Seasonal variation of horizontal winds and momentum fluxes from 53 MHz VHF radar observations over Gadanki, a tropical station in India

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1 Introduction

Tropics play a vital role in general circulation of the atmosphere. The general circulation of the atmosphere tries to redistribute energy, moisture and momentum which are in excess supply in low latitudes and that are in deficiency in middle and high latitudes. Seasonal changes in circulation of tropical atmosphere are very small over the large oceans, but large over the continents and the adjacent seas. This is because the continents, by virtue of their different thermal characteristics, create much larger seasonal temperature variations than the oceans. In summer the continents are transformed into centres of low pressure, while in winter they are relatively cool compared to the warm oceans. The tropical continents and the surrounding oceans, therefore, experience a seasonal reversal of wind direction known as monsoons. The basic and essential cause of monsoons is differential heating of large land and ocean areas, changing with season.

Previous studies have examined the changes of variance of vertical velocity, vertical shear as a function of altitude, season, time of day and background weather conditions. The oblique beam variances were studied using VHF radar observations at Flatland, Illinois, and at 50 MHz WSMR, New Mexico, by Nastrom et al. Dutta et al. have studied mean variances with the Indian MST radar using diurnal cycles for different scale heights. Chang et al. have studied the same thing for Christmas Island. The main objective of this paper is to discuss the variation of horizontal winds and their variances, vertical shears, momentum fluxes as a function of altitude, hour of the day and season over three years from September 1995 to August 1998.

2 System description and data base

National MST radar facility provides good opportunities to observe lower, middle and upper atmosphere with excellent spatial and temporal resolutions. The Indian MST radar located at Gadanki (13.5°N, 79.2°E), Tirupati, a tropical station, is highly sensitive to VHF coherent phased array radar with a large power aperture product of 7×10⁶ W m². Detailed system description is given by Rao et al. Three years of data collected using Indian MST radar, are used to study horizontal winds and their variability as a function of season with a height resolution of 150 m and time resolution of 1.5 min in the troposphere and stratosphere.

Three years of daily collected data [30 min around 1700 hrs LT (1200 hrs GMT)] of zonal (u), meridional (v), and vertical (w) velocities are available with some gaps from September 1995 to August 1998. The full set of observations over a given period is characterized by its mean and variance about
the mean. Seasons are classified as monsoon (June, July, August and September), post-monsoon (October, November and December), winter (January and February) and summer (March, April and May). Data base also includes one diurnal cycle of 24 hours [4/5 July 1997, 13/14 Oct. 1997, 15/16 Jan. 1998 and 16/17 Mar. 1998] collected in each season as a typical case to study daily and seasonal variations.

3 Results and discussion

3.1 Diurnal variation of horizontal winds

To study diurnal variation of zonal winds, meridional winds, variances and vertical flux of horizontal momentum, data are sorted according to hour of the day during each season. Figure 1 shows diurnal variation of contour plot of zonal winds in four different seasons. Zonal winds are eastward up to an altitude of 6 km and from that altitude winds change to westward. Westward winds are increasing with altitude and show a maximum of 42 ms$^{-1}$ around 16 km over the whole day. Above that altitude there will be a slight change in direction of wind over the entire diurnal cycle. The dominant winds are easterlies during the monsoon season. These westward winds (easterlies) of magnitude greater than 30 ms$^{-1}$ are known as ‘tropical easterly jet’. These jet streams are found during south-west monsoon season over southern part of India. Maximum winds of ~ 42 ms$^{-1}$ are found in the month of July every year.

During post-monsoon season winds are westward up to an altitude of 6 km and from that altitude winds changed to eastward and reach a maximum of 16 ms$^{-1}$ around 12 km. A special feature is noted that maximum winds occur during daytime hours. Above 15 km altitude a slight change in the direction of flow is observed. During winter season, westward winds are observed at lower altitude up to 6 km for a few hours and above that altitude, it was changed to eastward winds of magnitude 6-9 ms$^{-1}$ around 10-12 km during the entire day. It is also observed that winds greater than 9 ms$^{-1}$ occur from 2200 hrs LT to 1000 hrs LT. During summer season, westward winds are observed in the lower altitude region up to 7 km. Above that altitude winds are of magnitude ~ 20 ms$^{-1}$ up to 10 km. Above 10 km almost a stream of winds larger than 20 ms$^{-1}$ is observed around 12 km. Above 15 km, there will be a slight decrease in the magnitude of the winds. Strong easterlies are found at around 16 km during monsoon season and westerlies at around 12 km during summer, post-monsoon and winter seasons. Westerly wind maxima occur in association with a westerly jet of the middle latitudes which shifts equatorward during winter and is at a lower altitude, associated with lower tropopause. On the other hand, the easterly jet of summer monsoon occurs at a higher level and is associated with a higher tropopause.

