GPS sonde wind measurements. GPS sondes were launched daily during September–October 2002 from the National Atmospheric Research Laboratory in Gadanki, India, at 1200 UTC. The spatial separation between GPS sonde launch and MST radar is about 100 m. The sonde provides vertical profiles of temperature, pressure, and relative humidity and also the magnitude and direction of the winds. The GPS sondes used in our experiments were a standard type (Vaisala RS-80) suspended from 500-g balloons filled with hydrogen so as to achieve ascent rates typically of 5 $\mathrm{m\,s^{-1}}$. Sonde reports information at every 1-sec interval, corresponding to a vertical resolution of approximately 5 m. So the wind information of GPS sonde is interpolated to the 150-m-range resolution for comparison with MST radar resolution of 150 m. During the balloon launch time MST radar was operated continuously for 2 h with the specifications shown in Table 1. To minimize the spatial separation of radar and balloon measurements, attention is also concentrated on balloons, which travel within 10 km of the radar site. Another quality control check has been made on radar data in which we considered data with vertical velocities less than 30 $\mathrm{cm\,s^{-1}}$ that essentially indicate "clear air" conditions. Therefore the study was limited to only 20 days of observations out of all the available data during September–October 2002.

3. Results and discussion

a. Influence of tilt angle on horizontal winds

Horizontal wind velocities are computed for different zenith angles of 3°, 6°, 9°, 10°, 12°, and 15° using the four-beam technique, as it gives the best performance in wind velocity estimation (Adachi et al. 2005). A variety of statistics were derived to investigate the relationship between GPS wind measurements and radar wind measurements. All the means and standard deviations (SDs) are scalar not vector statistics. The mean and SD for the difference of two measurements are calculated as follows:

$$V_{(D)i} = V_{(\mathrm{GPS})i} - V_{(\mathrm{RAD})i},$$

$$\text{mean } \mu_D = \frac{1}{N}\sum_{i=1}^{N} V_{(D)i},$$

$$\text{standard deviation } \sigma_D = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(V_{(D)i} - \mu_D)^2},$$

where N is the number of observations.

Another important statistical parameter that gives the direct comparison of all the measurements is percentage error (PE). If a represents the true/reference (GPS) value, and b represents the (radar) measured value, the percentage error (δ) is

$$\delta = \frac{|a - b|}{|a|} \times 100\%.$$

Figure 1 shows values of SD for different tilt angles from a height range of 3.6–18 km. The SD values are averaged over 3-km intervals. It is apparent from Fig. 1 that SD is highest for 3° in all the heights and is least for

TABLE 2. SD of wind velocities for different zenith angles.

			Zonal			
Height (km)	3°	6°	9°	10°	12°	15°
3.6–6	2.32	2.04	1.65	1.31	1.41	1.65
6.0–9.0	2.02	1.63	1.53	1.30	1.32	1.57
9.0–12.0	2.07	1.68	1.64	1.11	1.21	1.55
12.0–15	2.90	2.31	1.97	1.41	1.34	1.84
15.0–18	3.85	3.47	2.88	2.1	2.08	2.76
			Meridional			
Height (km)	3°	6°	9°	10°	12°	15°
3.6–6	2.20	1.65	1.39	1.17	1.03	1.41
6.0–9.0	1.81	1.48	1.16	1.02	1.10	1.34
9.0–12.0	2.06	1.75	1.46	1.15	1.03	1.59
12.0–15	2.63	1.97	1.50	1.21	1.28	1.79
15.0–18	2.73	2.34	2.09	1.72	1.67	2.16

10° and 12°. The averaged value of SD for all the heights for 3°, 6°, 9°, 10°, 12°, and 15° angles is 2.63, 2.24, 1.91, 1.44, 1.47, and 1.87 m s^{-1}, respectively. Similarly, in the case of meridional winds the SD is maximum for 3° and minimum for 10° and 12°. The averaged values of SD for meridional winds for zenith angles of 3°, 6°, 9°, 10°, 12°, and 15° are 2.29, 1.84, 1.52, 1.25, 1.22, and 1.66 m s^{-1}, respectively. For both zonal and meridional winds, 10° and 12° have less SD compared to all other angles. Table 2 gives the statistics of SD for zonal and meridional velocities averaged over a 3-km interval. Figure 2 shows the percentage of data points having SD less than 5 m s^{-1} in which zonal velocities are represented within intervals of 1 m s^{-1} and meridional velocities are represented within intervals of 0.5 m s^{-1}. This figure shows the total number of data points averaged for 20 days of observations. In the case of zonal winds, the percentage of data points having SD within 2 m s^{-1} for zenith angles 3°, 6°, 9°, 10°, 12°, and 15° is 27%, 46%, 57%, 64%, 67%, and 61%, respectively. Similarly, in meridional winds the percentage of data points having SD within 1.5 m s^{-1} for zenith angles 3°, 6°, 9°, 10°, 12°, and 15° is 7%, 35%, 50%, 57%, 57%, and 52%. In both cases the maximum number of data points was observed for zenith angles 10° and 12° while the minimum number of points was observed for zenith angles 3° and 6°.

