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Low-latitude mesospheric mean winds observed by Gadanki mesosphere-stratosphere-troposphere (MST) radar and comparison with rocket, High Resolution Doppler Imager (HRDI), and MF radar measurements and HWM93

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[1] Low-latitude mesospheric winds are investigated using data collected from 1995 to 2006 (11 years) by Indian MST radar located at Gadanki (13.5°N, 79.2°E). Clear eastward and westward flow in zonal wind is noticed during solstices and equinoxes, respectively. The meridional wind shows equatorward flow below 75 km and poleward flow above 75 km quite consistent with that observed with other techniques. The winds show a clear semiannual oscillation (SAO) with maxima during equinoxes. The strength of the SAO during spring is larger than that of fall equinox, and the first peak occurs at higher altitudes than the second peak. The observed features are compared with other techniques, namely, rocket, High Resolution Doppler Imager (HRDI), and medium frequency (MF) radar and also with horizontal wind model HWM93. In general, good comparison is seen among various techniques, with some discrepancy observed in amplitudes. Interestingly, decrease in eastward wind with time during winter months is noticed. The significance of the present results lies in showing the consistency/inconsistency of various experimental techniques to measure the middle atmospheric winds, which are very important to assess the climate variability.

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1. Introduction

[2] The dynamics of middle atmosphere, mainly the mesosphere, attained great interest as the amplitudes of long period waves, tides, and gravity waves become comparable in magnitude to that of the prevailing wind and hence the waves deposit their momentum and alter the dynamics. Middle atmospheric dynamics and its variability remained far from understood mainly owing to lack of observations. However, recent development in the observational techniques expanded the knowledge of the middle atmospheric dynamics. Out of the global middle atmosphere, the equatorial and low-latitude mesosphere shows different behavior, due to relatively less Coriolis force, quasi-biannual oscillation (QBO) and semiannual oscillation (SAO) in the zonal wind [*Reed*, 1965; *Hirota*, 1978; *Andrews et al.*, 1987].

[3] Different techniques, like meteor radars and MF radars, rockets, and satellite-based instruments, have been used to study the mesospheric wind circulation. All these instruments, however, are unable to give continuous measurements in the altitude region of 65 to 85 km. Meteor and MF radars are able to provide continuous observations in the height region above 80 km. MF radars usually underestimate mesospheric winds owing to the technique they use [*Manson et al.*, 1987, 1992]. However, wealth of information has been provided by the MF radars particularly on large-scale motions. On the other hand, rocket and satellite observations are able to provide considerable amount of information at these heights but not with good temporal resolutions. Nevertheless, Upper Atmosphere Research Satellite (UARS) has provided new dimensions in understand-

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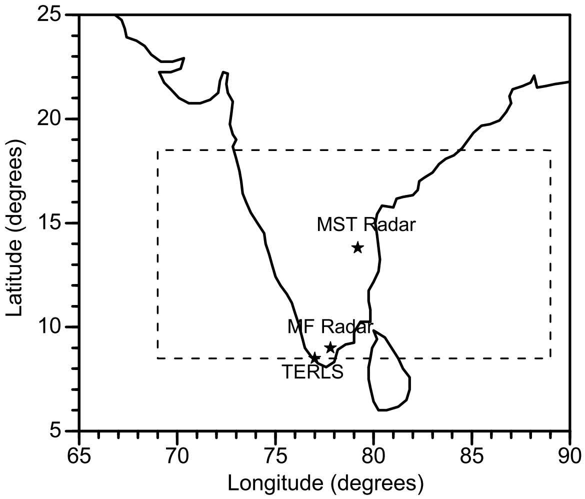

Figure 1. Map indicating the geographic locations of the ground-based instruments (Indian MST radar, Gadanki; MF radar, Tirunelveli; M-100 rocket, Thumba Equatorial Rocket Launching Station (TERLS)) which are used for the present study. Dotted rectangular box shows the latitude and longitude grid chosen from HRDI (High Resolution Doppler Imager) measurements for comparing with ground-based instruments.

ing the global circulation of middle atmosphere [*Burrage et al.*, 1996].

[4] A few models, like CIRA-86 [*Fleming et al.*, 1990], HWM93 [*Hedin et al.*, 1996] and GEWM [*Portnyagin*, 2006], also have given glimpses of the mesospheric circulation. These models, however, have been developed using either winds derived from temperature observations using geostrophic approximation (CIRA-86) or earlier observations of wind (empirical models like HWM93 and GEWM). Moreover, these models are not valid in tropics since the geostrophic approximation fails here [*Hirota et al.*, 1983] and also the observational database used from low latitude is less as compared to those of midlatitudes and high latitudes. Recently, *Portnyagin* [2006] have given a detailed review of mesospheric and lower thermospheric models and discussed the main reasons for the differences among the models.

[5] Among all instruments, VHF radars have proven to be powerful instruments for studying dynamical processes in the middle atmosphere. Since the pioneering work of *Woodman and Guillen* [1974], usage of the VHF radars has emerged as a promising way for studying the structures and dynamics of the atmosphere. The unique capability of this radar technique is to study the horizontal and vertical winds in lower atmosphere 4–20 km and in middle atmosphere ~65–85 km. Such observations are particularly valuable although they are restricted to one location, as they have better time and height resolution than any other techniques mentioned above. Beside these strengths, a few limitations also exist for the wind measurements using MST radars in middle atmosphere which are discussed in detail by *Hocking* [1997].

[6] On the other hand, the general circulation pattern over midlatitude and high-latitude mesosphere is fairly well clarified through various observational techniques and theoretical studies [*Meek and Manson*, 1985; *Manson et al.*, 1987; *Nakamura et al.*, 1996; *Middleton et al.*, 2002] and poorly understood over low latitudes. Only a few studies have been carried out in equatorial and low latitudes with limited data set using VHF radar [*Hitchman et al.*, 1997; *Ratnam et al.*, 2001], rocket soundings [*Chakravarty et al.*, 1992], MF radar [*Vincent*, 1993; *Rajaram and Gurubaran*, 1998], and meteor radar [*Raghava Reddi and Ramkumar*, 1997].

[7] Early observations of mean mesospheric winds at this latitude and their comparison with other ground-based, model, and satellite technique were confined to limited data set spanning over 4 years [*Ratnam et al.*, 2001]. However, in the present study we have used an unprecedented data set to make a comprehensive study on the horizontal mesospheric winds and the same is compared with other techniques. There exist few differences between different techniques as expected. The purpose of this paper is to describe the mesospheric horizontal winds estimated by Indian MST radar and also discuss the possibilities of the discrepancies between different techniques. This also gives an opportunity to assess the climate variability.