![Diurnal variation of zonal wind velocity (ms$^{-1}$) over different seasons](image-url)
Figure 2 shows a contour plot of a diurnal cycle of meridional winds in different seasons. During monsoon season, light northward winds at lower altitudes of troposphere and a strong band of magnitude ~ 6 ms\(^{-1}\) just above 16 km during the entire diurnal cycle are observed. Complex nature of meridional winds is observed during post-monsoon season with a maximum northward wind of ~ 4 ms\(^{-1}\) at around 8 km and above 16 km. In between 8 and 6 km, low winds are observed. During winter season, northward winds are dominant up to an altitude region of 16 km. Maximum northward winds of ~ 10 ms\(^{-1}\) are found at around 13 km over the entire diurnal cycle. During summer season northward winds are dominant up to an altitude of ~ 16 km and a maximum northward wind of ~ 14 ms\(^{-1}\) is concentrated around 10 km, and above 16 km weak southward winds are observed over the diurnal cycle. Nastrom and Eaton\(^4\) have also observed that mean zonal winds are from the west and mean meridional winds are from south at all times at WSMR, New Mexico.

3.2 Diurnal variation of variances

The variance is an indicator of the amplitude of the process such as gravity waves occurring on time scales comparable to or less than the averaging time\(^4\). Variances are calculated using the formula \(\text{Var} = (u_i - \bar{u})^2\), where \(u_i\) represents the mean of all instantaneous \(u_i\) (velocity) values. Figure 3 shows zonal variances over the diurnal cycle in four different seasons at four different altitudes. During monsoon season, the zonal variances are low at an altitude of 3.75 km with a peak value of 30 m\(^2\)s\(^{-2}\) at around 1800 hrs LT and decreasing with time. These zonal variance values are increasing with altitude up to 12.75 km from the early morning and show a peak of ~ 50 m\(^2\)s\(^{-2}\) around 1500 hrs LT, and then decreasing towards midnight hours. Above that altitude they are decreasing. During post-monsoon season, the variances are increasing with altitude up to 8.25 km and above that altitude the variances are decreasing. At an altitude of 8.25 km the variances are maximum of 40 m\(^2\)s\(^{-2}\) at around 1000 hrs LT and another maximum of 35 m\(^2\)s\(^{-2}\) is seen at around 1600 hrs LT. During nighttime hours, low variances indicate minimum perturbations. At an altitude of 12.75 km variances are oscillating, indicating large fluctuations during the entire day. During winter season, the zonal variances are very low up to an altitude of 12.75 km. Slight increase in the variance values with a maximum of ~ 30 m\(^2\)s\(^{-2}\) is observed at 0500 hrs LT at an altitude of 15.75 km. During summer season, there is a large diurnal variation in the variance values. The values are increasing with altitude up to 12.75 km and then decreasing. Maximum values of 150 m\(^2\)s\(^{-2}\) and 130 m\(^2\)s\(^{-2}\) at an altitude of 12.75 km are observed at around 0700 hrs LT and 1200 hrs LT, respectively.
and low values are observed during nighttime. In almost all the seasons daytime values are larger compared to nighttime values. Large variance values indicate large perturbations in winds. In general, maximum zonal variance values are observed in summer and minimum in winter season. These maximum values are found to be above or below the easterly or westerly maxima due to large gradients.