Figure 3 shows scatterplots between GPS sonde wind measurements and radar-derived wind measurements for different zenith angles. A total of 1940 data points were presented in the height range of 3.6–18 km. The left panel shows the zonal wind component and the right panel shows the meridional wind component. We have drawn two zenith angles in the same plot whose correlation coefficients (CCs) are nearly the same and the values are shown in the figure. We have plotted the combinations of 3° and 6°, 9° and 15°, and 10° and 12°. It is noticed from the figure that the values of CC are maximum for beams tilted 10° and 12° and are minimum for beams tilted 3° and 6°. Meridional velocity follows a similar pattern of zonal components for the same zenith angles. Table 3 gives statistics of CC of zonal and meridional wind components averaged over 3-km intervals. At all heights, 10° and 12° has better CC than other off-zenith angles.

The difference of horizontal wind velocities between GPS and radar for all the observation days is shown in Fig. 4 with an interval of 1 m s^{-1} for zonal and meridional wind components. It is observed that most of the

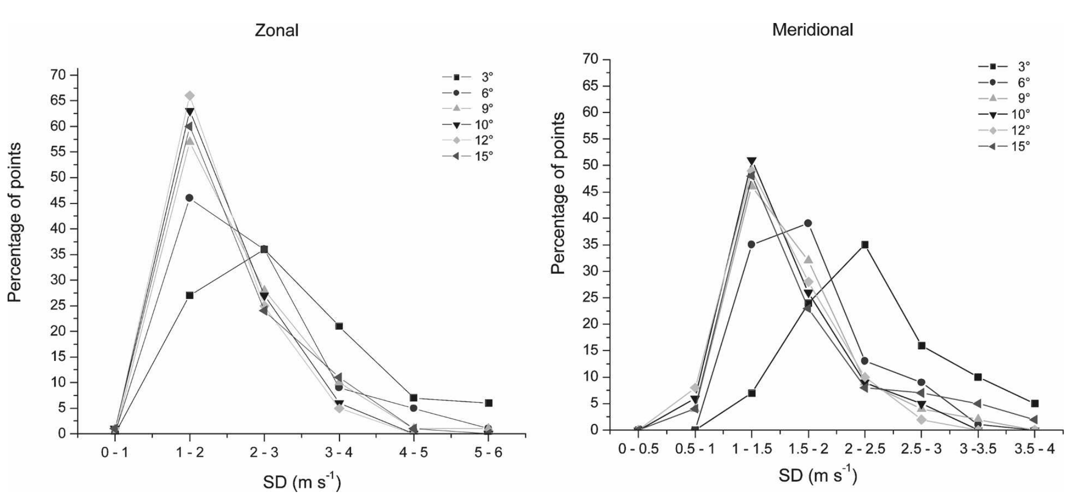

FIG. 2. Percentage of data points having SD differences in the horizontal wind velocities between GPS sonde and radar measurements with an interval of 1 m s^{-1} for the zonal component and 0.5 m s^{-1} for the meridional component.