2. Observational Database

[8] Present study is mainly focused to delineate the characteristics of low-latitude mesospheric mean winds observed by high time and vertical resolutions observations made using the Indian MST radar. In addition, we also make use of other techniques like ground-based (MF radar, rocket), space-borne (HRDI/UARS), and model (HWM93) data sets for comparison. The locations of the ground-based techniques used in the present study are illustrated in Figure 1. The dotted rectangular box in Figure 1 shows the nominal latitude and longitude region where HRDI data have been used for the comparison. Brief description of each technique and their measuring principles are explained below. Also their advantages/limitations are explained while describing the results. Period of observations for the present study for various techniques and their basic measuring principle along with the reference can be found in Table 1.

2.1. Indian MST Radar, Gadanki (13.5°N, 79.2°E)

[9] The Indian MST radar [*Rao et al.*, 1995] is a high-power coherent pulsed Doppler radar operating at 53 MHz and is located at Gadanki, a tropical station in India. This VHF radar provides winds in troposphere, lower stratosphere, and mesosphere (65–85 km) and it operates in Doppler Beam Swinging (DBS) mode. The main experimental specifications used for the observations related to the present study are given in Table 2. VHF radar echoes from the mesosphere result from refractive index irregularities due to electron density fluctuations having scale sizes of half the radar wavelength (~3 m) (i.e., through Bragg scattering) or from electron density gradient (i.e., through Fresnel reflection/scattering). Atmospheric scatterers are advected with the background air motions, hence three-dimensional velocity vector can be directly deduced from the Doppler shifts of radar echoes received in three independent beam directions. The MST radar wind observations from 1995 to 2006 in the altitude region 65 to 85 km have been used in this study. A more detailed description of the

Table 1. Various Techniques Used, Their Location, Duration of the Observations, Heights and Vertical Resolution, and Basic Measurement Principle Along With the Reference

System Used	Location	Duration of Observations	Height Considered (Vertical Resolution)	Basic Technique	Reference
MST radar	Gadanki (13.5°N, 79.2°E)	1995–2006	65–85 km (2.4 km)	Doppler Beam Swinging (DBS)	*Rao et al.* [1995]
MF radar	Tirunelveli (8.7°N, 77.8°E)	1993–2001	70–86 km (2 km)	Spaced Antenna (SA)	*Vincent and Lesicar* [1991]
M-100 Rocket	TERLS (8.5°N, 77°E)	1977–1991	65–85 km (1 km)	Chaff Payload	*Schmidlin* [1986]
HRDI	8.5°N–18.5°N and 69°E–89°E	1991–2000	65–85 km (2.5 km)	Doppler shifts of O_2 absorption/emission bands	*Hays et al.* [1993]
HWM93	13.5°N and 79.2°E	–	65–85 km (1 km)	Various ground-based and satellite measurements	*Hedin et al.* [1996]

data and signal detectability has been given by *Kumar et al.* [2007].

2.2. MF Radar, Tirunelveli (8.7°N, 77.8°E)

[10] Mesospheric winds observed during 1993 to 2001 with a MF partial-reflection (PR) radar located at Tirunelveli have been used for comparison. This radar operates at 1.98 MHz with a peak transmitter power of 25 kW and provides winds through Spaced Antenna (SA) analysis [*Briggs*, 1984]. The MF radar technique is based on drift measurements of weakly ionized irregularities in the D and lower E regions, which are assumed to move with the neutral wind. The system details, the mode of operation and the method of wind estimation are described by *Vincent and Lesicar* [1991] and will not be repeated here. Some of the results on mean wind climatology observed by this radar is given by *Rajaram and Gurubaran* [1998]. Daytime winds available between 1000 to 1600 LT for the height region of 70–86 km are used for comparing with MST radar observed winds. Average values of winds over 24 h are used to find out the amount of discrepancy that can be expected while averaging for daytime alone. Height resolution of these observations is 2 km.

2.3. Rocket Measurements, Thumba (8.5°N, 77°E)

[11] Wind measurements made by Soviet Meteorological M-100 rocketsondes (M-100) from Thumba Equatorial Rocket Launching Station (TERLS) available between the years 1977 and 1991 are utilized for the present study. Note that there is no overlap between these and the observations from MST radar. These rocketsondes with chaff payload were launched once in a week, on every Wednesday, i.e., on the International Geophysical Day, from TERLS, Thumba and these data are available at the IMAP data center, Bangalore, India. Horizontal wind velocities are determined from the time derivatives of horizontal displacements of the chaff tracked by radar. The weekly values of horizontal winds from M-100 rockets were averaged over a period of 1 month to obtain monthly mean values at every 1-km interval. The same months for different years were averaged to get monthly mean values. More than 700 launches have been used to derive the mean monthly profiles and the same is used in the present study. Some of the results on mean structure of winds from these observations are given by *Chakravarty et al.* [1992].

2.4. High Resolution Doppler Imager (HRDI) Horizontal Winds

[12] The HRDI on board the UARS measures horizontal wind field in the stratosphere (10–40 km) and the mesosphere and lower thermosphere (50–115 km) using the Doppler shift of rotational lines of molecular oxygen [*Hays et al.*, 1993]. The HRDI wind data used in the present study are the level 2B MLT winds. Here we have selected the HRDI winds between the grids 8.5°N to 18.5° N and 69°E to 89°E from 1991 to 2000, ignoring the latitudinal variations within this band, to get reliable number of profiles for each month. We have also estimated latitudinal difference in the zonal and meridional winds between Thumba (8.5°N) to MST radar (13.5°N) from HRDI measurements. Difference in the zonal (meridional) wind during summer and winter is found to be (not shown here) 6 m/s (3 m/s) and 2 m/s (<2 m/s), respectively which are not so significant when compared to their background winds magnitude. More or less same differences are also noticed between 8.5°N and 18.5°N. Much attention is given to the monthly mean values observed during daytime (1000 to 1600 LT) in between 65 and 85 km. However, complete 19 h values (since HRDI provide 19 h observations) are used to find out the amount of discrepancy that can be expected while averaging during daytime alone.

2.5. Horizontal Wind Model 93 (HWM93)

[13] Horizontal winds derived from HWM93 are also used for comparison. HWM93 is an extended version of HWM90 thermospheric wind model [*Hedin et al.*, 1996]. This is the only model presently available with high spatial and temporal resolution. HWM90 was extended into the mesosphere, stratosphere, and lower atmosphere to provide a single analytic model for calculating zonal and meridional wind profiles representative of the climatological average for various geophysical conditions. This is an empirical model and is based on the measurements conducted by the global

Table 2. Indian MST Radar Experimental Specifications Used for the Present Study

Parameter	Specification
Power aperture product (peak)	3×10^{10} W/m^2
Beam width	3°
Pulse width	8/16 μs (uncoded)
Interpulse period	1000 μs
Number of fast Fourier transform points	128/256/512
Number of coherent integrations	32/64/128
Number of incoherent integrations	1/2/4
Range resolution	1.2 km/2.4 km
Number of beams	Six (E, W, Zenith X, Zenith Y, N and S)
Beam angle	10°