Figure 4 shows height-time plot of meridional variances for four seasons at four different altitudes. During monsoon season, variances increase with altitude and show maximum values of 60 m$^2$s$^{-2}$ at around 0900 hrs LT at an altitude of 15.75 km. A large diurnal variation is observed in monsoon season. During post-monsoon season, the meridional variances increase up to 12.75 km and show a maximum of 27 m$^2$s$^{-2}$ at around 1200 hrs LT and then decrease with altitude. Low values are observed during nighttime. During winter season, the values are increasing up to 8.75 km and then slowly decreasing with altitude. Maximum values of ~ 35 m$^2$s$^{-2}$ are observed at around 0600 hrs LT and 0800 hrs LT at an altitude of 8.25 km. During summer season, the values are increasing from 3.75 km to 12.75 km and then decreasing. Maximum values of 65 m$^2$s$^{-2}$ are observed at around 0700 hrs LT and a slight decrease is seen in the values in the subsequent hours. In general, zonal variances are larger compared to meridional ones, indicating large perturbations in zonal winds. Large variance values are observed when the wind gradients are large. Seasonal means of variances are reported by Nastrom and van Zandt for east and west beams and observed that variance on eastward beam is greater than that on westward beam at almost all the altitudes. Fritts and Liu observed that the horizontal velocity variances vary
considerably with location and time. Nastrom et al.\textsuperscript{19} have studied changes in the horizontal wind as a function of altitude, season, time of day and among beam pointing in the vertical and the oblique directions using data from Flatland VHF Radar. The summary of Figs 3 and 4 is given in Table 1. It is generated through the spectral analysis subjected to the diurnal cycle in different seasons at some particular altitudes for zonal and meridional wind components. Table I shows amplitude (m/s), percent of estimated maximum variance (PEV) and phase (hour of maximum wind in hrs LT) of diurnal cycles of each season.

3.3 Diurnal variation of momentum flux

Vertical flux of horizontal momentum is calculated using the method given by Vincent and Reid\textsuperscript{11}. The momentum fluxes are proportional to the difference between the variances of the radial velocities in two opposite directions. Therefore, zonal and meridional momentum fluxes per unit mass are estimated following Narayana Rao et al.\textsuperscript{12} from the relationships

\begin{equation}
U'W' = \frac{(V'_E)^2 - (V'_W)^2}{2 \sin 2\theta}
\end{equation}

\begin{equation}
V'W' = \frac{(V'_N)^2 - (V'_S)^2}{2 \sin 2\theta}
\end{equation}

where \((V'_E)^2, (V'_W)^2, (V'_N)^2\) and \((V'_S)^2\) are variances of the radial (east, west, north and south) velocities and the overbar denote the time average.
Table 1—Amplitude, percent of estimated maximum (PEV) variance and phase of diurnal cycles of each season

<table>
<thead>
<tr>
<th>Season</th>
<th>Altitude km</th>
<th>Amplitude m/s</th>
<th>Zonal wind PEV (max)</th>
<th>Phase hrs LT</th>
<th>Meridional wind Amplitude m/s</th>
<th>PEV (max)</th>
<th>Phase hrs LT</th>
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<tr>
<td>Monsoon</td>
<td>12.75</td>
<td>2.440</td>
<td>0.489</td>
<td>15.00 (Westward)</td>
<td>0.846</td>
<td>0.308</td>
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<td></td>
<td>14.25</td>
<td>3.140</td>
<td>0.330</td>
<td>08.00 (Westward)</td>
<td>1.189</td>
<td>0.233</td>
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<td></td>
<td>15.75</td>
<td>3.840</td>
<td>0.312</td>
<td>07.00 (Westward)</td>
<td>2.280</td>
<td>0.600</td>
<td>03.00 (Northward)</td>
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<tr>
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<td>2.480</td>
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<td></td>
<td>14.25</td>
<td>2.390</td>
<td>0.241</td>
<td>19.00 (Eastward)</td>
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<td>21.00 (Eastward)</td>
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<td>0.109</td>
<td>20.00 (Northward)</td>
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</table>

Figure 5 shows hourly variation of vertical flux of zonal momentum observed in different seasons at four different altitudes. During monsoon, vertical flux of zonal momentum is upward with a maximum of ~1.8 m²s⁻² at around 0000 hrs LT at an altitude of 12.75 km. The downward flux is maximum of ~2.5 m²s⁻² around 1800 hrs LT at an altitude of 3.75 km and of ~2.75 m²s⁻² at around 2200 hrs LT at an altitude of 15.75 km. Downward fluxes are decreasing with altitude during monsoon season. During post-monsoon season it is upward with a maximum of 1.2 m²s⁻² at an altitude of 8.25 km at around 1700 and 0600 hrs LT. Upward fluxes show higher values compared to downward fluxes. During winter season fluxes around 15.75 km are dominant. Upward flux of maximum of 1.0 m²s⁻² at around 0600 hrs LT and a
downward maximum of $\sim -1.2$ m$^2$s$^{-2}$ at around 1200 hrs LT and 0400 hrs LT at an altitude of 15.75 km are observed. During summer season it is upward around 0700 hrs LT with a maximum of 4.5 m$^2$s$^{-2}$ around 0800 hrs LT and downward maximum of $-3$ m$^2$s$^{-2}$ at around 1200 hrs LT at an altitude of 12.75 km. In general, upward fluxes are observed to be maximum in summer and minimum in winter season. Downward fluxes are maximum in monsoon and minimum in post-monsoon.