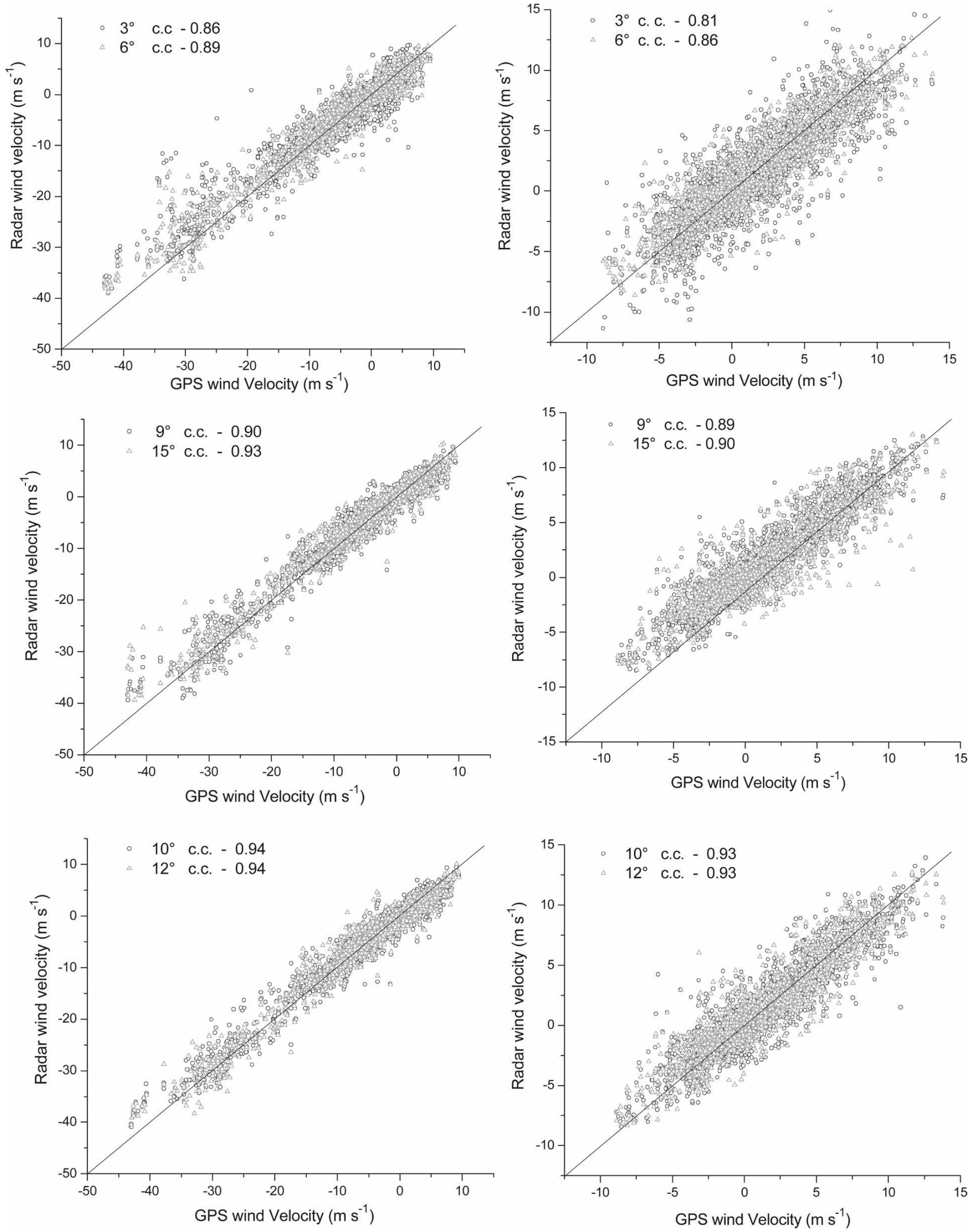

FIG. 3. Scatterplots of the GPS sonde vs the radar measurements for different tilt angles from a height range of 3.6–18 km. (left) Zonal velocity and (right) meridional velocity.

points were within ± 1 m s^{-1} for tilt angles 10° and 12° when compared with other zenith angles. In spite of general agreement between GPS sonde and radar, there are few points where velocity difference is too high. These points were identified especially at higher heights where the spatial separation between GPS sonde and radar is more and the difference can be attributed to the small difference in wind fields as separation increases. Another important statistical parameter that gives the direct comparison of all the measurements is PE. For the calculation of PE we have ignored horizontal velocities less than 1 m s^{-1} measured by both GPS sonde and MST radar, since PE is a direct difference between the two measurements, so small varia-

TABLE 3. CC of wind velocities for different zenith angles.