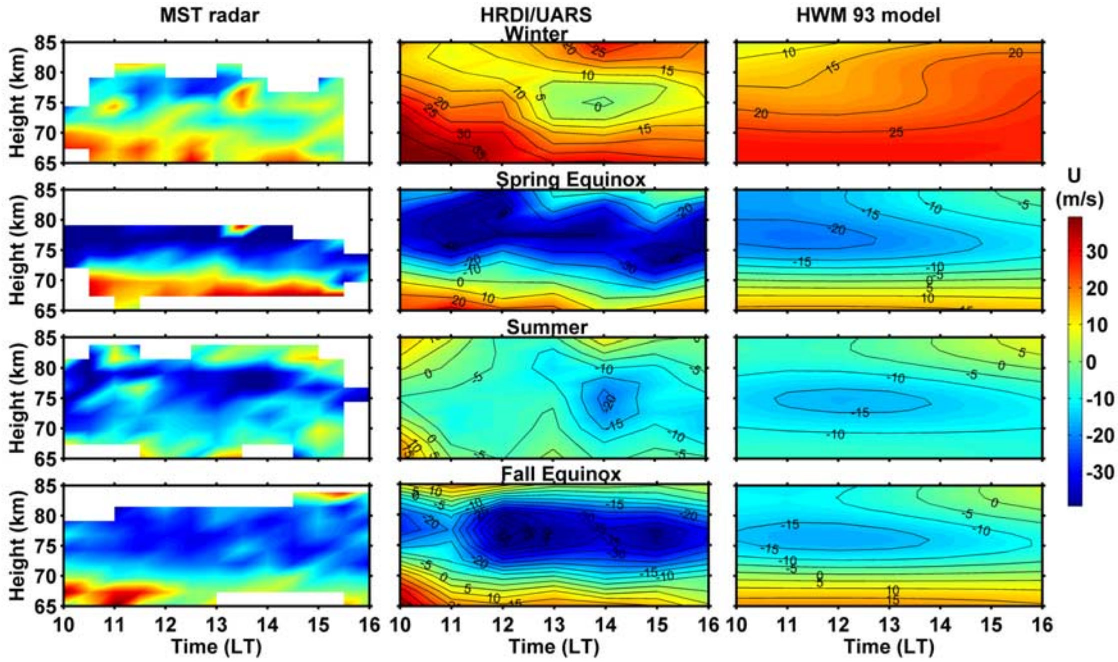

Figure 2. Local time variation of zonal wind observed by (left) MST radar, (middle) HRDI, and (right) HWM93 during (top to bottom) winter, spring equinox, summer, and fall equinox.

network of MF and meteor radars, gradient winds from CIRA-86 plus rocket soundings, incoherent scatter radar.

3. MST Radar Data Analysis

[14] The MST radar observations from mesosphere are mainly due to fluctuations in electron density which will be less during nighttime and hence daytime observations are only means to get reliable signals for wind estimation. So we restricted our analysis to daytime observations (1000 to 1600 local time (LT)) in the 65–85 km height region. The Indian MST radar was operated in two modes for mesospheric studies. In the first mode (mode 1), the radar was operated continuously from 1000 to 1600 LT twice in a month (observations since 1995 are of this type). From a previous study conducted at this location [*Ratnam et al.*, 2002], it was found that strong echoes usually occur in between 1100 and 1500 LT depending upon the season. By

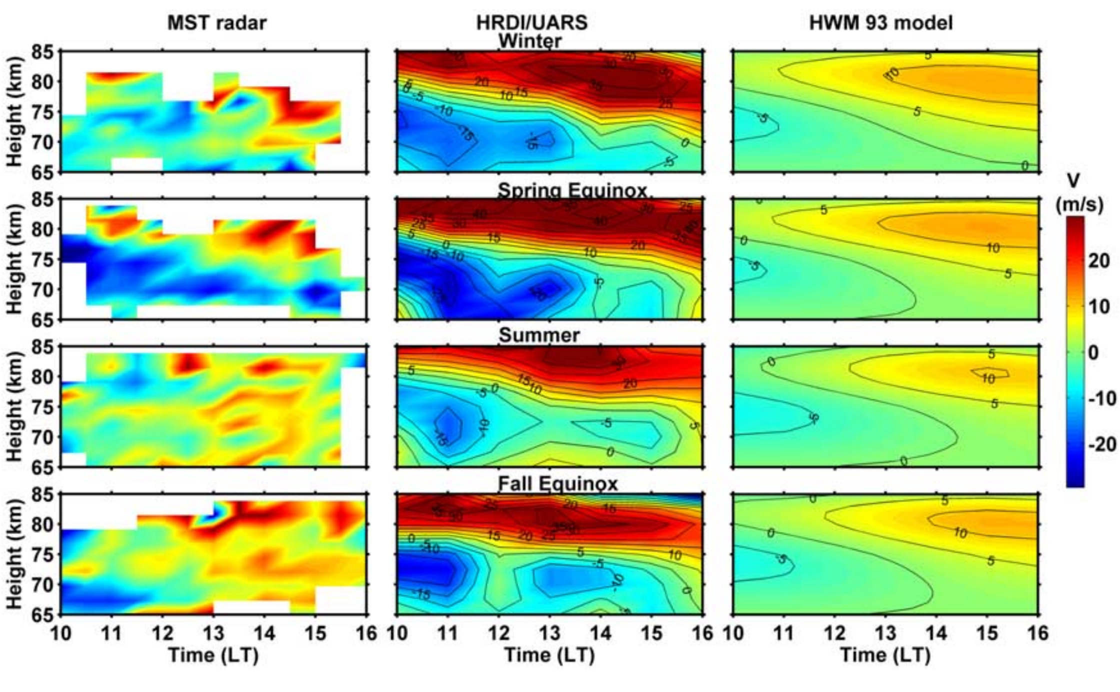

Figure 3. Same as Figure 2, but for meridional wind.

