CHAPTER III

Variability in horizontal winds in the lower troposphere from high-resolution UHF radar measurements

3.1 Introduction

Wind is an important parameter in atmospheric science field. It is having a major influence in the atmosphere dynamics and energetics, through the transport of heat, mass and moisture. These transport processes, in turn, affect the local weather, as well as climate. Hence, the characterization of wind and its variability is extremely important especially in the highly variable Asian monsoon region. Detailed observations of winds are necessary with high spatial and temporal resolutions. The ability to understand atmospheric phenomena increases as the ability to observe them with finer resolution in time and space increases. Wind profilers have proven to be powerful tool to obtain vertical profiles of three components of wind velocities and are widely used for not only atmospheric research but also for operational weather prediction. In clear air, the technique involves the backscattering of the UHF/VHF radar signal from turbulent variations in the refractive index and measuring the Doppler shift of the return. The Doppler shift provides a measure of the line-of-sight motion of the turbulence, and, if the turbulence is “frozen” in the medium, the line-of-sight of turbulence motion is the same as the line-of-sight wind velocity. Three or more beam directions (non-coplanar) can be used to get a complete wind velocity vector. The technique has been described in number of reviews including those by Gage and Balsley (1978), Balsley and Gage (1980), Rottger (1980) and Larsen and Rottger (1982).

UHF/VHF Wind profiler radars are an excellent tool for making high-resolution measurements of atmospheric winds, as well as to study associated vertical shears of horizontal winds and various atmospheric turbulence parameters. Several studies are confined to mid and high latitudes (e.g., VanZandt et al., 1978; Smith et al., 1983; Nastrom et al., 1986) and some measurements are available at low latitudes (Sato and Woodman, 1982; Tsuda et al., 1985; Jain et al., 1995; Rao et al., 1997). Ghosh et al.
(2001) have studied VHF radar observation of atmospheric winds, associated shears and $C_n^2$ at a tropical location with their interdependence and seasonal pattern. From Pune wind profiler data, wind speeds in excess of $15 - 20 \text{ m s}^{-1}$ have been frequently observed during active southwest monsoon phase in the month of July 2005 and this peak wind was found to occur around $2 - 3 \text{ km}$ (Joshi et al., 2006). Seasonal, annual and inter-annual features of turbulence parameters over Pune observed with the UHF wind profiler have been described by Narendra Singh et al. (2008). Some results of time-height variations in vertical winds obtained from Pune wind profiler are discussed by Deshpande and Ernest Raj (2008).

The purpose of this paper is to present the observational results obtained from high resolution wind profiler data in the troposphere in order to bring out the mean features and variability of the horizontal winds on monthly and seasonal scales and how they are associated with monsoon precipitation over the region. A brief description of the wind profiler radar system and data set used here has been given initially followed by presentation and discussion of the results.

### 3.2 Data Description

The 404 MHz Wind Profiler at Pune ($18^\circ\ 32'\ N,\ 73^\circ\ 51'\ E,\ 559\ m\ above\ mean\ sea\ level$) was in continuous operation for nearly four years since June 2003. The wind data collected has been quality checked and archived for scientific user community. The system has height coverage from $1.05 \text{ km}$ to about $6 - 10 \text{ km}$ (upper altitude depending on weather conditions) at height intervals of $300\ m$. One set of vector wind profiles is obtained in about $6 \text{ min}$, depending on the dwell time utilized for each radial beam measurement. The technical specifications of the Pune Wind Profiler System and details inclusive of signal processing, data quality control and preliminary validation of the wind profiler data products with the other conventional instruments have been given in Pant et al. (2005) and also described briefly in Chapter 2 of this thesis.