			Zonal			
Height (km)	3°	6°	9°	10°	12°	15°
3.6–6	0.85	0.88	0.91	0.94	0.94	0.93
6.0–9.0	0.86	0.90	0.90	0.94	0.94	0.93
9.0–12.0	0.85	0.89	0.90	0.95	0.94	0.92
12.0–15	0.86	0.91	0.92	0.96	0.96	0.95
15.0–18	0.87	0.90	0.90	0.93	0.93	0.91
			Meridional			
Height (km)	3°	6°	9°	10°	12°	15°
3.6–6	0.83	0.89	0.92	0.95	0.94	0.92
6.0–9.0	0.85	0.88	0.91	0.94	0.94	0.92
9.0–12.0	0.81	0.87	0.89	0.92	0.93	0.89
12.0–15	0.80	0.86	0.91	0.93	0.93	0.90
15.0–18	0.75	0.81	0.85	0.89	0.89	0.87

tions in horizontal winds are reflected as large PE values. Figure 5 shows PE for different zenith angles for both zonal and meridional velocities. It is observed that PE is highest for 3° in both zonal and meridional components. Table 4 shows values of PE for zonal and meridional components averaged over 3-km intervals. From Table 4 it is observed that PE values are least for 10° and 12° compared to all other zenith angles.

b. *Influence of aspect sensitivity on winds*

To examine the influence of aspect sensitivity for different zenith angles the effective beam angle has been estimated following Hocking et al. (1986) using the expression

$$\theta_{\text{eff}} = \theta\left[1 + \frac{\sin^2\theta_o}{\sin^2\theta_s}\right]^{-1}, \tag{1}$$

in which it is assumed that the two-way polar diagram of the vertically pointing radar beam is proportional to $\exp(-\sin^2\theta/\sin^2\theta_o)$, where θ_o is the e^{-1} half-width of the radar polar diagram of vertical beam. When the radar beam is directed vertically, then the effective radar beam in the presence of anisotropic scatterers is narrower than the true radar beam. In addition, if the radar is pointed off vertical at some angle from zenith, then the effective radar beam has a maximum, which is closer to overhead than the maximum of the radar beam alone. The polar diagram of the backscatter is assumed to be proportional to $\exp(-\sin^2\theta/\sin^2\theta_s)$, where θ is the beam pointing angle and the nature of the returned signal examined in terms of the parameter θ_s, which is the e^{-1} half-width of the radar polar diagram of the backscatter. The parameter θ_s, which is a measure of the degree of anisotropy, can be derived from power received for two zenith angles θ_1 and θ_2 assuming that these two zenith angles share the common θ_s. Using the expression derived by Hooper and Thomas (1995) from the relations given by Hocking et al. (1986, 1990),

$$\theta_s = \sin^{-1}\sqrt{\frac{\sin^2\theta_2 - \sin^2\theta_1}{\ln[P(\theta_1)/P(\theta_2)]} - \sin^2\theta_o}. \tag{2}$$

The parameter θ_s describes the degree of aspect sensitivity and it may be height dependent. If θ_s is tending to zero it is truly a specular reflection and small values of θ_s mean large anisotropy while the much larger values of θ_s represent a greater degree of isotropy at all heights (in practice any value in excess of about 20° can be regarded as almost isotropic). This implies that one shape of scatter contributes to the major part of the scattering over these off-vertical angles. The value of θ_s could then be adopted to derive the effective beam pointing angle in attempting to correct radar measure-

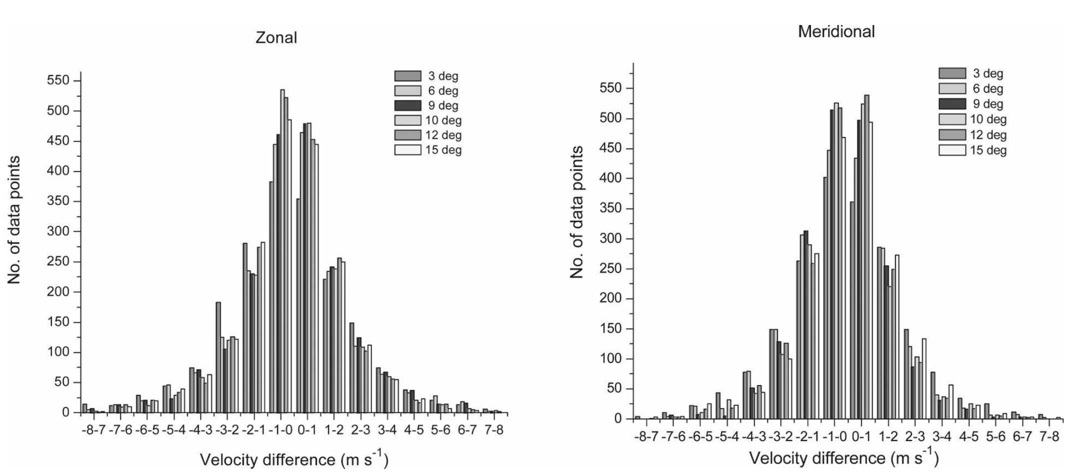

FIG. 4. Horizontal wind velocity differences between GPS sonde and radar plotted with an interval of 1 m s^{-1}.