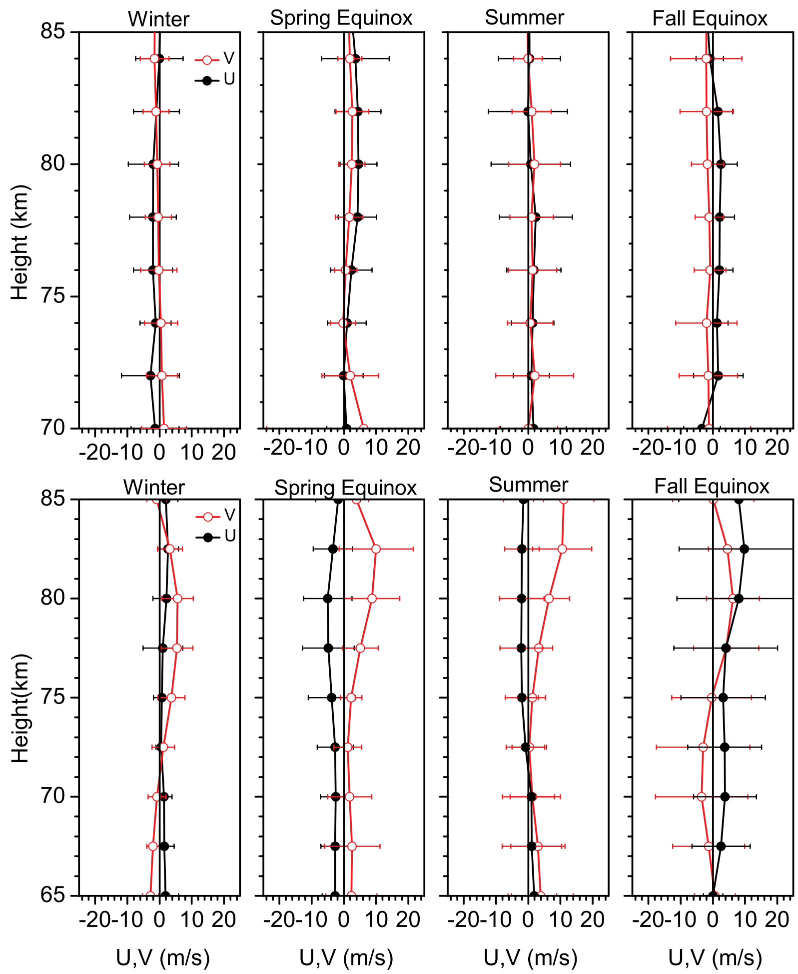

Figure 4. Profiles of differences in zonal and meridional winds observed during different seasons while averaging day time alone (10–16 h) and 24-h average for (top) MF radar and (bottom) HRDI/UARS.

considering this, the radar was operated in another mode (mode 2) for about 1 h randomly on 5 days in a week between 1100 and 1500 LT during June 2000 to March 2006. The entire data set starting from August 1995 until March 2006 (nearly 11 years) in between 65 and 85 km has been utilized for the present study.

[15] Profiles of individual days are carefully examined for interference and the same is removed by specially made algorithm. A more detailed description of the data processing is presented by *Kumar et al.* [2007]. The radial velocities (line-of-sight velocities) were excluded for wind estimation if the signal detectability falls below 5 dB. Since the mesospheric returns are intermittent, the wind estimation has been done by using half-hourly averaged radial velocities instead of scan wise wind estimation (which may lead to spurious values). In order to remove outliers in the data, consensus average technique [*Brewster*, 1989] has been used instead of the simple arithmetic average. For the present study, a window of 2.5 m/s has been adopted for the consensus average.

[16] Since data used for this study do not have uniform range resolution (1.2 and 2.4 km), data have been suitably averaged to get a uniform range resolution of 2.4 km. Horizontal wind vectors (u and v) have been derived using following expressions:

$$\bar{u}(z) = \frac{U_E(R) - U_W(R)}{2\sin\theta} \quad (1)$$

$$\bar{v}(z) = \frac{U_N(R) - U_S(R)}{2\sin\theta}, \quad (2)$$

where $U_i(R)$ are the radial velocities in the E, W, N, and S directions, R is echo range and $z = R\cos\theta$, θ is the zenith angle. For present data set the off zenith angle used is 10°.

[17] The half-hour resolution data have been used to study the local time variation as a function of season, whereas for monthly variation, the half-hourly data points available between 1000 to 1600 LT are averaged and represented as daytime mean wind. In this way, the effects of internal gravity waves and tides to some extent could be considerably reduced. Finally, the monthly mean profiles from all instruments have been suitably interpolated/extrap-

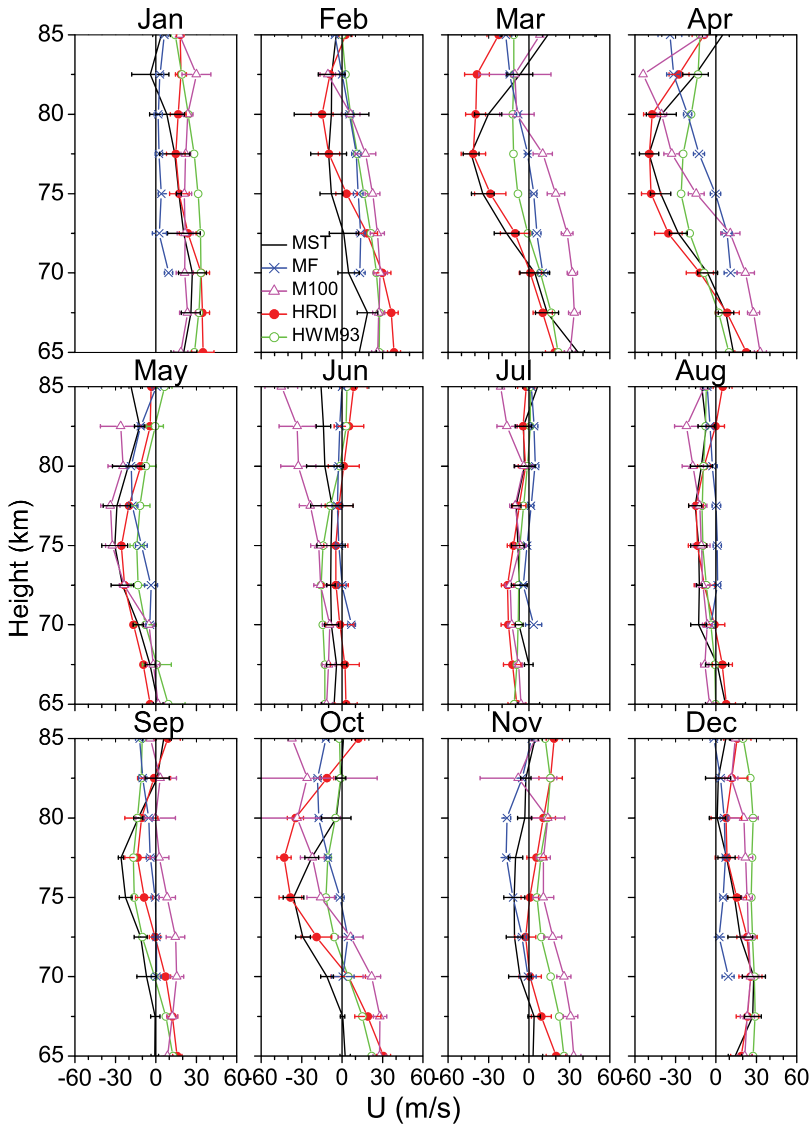

Figure 5. Monthly mean profiles of zonal wind derived from rocket sounding, MF radar, HWM93, HRDI, and MST radar. Horizontal bars indicate the standard error.

olated to get a uniform resolution of 2.5 km and is used for the monthly comparison.