Figure 6 shows diurnal variation of vertical flux of meridional momentum for four different seasons. It is upward with a maximum of $\sim 2.2$ m$^2$s$^{-2}$ at around 2300 hrs LT at an altitude of 12.75 km and a downward maximum of $\sim -1.2$ m$^2$s$^{-2}$ is seen around 0300 hrs LT at an altitude of 15.75 km during monsoon. During post-monsoon season, fluxes have upward and downward values during daytime and low values in nighttime. The upward flux is maximum of 0.5 m$^2$s$^{-2}$ at around 1700 hrs LT and downward of $\sim -0.3$ m$^2$s$^{-2}$ at around 1500 hrs LT at an altitude of 8.25 km. During winter season, the flux is upward with a maximum of $\sim 0.6$ m$^2$s$^{-2}$ at around 0600 hrs LT at an altitude of 12.75 km and a downward maximum of $\sim -1.2$ m$^2$s$^{-2}$ at around 0600 hrs LT at an altitude of 8.25 km. During summer season, flux is upward with a maximum of 4 m$^2$s$^{-2}$ at around 0600 hrs LT and a downward maximum of $-1.5$ m$^2$s$^{-2}$ is observed around 0600 hrs LT at an altitude of 12.75 km. Large upward fluxes are observed during daytime in summer and during nighttime in monsoon seasons. Momentum fluxes are increasing with altitude in almost all the seasons, indicating upward transport of mass, momentum and energy from lower troposphere to upper troposphere. Tsuda et al.\(^{13}\) reported that monthly mean zonal momentum fluxes are $\sim 6$-10 m$^2$s$^{-2}$ with daily variations between $-10$ and $+10$ m$^2$s$^{-2}$ in fall and winter seasons. The monthly mean momentum fluxes are $\sim 4$ m$^2$s$^{-2}$ in summer, but much smaller in fall and winter seasons and exhibited similar daily variations to the zonal fluxes.
3.4 Monthly variation of horizontal winds

Time-height contours of monthly averaged zonal winds from 4 to 20 km, with a resolution of 150 m, for the three consecutive years, from September 1995 to August 1998 are shown in Fig. 7. The radar was not operated in May 1996 and November-March 1997 and gaps are shown in Fig. 7. From Fig. 7, it is observed that up to 8 km, the zonal wind is eastward. Above 8 km, the zonal wind is westward in the months of June-November. The zonal wind reached a maximum value of $\sim 42$ m s$^{-1}$ in the month of July at around 16 km. The zonal velocities of more than 42 m s$^{-1}$ are observed on individual days. This indicates that the easterly jet is more intense in the month of July. Above 6 km, the zonal wind is westward in the months of January-April with a peak amplitude of $\sim 10$ m s$^{-1}$. Above 8 km, eastward winds change to westward winds in the months of June-September.

The maximum amplitude of eastward (westerly) wind is observed in the months of summer with a peak amplitude of 10 m s$^{-1}$. However, westerly winds of more than 20 m s$^{-1}$ are observed occasionally associated with subtropical westerly jet stream in February or March. Annual oscillations are observed in the months of June, July and August with a peak of 42 m s$^{-1}$ in the months of January-March with a peak value of 10 m s$^{-1}$, every year during south-west monsoon and winter season. From the height-time contours of monthly mean meridional wind observed with the Indian MST radar for three consecutive years, below about 6 km, meridional wind is seen to be southward with a peak amplitude of 2.0 m s$^{-1}$. Southward winds of $\sim 6$ m s$^{-1}$ are seen in the months November-June in the altitude region of 10-16 km, whereas they are absent in the month of February 1996. The maximum amplitude of northward winds is
observed in the months of November-December and March-May with a peak value of ~10 m s⁻¹.

Figure 8(a) and (b) shows the vertical profiles of seasonal variation of zonal and meridional winds in different seasons (plotted using three years data). From Fig. 8(a), it is clear that zonal winds are very low below 7 km in all the seasons. The zonal wind shows an eastward flow below 7 km with an amplitude of 5 m s⁻¹ and above 7 km, there is a change in direction and winds flow westward (easterly) and reach a maximum velocity of 28 m s⁻¹ at around 16 km during monsoon season and then decrease in magnitude in the monsoon season. The easterly jet on any given day may be much stronger than the mean, but often confined to a region near the tropopause. Generally, the wind flow is from a region of high pressure to low pressure region. Strong winds are due to large temperature gradients. The flat nose of the mean jet partially results from the large vertical excursions of the daily jets associated with changes in tropopause height during passing in baroclinic systems. At the centre of the jet, the turbulence is low and thus radar echoes are weak, and have low signal-to-noise values. Narayana Rao et al. have also identified maximum zonal wind during the jet stream in the month of July at around 16 km.