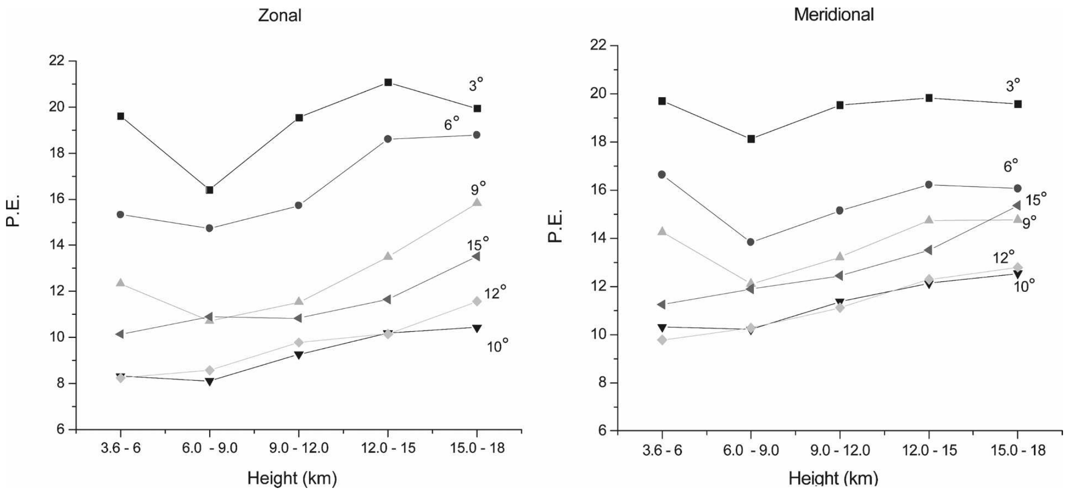

FIG. 5. PE in horizontal wind velocities calculated for different tilt angles.

ments of winds at different zenith angles for the aspect effect, rather than the smaller values derived by including measurements of signal strength in the vertical direction.

It is demonstrated that the use of power in the vertical beam will generally provide too small a value of θ_s from Eq. (2), then too small a value of θ_{eff} from Eq. (1) and hence too large a correction to the horizontal wind speeds (Hooper and Thomas 1995). We have also observed similar kinds of large variations in horizontal winds when we use the vertical beam. Therefore, only the off-vertical beams were considered for the calculation of θ_s.

Figure 6 shows the values of θ_s derived from the combinations of off-vertical beam directions 6°/12° and 9°/15° taken on 20, 21, 23, and 24 September and Fig. 7 shows that of 25, 26, 28 September and 9 October. It is seen that the values derived from 6°/12° and 9°/15° ratios are very similar in most of the cases, suggesting that a single value of θ_s can represent the signal strength measurements at these zenith angles (i.e., one shape of scatter contributes to the major part of the scattering over these zenith angles). Thus the effective beam angle is derived from the comparison of echo powers at zenith angles of 6° and 12° in east–west polarization. It is already explained that wind observation from 3° and 6° off-zenith angles has a maximum error compared with other off-zenith angles of observations; hence the aspect correction for wind measurements is applied only on off-zenith angles of 9°, 10°, 12°, and 15°. Figure 8 shows a comparison of zonal and meridional velocities between GPS and radar measurements. It also includes radar winds derived from the effective beam angle for a tilt angle of 10° on 25 September 2002. It is observed that the aspect corrected profile provides better agreement with the GPS wind measurements. Such comparison of GPS and radar measurements for several individual days shows that the correction for aspect sensitivity can improve the agreement between the two measurements. The overall effect of applying the aspect correction to radar measurements shows significant improvement in all statistical parameters.

It is observed from Fig. 9 that the values of SD in both zonal and meridional winds are less than the values prior to aspect correction as shown in Fig. 1 and come down to between the range 0.2 and 0.4 m s^{-1}. The regression analyses of these comparisons show that CC are enhanced a little after making correction with the effective beam angle. After aspect correction, the CC of zonal winds for zenith angles of 9°, 10°, 12°, and 15° are 0.92, 0.96, 0.96, and 0.94, respectively. Similarly for meridional winds the CC are 0.91, 0.94, 0.95, and 0.92, respectively. Figure 10 shows the PE for zonal and me-

TABLE 4. PE of wind velocities for different zenith angles.