In the present study, the horizontal wind velocity (zonal and meridional components) data measured by the Pune wind profiler during the 3-yr period, June 2003 – May 2006, has been used to investigate and discuss the monthly and seasonal means with their variability and the occurrence of Monsoon Low Level Jet (MLLJ) during South
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West monsoon months (June – September). As per the observational protocol of the wind profiler operation, during the SW monsoon months, hourly averaged profiles, numbering eight each day, at 3-hr interval during day and night (i.e., at 0200, 0500, 0800, 1100, 1400, 1700, 2000, 2300 hrs Local Time, LT) are available to the user scientists. But during the other months of the year, they are available during daytime hours only (i.e., at 0800, 1100, 1400, 1700 hrs LT). Thus the 3-yr data set used in the present study comprises of a total of 4393 vertical profiles (3470 daytime profiles) in the height range 1.05 km to about 10.05 km measured on about 996 observational days with the 404 MHz UHF radar over this tropical station, Pune. However, as wind data is sparse at upper altitudes and due to many spurious wind values, vertical profiles up to an altitude of 8 km have only been shown in all the figures and discussed here. For uniformity, only daytime mean (i.e., average of 4 profiles between 0800 and 1700 hrs LT) for the entire 3-yr data have been computed to study monthly and seasonal/intra-seasonal means and variability. For investigating time variations during the four monsoon months of June to September, all the 8 profiles obtained in day and night have been used. The results are presented and discussed in the following section.

3.3 Results and Discussion

3.3.1 Seasonal mean and variability in vertical structure of zonal and meridional wind components

The daily mean vertical profile data for the 3-yr period is grouped into the main four tropical seasons, namely, pre-monsoon (March-May), southwest monsoon (June-September), post-monsoon (October-November) and winter (December-February) seasons. The seasonal mean profiles of zonal and meridional winds are computed from daily means and are shown plotted in Figure 3.1a and Figure 3.2a, respectively. The corresponding standard deviations (RMS deviations) are also plotted in Figure 3.1b and Figure 3.2b to study the overall seasonal mean vertical structure and variability on daily scale. In all the figures positive values of zonal wind imply westerly wind and positive values of meridional wind imply southerly flow. From Figure 3.1a it is clear that the zonal wind is showing significant seasonal variation. During pre-monsoon period, winds are westerly up to 8 km but in small magnitude. During monsoon period a predominant
low level zonal wind maximum centered around 2.5 km is noticeable with a peak average speed of about 6 ms\(^{-1}\) on a seasonal time-scale. Westerlies extend up to 7 km, thereafter zonal wind turns easterly. The existence of low-level westerly maximum shows the presence of Monsoon Low Level Jet (MLLJ) over the Pune latitude. But in the post-monsoon season the picture completely changes. During this period, lower tropospheric winds are easterly with a magnitude \(< 3 \text{ ms}\(^{-1}\). In winter season also the surface level winds are easterly, but the striking feature is the presence of a mid-tropospheric westerly maximum with a magnitude of around 3 ms\(^{-1}\) on a seasonal scale peaking at a height of around 6 km. This may be due to the influence of subtropical westerly jet stream which is having its maximum intensity in the subtropical regions at height of \(\sim 10 \text{ km}\). Thus the analysis of seasonality of zonal winds brings out two noticeable features; (i) the time evolution of low level westerly maxima during SW monsoon period, associated with the MLLJ which is a significantly good indicator of monsoon precipitation over the Indian monsoon region, and (ii) the presence of a mid level westerly maxima which may be due to the influence of subtropical westerly Jet stream during winter season.

**Figure 3.1a:** Seasonal mean vertical profiles of zonal wind for the four seasons, namely, winter (December-February), pre-monsoon (March-May), monsoon (June- September), post-monsoon (October-November) for the 3-year period June 2003 – May 2006
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Figure 3.1b: Standard deviation in seasonal mean zonal wind shown in Figure 3.1a

The magnitude of the meridional wind is less as compared to that of zonal wind, especially in the lower troposphere and its seasonal variation is also not as prominent as that in the zonal wind (Figure 3.2a). During pre-monsoon period surface level winds are northerly up to 3 km and southerlies prevail in 3-8 km range. Winds are predominantly southerly up to 7 km, though weak in magnitude, during southwest monsoon season. Northerly winds seem to prevail above that height. During post-monsoon season winds are mostly northerly throughout the lower troposphere. The winds are weak and again mostly northerly but fluctuating in magnitude during winter period.