4. Results and Discussion

4.1. Local Time Variations

[18] Daytime variations (using mode 1 data) of MST radar (1995–2006), HRDI (1991–2000) and HWM93 derived zonal and meridional winds sorted out according to the seasons, namely, winter (November–February), spring equinox (March–April), summer (May–August), and fall equinox (September–October) are depicted in the form of contour plots in Figures 2 and 3, respectively. Here the MST radar winds are illustrated with 30-min resolution where as the HRDI and HWM93 winds with 1 h resolution. The data gaps in the MST radar winds were due to the consensus average which rejects the data which do not pass the threshold level as mentioned in section 3. Data from MST radar for each season amounts to 36, 35, 46, and 31 days, respectively in the above mentioned seasons. Strong seasonal variation in the horizontal winds can be noticed although not much local time variations is observed in zonal and meridional winds. However, note that small-scale variations can be clearly noticed in the MST radar observation owing to better time resolution adopted.

[19] In all the observations, the zonal flow is eastward below 70 km and westward above with strong seasonal dependence, except in winter season. In winter, zonal winds show large discrepancy between observations and model. While, the eastward/westward flow below/above 70 km is observed in radar observations, a small signature of this is observed in HRDI and is completely missing in model. During other seasons, although observations and model show similar features there exists large variation in the magnitudes. In MST radar observations, note that strong shear zone around 70 km altitude around 10 h shifts down to 67 km around 16 h showing some tidal signatures

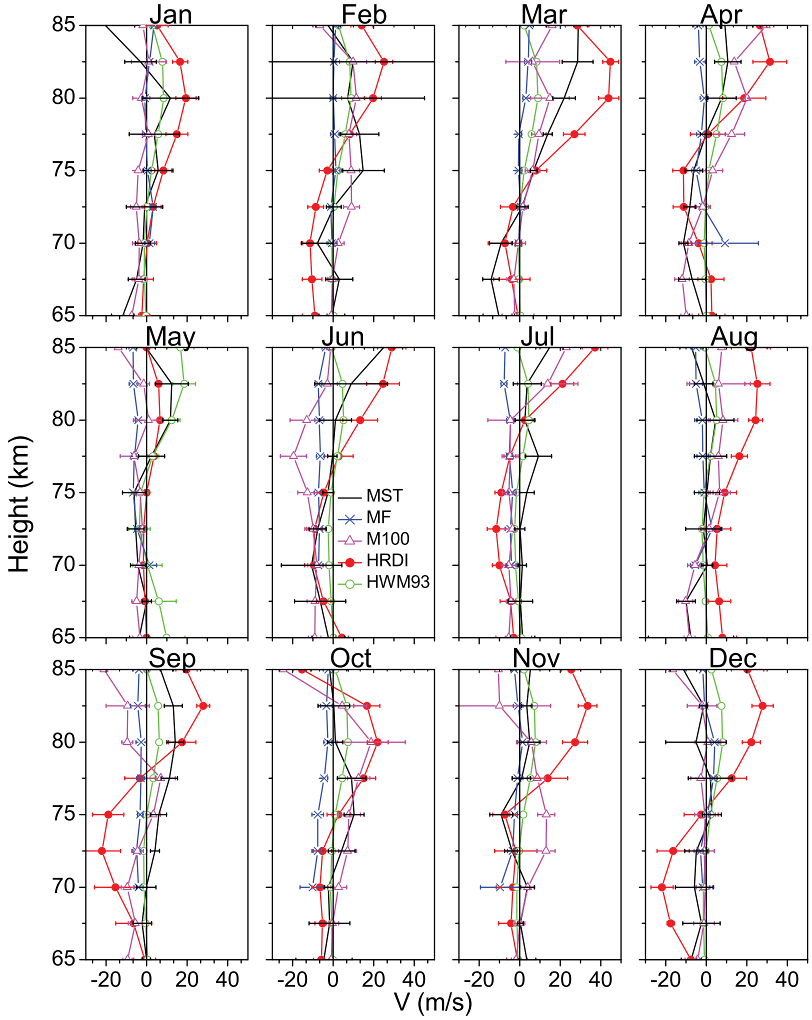

Figure 6. Same as Figure 5, but for meridional wind.

particularly during equinoxes and winter. This feature is also seen in HRDI observations but not in the model.

[20] The local time variations of meridional velocity illustrated in Figure 3 reveal that there is a large difference between the observations of MST and HRDI and model. The drastic change in heights of strong shear zones (zero line height) from morning hours to evening hours indicates large local time variation in meridional winds. This drastic variation is clearly observed in both HRDI and HWM93 model but it is not clear in MST observations, except during winter and spring equinox. On an average the meridional flow below 75 km is equatorward and above it is poleward. The strong northward flow in HRDI above 80 km can be attributed to tidal influence, which cannot be removed from the data by simple averaging. This point will be discussed in detail in later part of this study.

[21] Close inspection of the local time variations in zonal and meridional wind reveals that the meridional wind has large local time variation than the zonal wind. Note that the strong shear zone in zonal velocity (below 75 km) is below the meridional shear height (above 75 km). HRDI local time variations reveal that the tidal contribution is relatively more in meridional winds as compared to zonal winds. The altitudinal variation of horizontal winds will be explained in detail in later sections. Since large variations is observed within a day, now question arises whether MST radar observed day time mean winds will represent the mean background winds at mesospheric heights. Hence, before going to further analysis we investigate how much difference in the mean wind can be observed by taking daytime variations alone rather than complete 24 h observations.

[22] As discussed earlier, since the mesospheric echoes are greatly influenced by the presence of electron density fluctuations, which are prominent during the day, MST radar observations are confined to daytime only. This involves the difficulty of getting diurnal and semidiurnal components in order to truly represent the background mean winds. We have used a simple averaging of daytime wind velocity, which is widely used as the mean wind estimation for the MST radar. However, note that by using this simple averaging, the observed winds may be biased by any existing diurnal variations. To estimate the bias induced by tidal components in the averaging processes (between the daytime average wind and the 24 h average), we have estimated the difference between 10 and 16 h and 24 h average winds for MF radar and 19 h average winds for HRDI and are shown in Figure 4. In MF radar, the mean bias between 70 and 85 km was primarily found in the range