A slight eastward (westerly) wind of 1 m s⁻¹ is observed up to 10 km in post-monsoon season. During winter and summer eastward (westerlies) winds are dominant with a maximum of 7 m s⁻¹ around 11 km and 12 m s⁻¹ at around 12 km in summer season. In general, easterlies are dominant winds in monsoon season and westerlies in all other seasons. A reversal of wind direction is observed in monsoon season with reference to other three seasons. An easterly maximum is observed at around 16 km in monsoon and westerly maximum at around 12 km in summer, winter and post-monsoon seasons [Fig. 8(a)].
From Fig. 8(b), it is seen that meridional winds are southward up to 9.5 km in winter and monsoon and up to 8 km in summer. From that altitude, meridional winds move northward and reach maximum values of 2.8 m s\(^{-1}\) at around 12 km in summer, 4 m s\(^{-1}\) at around 14 km in winter and 4 m s\(^{-1}\) at around 12 km during post-monsoon seasons. In general, large values of zonal winds are observed compared to meridional winds. Westerly wind maxima occur in association with a westerly jet of the middle latitudes, which shifts equatorward during winter and is at a lower altitudes associated with lower tropopause. On the other hand, easterly jet of summer monsoon occurs at a higher level and is associated with a higher tropopause. The observations of Nastrom et al.\(^{10}\) reveal stratospheric summer easterlies above 17 km and zonal winds are from west during all other seasons; the maximum mean meridional winds occur during summer.

3.5 Seasonal variation of variances

Figure 9 shows mean vertical profiles of zonal and meridional variances observed during different seasons over three years. The zonal variances show low values up to 5 km in all the seasons and from the altitude of 11 km, zonal variances increase up to an altitude of 16 km with a maximum of 40 m\(^2\) s\(^{-2}\) in monsoon, 18 m\(^2\) s\(^{-2}\) at around 15 km in post-monsoon, 6 m\(^2\) s\(^{-2}\) around 11 km in winter and 20 m\(^2\) s\(^{-2}\) at around 12 km in summer season. The meridional variances exhibit low values and similar trend is seen in all the seasons. The variance values are slightly increasing and a maximum of 8 m\(^2\) s\(^{-2}\) is seen up to 14 km in monsoon and post-monsoon, 11 km in winter, 15 km in summer. Maximum values of 8 m\(^2\) s\(^{-2}\) are found in monsoon, post-monsoon, winter and summer seasons. Average variance values are ranging in between 0.2 and 22 m\(^2\) s\(^{-2}\) and are reported by Dutta et al.\(^{5}\). The average estimates of variance given by Chang et al.\(^{6}\) for Christmas Island range between 1 and 5 m\(^2\) s\(^{-2}\). In the present study mean variances are agreeing well with that estimated by Dutta et al.\(^{5}\). From the comparisons of means of zonal and meridional variances, it is found that zonal values are large at all heights except in winter season. During winter, meridional values are somewhat larger at all
altitudes. Nastrom et al.\textsuperscript{10} reported that mean variances are large for oblique winds than for the vertical velocity and also mean variances are larger for E-W plane than in the N-S plane, smallest during summer at all altitudes and are largest above about 6 km during autumn and winter. Zonal variances are the largest in monsoon, indicating large perturbations and smallest in winter, indicating low perturbations.

### 3.6 Seasonal variation of wind shear

Figure 10 shows absolute values of vertical shears of zonal and meridional winds over 150 m range for different seasons. The shear values have undergone five point adjacent averaging. Two different peaks of zonal shears are observed in almost all the seasons, with a maximum of $\sim$ 0.0048 m/s/m at around 12 km and 17 km in monsoon season, 0.0025 m/s/m at 9 km and 15.5 km in post-monsoon, 0.0025 m/s/m in winter and 0.003 and 0.0034 m/s/m at around 9 and 16 km in summer season. Vertical shears are large during monsoon season, subsequently in summer, post-monsoon and winter seasons. These large shears are observed above and below the easterly and westerly maxima in all the seasons, indicating strong temperature gradients and, in turn, vertical gradients of winds at that altitude region. In between the peaks of maximum shears, minimum shears are found around the easterly and westerly maxima, indicating minimum temperature gradients. The vertical shears of meridional winds are fluctuating with respect to altitude. The meridional shears are maximum of value $\sim$ 0.0025 m/s/m and 0.002 m/s/m at around 15 km in summer, $\sim$ 0.002 m/s/m at around 12 and 15 km in winter, $\sim$ 0.002 m/s/m at 11 and 15 km in post-monsoon, and $\sim$ 0.001 m/s/m at around 13 km and 0.0015 m/s/m at around 18 km in monsoon seasons.