Height (km)	3°	6°	9°	10°	12°	15°
Zonal						
3.6–6	19.61	15.33	12.33	8.31	8.24	10.15
6.0–9.0	16.41	14.73	10.72	8.11	8.57	10.90
9.0–12.0	19.55	15.73	11.53	9.26	9.78	10.84
12.0–15	21.07	18.61	13.50	10.19	10.15	11.65
15.0–18	19.94	18.78	15.84	10.44	11.56	13.52
Meridional						
3.6–6	19.70	16.64	14.26	10.32	9.78	11.25
6.0–9.0	18.13	13.84	12.1	10.21	10.27	11.89
9.0–12.0	19.54	15.15	13.22	11.36	11.12	12.45
12.0–15	19.84	16.23	14.74	12.13	12.29	13.51
15.0–18	19.58	16.06	14.77	12.54	12.79	15.36

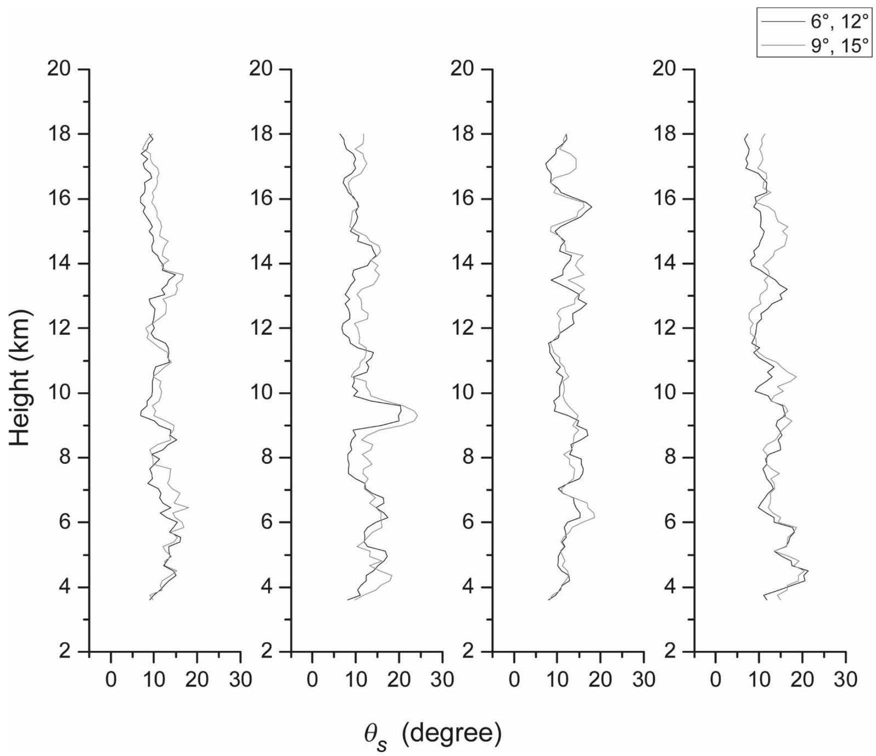

FIG. 6. Height profiles of θ_s for various beam combinations observed on 20, 21, 23, and 24 Sep 2002 in east–west plane.