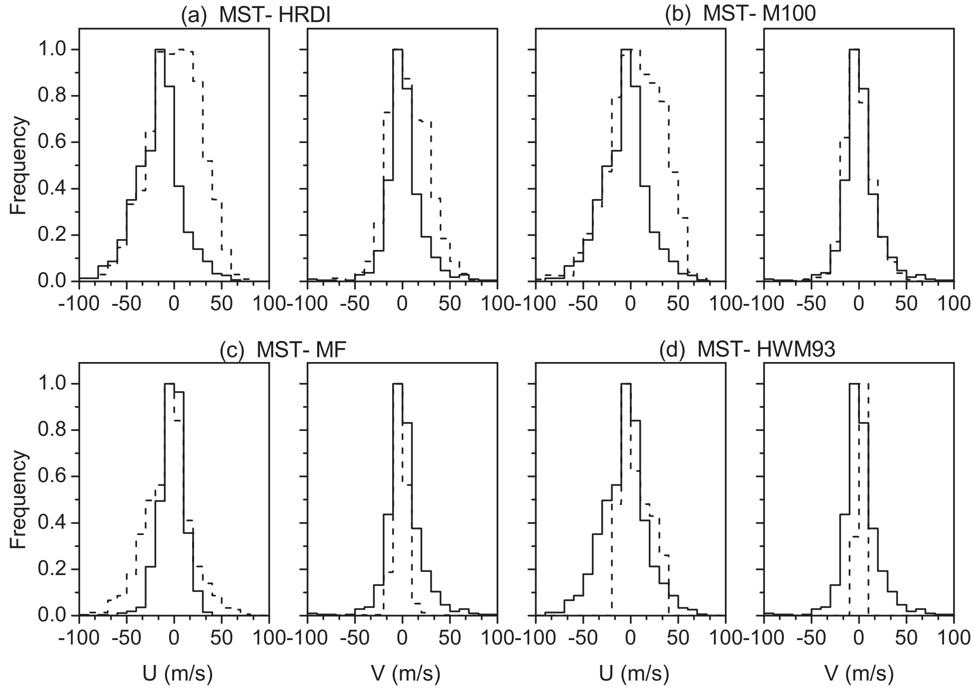

Figure 7. Normalized frequency distribution of zonal and meridional winds in the altitude range 65–85 km observed by MST radar (solid line) and (a) HRDI (dotted line), (b) rocket (dotted line), (c) MF radar (dotted line), and (d) HWM93 (dotted line). Note that the distribution in the case of MF radar is in the altitude range of 70–85 km only. Total number of observations used are 683(697), 764(764), 2374(2374), 885(885), and 252(252) for zonal (meridional) winds from MST radar, HRDI, rocket, MF radar, and HWM93, respectively.

of 2.5–5 m/s with larger bias during equinoxes. However, bias can reach as high as 10 m/s in the individual cases. In HRDI winds, larger biases are noticed than MF radar particularly above 75 km altitude. Notable feature is that bias is larger in meridional than zonal. This bias might be smaller at the lower heights (below 70 km) since the tidal amplitudes are usually smaller at lower heights [*Nakamura et al.*, 1996] as compared to those of higher altitudes. Thus, the daytime winds can be used to obtain mean winds over Gadanki.

[23] Another limitation in getting continuous height profile of velocity is that the echoes are not observed over the entire mesosphere, but in the form of layers. Moreover, the echoes are intermittent in time. These echoes are confined to a few kilometers primarily in the 70–80 km height region as discussed in detail by *Kumar et al.* [2007] and intermittent above and below 70–80 km. Thus the mesospheric mean winds are more reliable between 70 and 80 km than either at lower or higher altitudes. Note that practically this region cannot be properly sensed with any ground-based technique with good temporal resolution except by MST radars, thus providing valuable information in the middle of the mesosphere.

4.2. Monthly Variations of Horizontal Winds and Its Comparison

[24] Having verified that the bias is smaller at mesospheric heights while averaging day time alone than considering 24 h, simple averaging procedure is adopted for delineating the monthly variations in each of the techniques. To clarify the variabilities in the background wind derived from different instruments, the monthly averaged plots are illustrated in Figures 5 and 6 for zonal and meridional velocities, respectively. The MST radar (for the period 1995–2006), MF radar (for the period 1993–2001), M-100 rocket (for the period 1977–1991), HRDI (for the period 1991–2000), and HWM93 wind profiles are plotted for each month. Note that times of the observations of all the instruments do not match. In general, all the observations show similar trend even though the observations belong to different time spans. Inspection of the zonal profiles reveals that the MF radar observations show lower values compared to others, whereas the HRDI profiles show large values. During a few months (e.g., May, June), the rocket profiles show large variations above 80 km which could be due to ballistic effects. At higher altitudes there is a possibility of getting large errors due to problems in radar tracking than the lower altitudes, which lead to increased errors in the derived winds [*Schmidlin*, 1986]. Inspection of the meridional profiles also reveals that the MF radar observations are showing less values compared to other technique. The HRDI meridional velocity profiles also show large values compared to others, the differences are very large above 80 km, and this is due to the contribution of the diurnal tide, which is not nullified by simple averaging.

[25] Some height offset can be clearly noticed in the observations among different techniques similar to that reported by *Burrage et al.* [1996]. Hence an alternative way of comparison is done using normalized frequency distribution of the zonal and meridional winds with respect

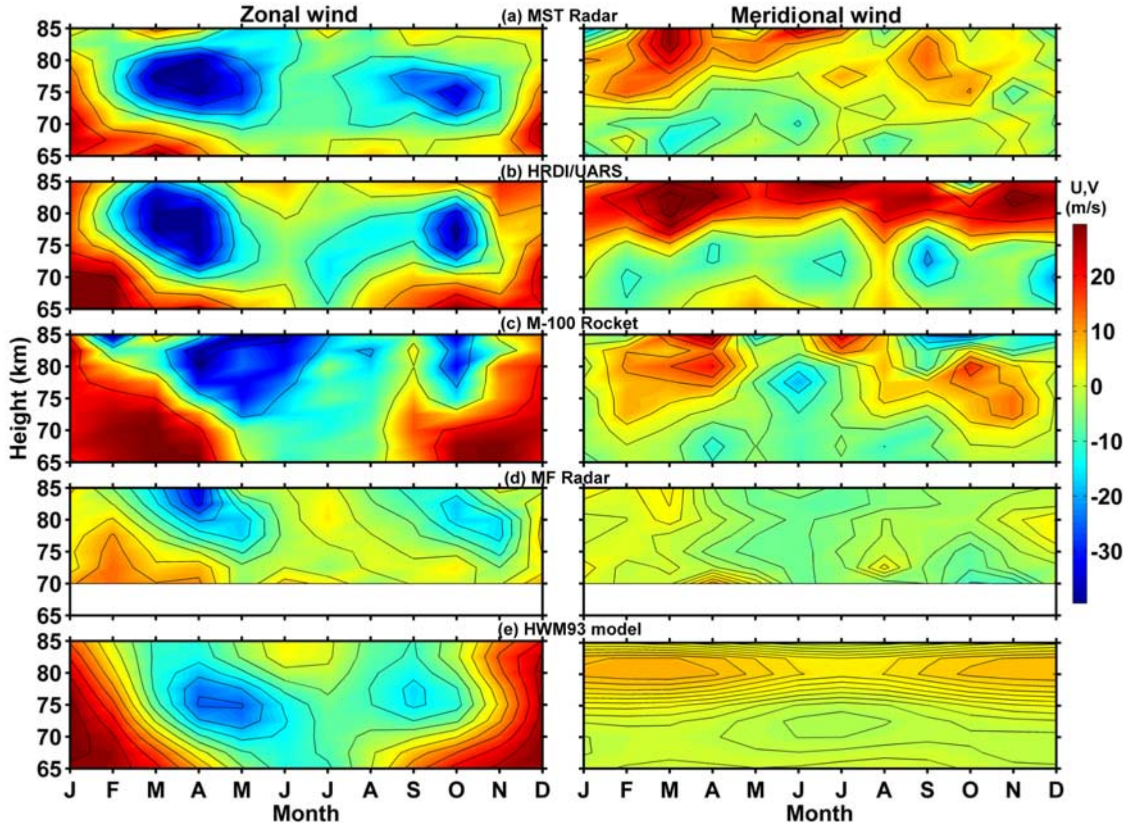

Figure 8. Composite monthly variation of zonal wind and meridional wind observed by (a) MST radar (1995–2006), (b) HRDI/UARS (1991–2000), (c) M100 rocket (1977–1991), (d) MF radar (1993–2000), and (e) HWM93.