Previous studies of wind shears and turbulence estimated between 7.0 and 10.5 km by Narayana Rao and Kishore\textsuperscript{15} show a good correlation between shears and turbulence. The seasonal means of absolute wind
Shears are estimated as 0.0066 m/s to 0.01 m/s for zonal and meridional winds over 600 m layers in the altitude range of 4-20 km at WSMR, New Mexico, by Nastrom et al.10. In the present study, absolute shears of zonal and meridional winds are ranging in between 0.005 s^{-1} and 0.003 s^{-1} over 150 m layers, and shears between 0.02 s^{-1} and 0.012 s^{-1} over 600 m layers are agreeing with the above estimates approximately. The slight change may be due to climatic changes and structure of the atmosphere over the tropical station, Gadanki. An interesting feature is observed from variances (Fig. 9) and shears (Fig. 10). At the altitudes of maximum shear, minimum variances and at the minimum shear maximum variances are observed. This feature is found in all the seasons, indicating an inverse relation between them.

3.7 Seasonal variation of momentum flux

Figure 11 shows vertical profiles of average vertical flux of zonal and meridional momentum over three years as a function of season. The vertical flux is upward with an eastward momentum of ~0.05 m^2 s^{-2} at around 12 km and downward with westward momentum of ~0.25 m^2 s^{-2} in summer season. Maximum upward fluxes of ~0.25 m^2 s^{-2} and 0.2 m^2 s^{-2} at around 9 and 17 km in monsoon, 0.325 m^2 s^{-2} and 0.1 m^2 s^{-2} at around 11 km and 18 km in post-monsoon and 0.25 m^2 s^{-2} at around 14 km in winter season are observed. Meridional momentum fluxes are low up to 16 km and show a downward flux of southward momentum of 0.2 m^2 s^{-2} at around 19 km in monsoon and a downward flux of maximum southward momentum at 9 km in post-monsoon and upward flux of northward momentum of value 0.4 m^2 s^{-2} in winter and slightly low values are observed in summer season. In general, the zonal momentum fluxes are larger compared to meridional fluxes with a maximum downward flux in monsoon season. Fritts
et al.\textsuperscript{17} observed fluxes of \(-0.1 \text{ m}^2\text{s}^{-2}\) to \(-1.0 \text{ m}^2\text{s}^{-2}\), with a mean of \(-0.2 \text{ m}^2\text{s}^{-2}\) in upper troposphere and lower stratosphere with the MU radar. Narayana Rao \textit{et al.}\textsuperscript{12} reported vertical fluxes of horizontal momentum computed using two beam method and significant westward and northward fluxes were observed and the values range from \(-1 \text{ m}^2\text{s}^{-2}\) to \(+1 \text{ m}^2\text{s}^{-2}\). The magnitudes of fluxes observed in the present study are comparable to earlier observations. Nastrom and Vanzandt\textsuperscript{8} reported that the mean observed zonal momentum fluxes were small at lower levels and increasingly negative at higher altitudes.

### 4 Summary and conclusions

Three years of common mode data of Indian MST radar is used for the present study. From the diurnal wind observations in different seasons, westward winds (easterlies) are found to be more pronounced at around 16 km during monsoon and eastward winds (westerlies) at around 12 km during summer, post-monsoon and winter seasons. Zonal wind variances are found to be large compared to meridional variances, indicating large perturbations. Upward fluxes of eastward momentum are found to be maximum in summer and minimum in winter season. Downward fluxes of westward momentum are found to be maximum in monsoon and minimum in post-monsoon seasons. In zonal winds annual oscillation are observed having maximum velocities during monsoon months of June, July and August. Seasonal variation of horizontal winds shows easterlies at around 16 km during monsoon and westerlies at
around 12 km in other seasons. Variances and shears are found to be inversely related in all the seasons. Zonal momentum fluxes are large compared to meridional momentum fluxes.

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