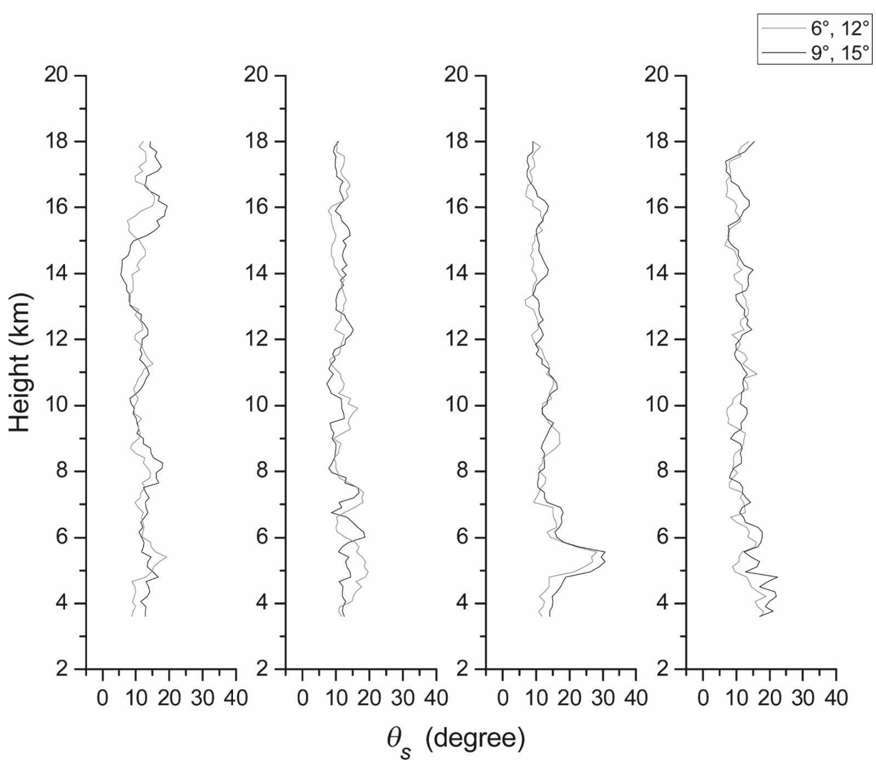

FIG. 7. Height profiles of θ_s for various beam combinations observed on 25, 26, 28 Sep and 9 Oct 2002 in east–west plane.

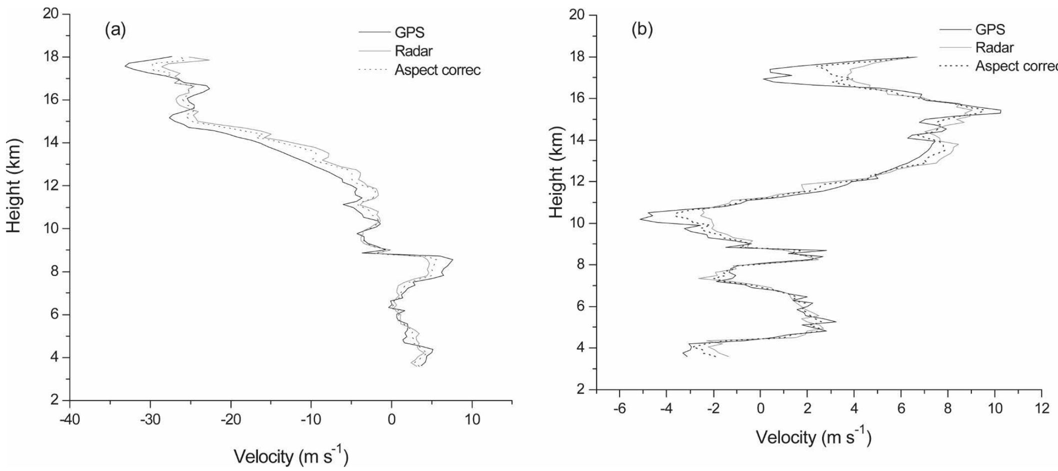

FIG. 8. Vertical profiles of horizontal velocities: (a) zonal and (b) meridional observed with GPS sonde (solid black), radar (solid red), and aspect corrected radar (dotted blue) on 25 Sep 2002.

ridional velocities after making correction with the effective beam angle. From the figure it is observed that there is significant variation in PE values in all the heights. The PE has been reduced on average by 4% and its value varies from 3% to 6%. All the values presented here are the average of 20 days of clear air observations. From all these results it is found that after correcting the effective beam pointing angle for the aspect sensitivity there is an improved agreement between GPS sonde and radar-measured winds and the accuracy of measuring horizontal winds is enhanced by 3%–6%.

This study has been carried out on the data obtained for the months of September and October and this study can be extended to understand the seasonal dependency on the observation reported here.