to MST radar observations and is shown in Figure 7. This figure clearly reveals the overestimation of HRDI and rocket measured zonal velocities and underestimation of MF, HWM93 zonal velocities with respect to MST radar observations. However, in case of meridional velocities, HRDI overestimates and MF radar and HWM93 underestimate with respect to MST radar observations. Interestingly, rocket measured meridional velocities are in good agreement with the MST radar observed meridional velocities.

[26] The larger values of horizontal winds in HRDI than MST radar may be due to the difference in sampling of the geophysical wind field by the remote sensing. The large discrepancy in the meridional wind is due to equatorial tidal structure and gravity waves which more frequently propagate in the meridional direction than the zonal direction [*Burrage et al.*, 1996]. The median profile of wind speed ratio of HRDI and MST show (not shown here) that the HRDI winds are larger by a factor of 1.3 than those of MST. The comparison between rocket and MST observations reveals that the winds are good in agreement. No difference in the meridional winds is noticed although some difference in the zonal velocities is found. It is important to remember that these two data sets do not correspond to common observational period and whatever the difference is found can also be attributed to some extent for the different time spans in addition to the different probing techniques.

[27] Clear inspection of Figures 7a and 7b reveals the large difference in eastward wind. There are three possibilities for the difference, namely, latitudinal variation, difference in measurement techniques, and difference in time span. As mentioned in the data analysis, the latitudinal variation is less than 6 m/s hence it cannot have much influence on the difference. If at all any difference in measurement techniques exist they should be reflected equally independent of direction (eastward/westward). But Figures 7a and 7b did not show such evidence and show large deviation in eastward compared to westward which is more evident from the higher-frequency distribution. In order to get clear idea about difference in measurement techniques, from the overlapped time region of HRDI and MST, 23 months of mean profiles are compared and no deviation is observed in the eastward only as we observed in Figures 7a and 7b zonal winds. Hence we strongly believe that large eastward deviations are due to different time spans. The same also clearly observed in Figure 8.

[28] The comparison between MST and MF radar observations reveals that the MF radar underestimates the MST radar winds. Note that MST radar winds are based on Doppler beam swinging (DBS) technique whereas MF radar uses Spaced Antenna (SA) technique and winds are derived by full correlation analysis (FCA). *Meek and Manson* [1985] observed that the MF radar winds are reduced by 35% owing to the low signal-to-noise ratio of radar echoes and their numerical modeling has demonstrated the effec-

Table 3. RMS Deviations of Least Squares Fit Applied for Zonal and Meridional Winds for SAO (AO) Observed at Different Heights for MST Radar, MF Radar, Rocket, HRDI/UARS, and HWM93[a]

	Zonal					Meridional				
Height (km)	MST	MF	M100	HRDI	HWM93	MST	MF	M100	HRDI	HWM93
65	**10.24** (10.93)	-	13.39 (**9.53**)	16.81 (**11.64**)	14.62 (**3.56**)	4.68 (**4.45**)	-	3.23 (**2.86**)	**8.20** (11.70)	0.73 (**0.32**)
67.5	10.20 (**5.42**)	-	14.42 (**8.52**)	17.37 (**10.25**)	15.79 (**2.44**)	**4.43** (4.5)	-	3.84 (**2.70**)	**8.04** (12.56)	**0.20** (0.32)
70	12.12 (**8.81**)	**5.90** (6.70)	14.35 (**7.47**)	16.90 (**11.24**)	15.81 (**5.49**)	**4.72** (7.76)	**5.13** (8.16)	4.45 (**3.24**)	**7.09** (11.10)	**0.35** (0.36)
72.5	**9.48** (12.86)	**4.37** (5.45)	16.46 (**8.40**)	15.77 (**15.35**)	15.36 (**9.03**)	**2.95** (3.43)	4.10 (**3.28**)	5.79 (**5.22**)	9.82 (**7.34**)	0.94 (**0.32**)
75	**8.60** (15.99)	8.43 (**5.80**)	19.93 (**11.29**)	**13.12** (19.42)	14.43 (**11.13**)	10.15 (**6.48**)	3.46 (**2.38**)	**5.35** (5.93)	10.06 (**7.71**)	1.41 (**0.38**)
77.5	**9.60** (15.40)	8.67 (**8.25**)	19.52 (**12.38**)	**11.37** (21.1)	12.59 (**10.97**)	**3.60** (5.01)	2.92 (**1.64**)	**5.62** (8.08)	8.88 (**7.33**)	1.51 (**0.62**)
80	9.84 (**9.40**)	**5.65** (9.35)	17.83 (**14.73**)	**11.58** (18.70)	10.27 (**10.05**)	**5.50** (8.32)	2.99 (**1.82**)	**8.03** (10.01)	**8.63** (9.60)	1.42 (**0.81**)
82.5	5.40 (**2.51**)	**4.51** (9.62)	18.50 (**15.30**)	13.94 (**13.53**)	**7.94** (9.19)	7.15 (**6.88**)	3.36 (**1.72**)	9.18 (**6.64**)	**7.12** (9.67)	1.33 (**0.67**)
85	9.11 (**8.22**)	**6.56** (10.17)	31.95 (**26.53**)	16.65 (**10.99**)	**5.86** (8.09)	13.17 (**11.23**)	4.18 (**2.39**)	17.88 (**13.06**)	15.41 (**12.45**)	1.38 (**0.13**)

[a]Boldface denotes best fits.

tiveness of random noise in reducing FCA wind magnitudes. Earlier observations by *Manson et al.* [1992] clearly illustrated that the MF radar winds underestimating the mean winds by a factor of 1.35 to 1.5. The median profile of wind speed ratio of MST and MF radar observations (not shown) in the present study show 1.5 to 3 times underestimation in the MF radar than those of the MST radar.

[29] The comparison between MST radar winds and HWM93 winds reveals that the model winds are underestimating the horizontal winds. This comparison is similar to the MST and MF radar comparison. As mentioned above the model winds are the climatological mean profiles deduced from gradient winds from CIRA-86 plus rocket soundings, incoherent scatter radar, MF radar, and meteor radar. The contribution from MF radar to the model could be one of the reasons for this discrepancy in addition to the smoothing functions used in the model.

[30] Figure 8 shows the composite monthly behavior of zonal (left panels) and meridional (right panels) winds obtained from different techniques. This is similar to Figures 5 and 6, but in 3-D view to understand and represent the seasonal behavior of the winds in a better way. A clear SAO is observed in between 70 and 85 km with peak westward wind during the equinoxial months. Although all observations show similar behavior of SAO, there exists difference between the heights and intensity of SAO among different techniques. However, notable feature in all the observations is that the first peak of the SAO is stronger than the second peak, nearly twice of the second peak. This feature is consistent with reported from other locations [*Vincent*, 1993; *Garcia et al.*, 1997; *Rajaram and Gurubaran*, 1998]. From MST radar composite monthly wind, note that westward flow during the fall equinox (~20 m/s) is much weaker than the spring equinox (~40 m/s) in contrast to early observations by *Ratnam et al.* [2001]. It is interesting to note that the first peak of SAO is observed relatively at higher heights than the second peak of SAO. The seasonal asymmetry of SAO can be ascribed to interhemispheric differences in planetary wave activity which is source for the SAO [*Garcia et al.*, 1997]. The possibility of gravity wave activity is not ruled out and discussed in detail elsewhere [*Fritts and Alexander*, 2003].

[31] The eastward flow during winter period can be related to the mesospheric westerly jet of winter hemisphere. The eastward wind prevailing in winter decreases with increasing height, which is consistent with that reported by *Xiao et al.* [2007]. Inspection of the composite monthly variations of M-100 rocket, HRDI, and MST radar observations, which belongs to different time spans, imposes a surprising result that the eastward flow during winter months decreases with time. It is clearly noticed that the wind reversal height also decreases similar to the winter eastward flow. It may not be artifact because all the three techniques will provide relatively good information below 80 km. However, as shown in Figure 8c the zonal winds around 85 km showing westward flow in summer months may be the artifact. At these heights larger errors in radar tracking occur than the lower altitudes, which lead to increased errors in the derived winds [*Schmidlin*, 1986].

[32] Figure 8 (right) illustrates the meridional flow observed with different techniques. These panels clearly reveal the transequatorial flow of meridional winds: equatorward (southward) flow below 75 km and poleward (northward) flow above 75 km. There are large discrepancies between the magnitudes and the same can be attributed to the difference in data sampling methods as mentioned above. Figure 8b (right) reveals a strong poleward flow in HRDI meridional wind at and above 80 km and the same is due to diurnal tide signature, which cannot be nullified by the simple average of the wind profiles. The diurnal tide signature is maximum during equinoxial months. The MST radar meridional winds also show semiannual oscillation, although not clear like zonal winds: first maxima during March–April and second maxima during September–October. The SAO nature in meridional wind is consistent with earlier reports [*Raghava Reddi and Ramkumar*, 1997]. It is also to be noted that the second maxima (~10 m/s) is much weaker than the first maxima (~20 m/s). Similar to that observed in zonal wind the first maximum occurs at higher heights compared to second maxima. Similar SAO structure is also observed in the M-100 rocket observations. This signature is not clear in MF radar and HWM93 model winds. To quantify the seasonal variations, a least squares fit to the annual and semiannual oscillations was computed at each altitude for all the techniques. The values of root-mean-square (RMS) deviation and their best fits are provided in Table 3.

5. Summary and Conclusions

[33] The climatological features in the horizontal mesospheric winds are presented using the data collected from Indian MST radar from 1995 to 2006. The climatological horizontal winds prevailing over low-latitude station

Gadanki are estimated using consensus averaging with a temporal resolution of 30 min to understand the local time variation. The local time variations of MST radar winds are compared with HRDI and HWM93 local time wind variations which show good agreement except in winter season. The zero line height is observed decreasing from morning hours to evening hours both in zonal and meridional winds. The zero line variation is found to be larger in the meridional wind than the zonal wind. These variations in MST radar during equinoxes are also observed in HRDI zonal observations but not in model winds. Attempt is also made to compare the observed features with other ground-based (MF and rocket), models (HWM93) and satellite (HRDI/UARS) techniques over low latitude using large data set. In general, comparison show good agreement in trend but large differences in the amplitudes is noticed as expected.

[34] The day-mean wind has been used to identify the monthly variation and comparison. The M-100 observations are in good agreement both in zonal and meridional winds of MST radar, where as the HRDI overestimates the winds and this overestimation is large in meridional winds than in zonal winds. These discrepancies are expected owing to the geophysical variances, which are high in meridional component arising from the gravity wave contamination. The MF radar observations are underestimating the MST radar winds by a factor of 1.5 to 3 and are consistent with *Manson et al.* [1992].

[35] The monthly mean zonal winds show westward and eastward flow during equinoxes and solstices. At midlatitudes, the mean wind pattern during solstices is driven by pole-to-pole differential solar heating and the Coriolis force acting upon the resulting meridional circulation leads to westward during summer and eastward during winter in the mesosphere [*Andrews et al.*, 1987]. The present observations reveal the outer extension of this feature to low latitudes and consistent with the earlier observations [*Reed 1966*; *Rajaram and Gurubaran*, 1998]. The monthly mean wind pattern show clear semiannual oscillation with peaks during equinoxes around 70–80 km supporting the mesospheric semiannual oscillation (MSAO) reported elsewhere [*Burrage et al.*, 1996, and references therein]. Note that the MSAO have amplitudes of 15 m/s and 12 m/s at 75–80 km and 70–75 km, respectively, which are considerably less than compared to that observed at Ascension Island (8°S) reported by *Hirota* [1978] which is expected owing to MSAO latitudinal variation. Large westward winds are observed during spring equinox and are nearly two times greater than fall equinox. The similar seasonal asymmetry in the tropical middle atmosphere was reported by *Garcia et al.* [1997]. Both gravity waves and planetary-scale waves likely participate in driving these oscillations [*Fritts and Alexander*, 2003] and the interhemispheric differences of these wave activities could be one of the possibilities for this seasonal asymmetry. Although different techniques used in the present study show similar SAO features but vary both in the altitude it peaks up and also the amplitudes. The SAO signature has been observed in MST meridional wind also, less in extent than zonal, and is consistent to observations at low altitudes [*Raghava Reddi and Ramkumar*, 1997; *Rajaram and Gurubaran*, 1998].

[36] From the long-term continuous data set, which is obtained by combining rocket, HRDI, and MST radar observations, interestingly decrease in the eastward wind is noticed. The eastward (westward) wind up to 60–70 km in winter (summer) is due to heating of stratospheric ozone located around 50 km. Earlier observations by *Stolarski et al.* [1991] showed negative trends in the stratospheric ozone which leads us to say that the decrease in eastward wind may be due to the dilution of stratospheric ozone. However, detailed study is needed to explore clear reasons for the same. Long-term variation of mesospheric SAO (and QBO) and its link with stratospheric QBO will be presented in future work

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