4. Conclusions

A detailed analysis on the effect of tilt angles on horizontal wind estimation using radar in comparison with GPS sonde observation is presented. The experiment was conducted on clear air conditions, considering uniform wind fields in the observation region. Observations are carried out on off-zenith angles of 3°, 6°, 9°, 10°, 12°, and 15° of the radar, and various statistical parameters such as standard deviation, correlation coefficient, and percentage error were estimated along with GPS sonde observations. In all the observations it is found that wind estimated with 10° and 12° off-zenith observations has better agreement with GPS sonde measurements. An improvement up to 1.2 m s^{-1} in standard deviation, 0.08 in correlation coefficient, and

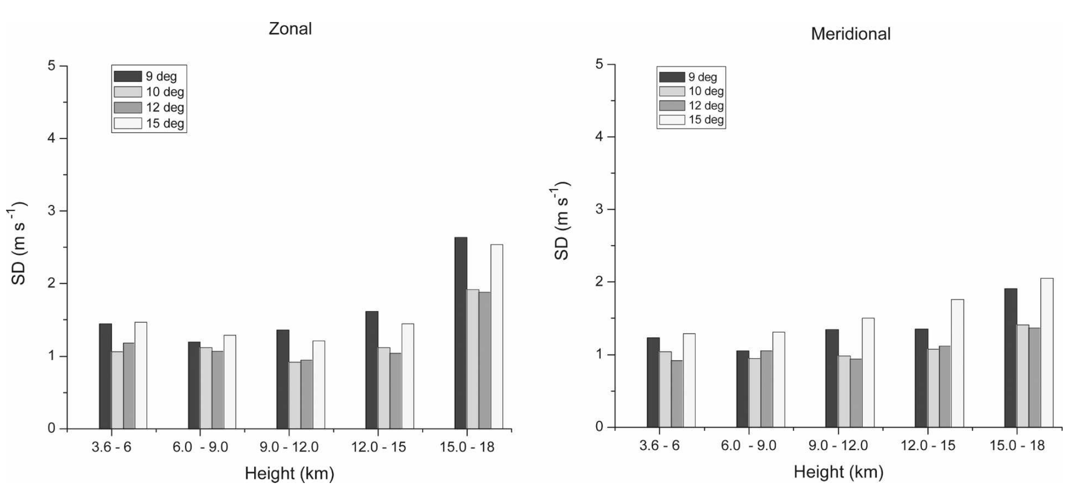

FIG. 9. SD differences in wind velocities between the GPS sonde and the radar observations for different tilt angles after effective beam angle correction.

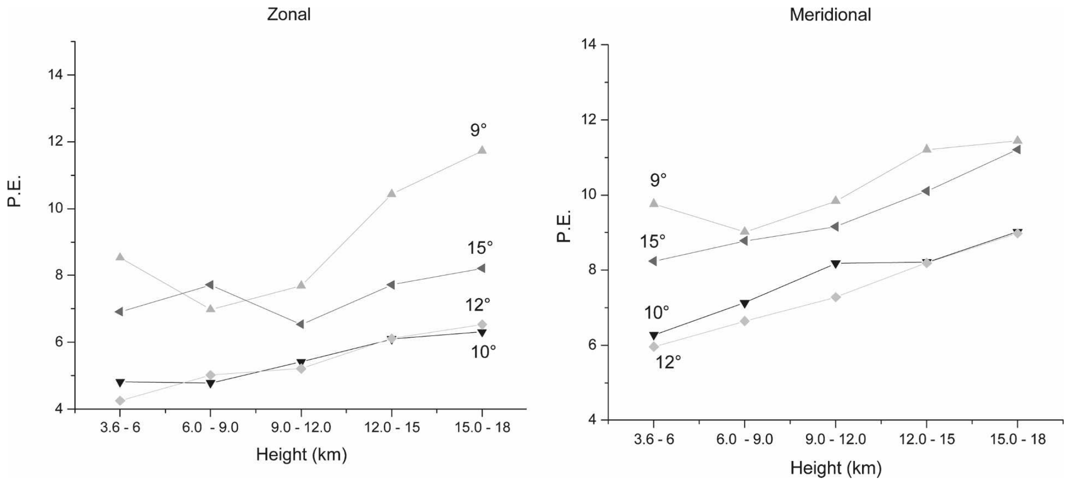

FIG. 10. PE in horizontal wind velocities after effective beam angle correction.

10% in percentage error is observed. The study is extended to understand the influence of aspect sensitivity on the estimation of wind velocities by introducing effective beam angle. It is observed that applying the effective beam angle correction in deriving wind velocity has brought out a better comparison with GPS sonde observations. The statistical parameters estimated also show better values after correcting with the effective beam angle. An improvement of 0.2 m s^{-1} in standard deviation, 0.02 in correlation, and 3%–6% in percentage error is observed after applying the effective beam angle correction. This quantitative and qualitative analysis thus concluded that the optimum beam angle for horizontal wind estimation from MST radar is in between 10° and 12°, and applying the effective beam angle improves the velocity estimate.

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