Variability (standard deviation) appears to be increasing with altitude in the troposphere during all the seasons in both zonal and meridional winds (Figures 3.1b and 3.2b). However, below 3 km altitude, variability in zonal wind is slightly higher during monsoon season compared to that in other seasons. During pre-monsoon, winter and post monsoon seasons the variability in zonal winds is high above 4 km altitude. Variability in meridional winds throughout the lower troposphere seems to be relatively lesser during monsoon compared to that in the other seasons. But meridional winds above 4 km seem to be highly variable on a seasonal scale.
Figure 3.2a: Seasonal mean vertical profiles of meridional wind for the four seasons, namely, winter (December-February), pre-monsoon (March-May), monsoon (June September), post-monsoon (October-November) for the 3-year period June 2003 – May 2006

Figure 3.2b: Standard deviation in seasonal mean meridional wind shown in Figure 3.2a
3.3.2 *Monthly mean vertical variation of zonal and meridional wind*

To study the variations of zonal and meridional winds on a monthly mean scale and month-to-month evolution, monthly mean vertical profiles are obtained from January to December for the 3 year period (June 2003 - May 2006) and shown plotted in Figures 3.3a, 3.3b, and 3.3c for zonal wind and in Figures 3.4a, 3.4b, and 3.4c for meridional component of wind. Monthly mean zonal winds over this location show that winds are easterly up to a height of 4 km and westerly above this height from January to March months. During January a westerly maxima is seen around 6 km with a mean magnitude of 7 ms\(^{-1}\) and this mid level westerly maxima is existing right up to the month of April. After that it weakens and then evolution of low-level westerly maxima is observed during the SW monsoon months from June to September. This low-level westerly wind maximum shows relatively higher magnitude (8-9 ms\(^{-1}\)) in the months of July and August. It loses its strength in the post-monsoon and disappears by the month of October.

![Monthly mean vertical profiles of zonal wind for the four months](image)

**Figure 3.3a:** Monthly mean vertical profiles of zonal wind for the four months, namely, January, February, March, April during the 3-year period June 2003 – May 2006
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Figure 3.3b: Same as in Figure 3.3a but for the months of May, June, July, August during the 3-year period June 2003 – May 2006

Figure 3.3c: Same as in Figure 3.3a but for the months of September, October, November, December during the 3-year period June 2003 – May 2006
Tropospheric winds are westerly and small in magnitude in the month of April. But in May, winds are westerly up to 3 km and above that, easterlies prevail. Westerly winds are extending up to 8 km during June, July, August months with considerable magnitude in the lower level. During October and November months easterlies prevail in the entire lower troposphere at small magnitudes of wind speed. During December month, easterlies are prevailing up to 5 km with a westerly wind regime between 6 km and 8 km altitudes, however with small magnitude of winds. Thus from the analysis of monthly mean profiles of zonal winds two prominent features are noticed. It is the time evolution of a low level westerly maximum on a monthly scale which starts in the month of April, reaches maximum intensity in July-August months and then completely disappears by the month of October. The other is the time evolution of a mid level westerly maximum (6 km - 8 km) which starts appearing in the month of December and reaches its maximum intensity during January and weakens thereafter.

**Figure 3.4a:** Monthly mean vertical profiles of meridional wind for the four months, namely, January, February, March, April during the 3-year period June 2003 – May 2006
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Figure 3.4b: Same as in Figure 3.4a but for the months of May, June, July, August during the 3-year period June 2003 – May 2006

Figure 3.4c: Same as in Figure 3.4a but for the months of September, October, November, December during the 3-year period June 2003 – May 2006
In comparison to the zonal winds, the variation of meridional winds on a monthly scale is small. During January-May period, the surface winds are northerly (up to 3 km). The magnitude of winds is very small and is undulating around zero. However, the development of the wind maxima is clearly noticeable. During June-September months prevailing winds are southerly up to 3 km, with maximum intensity seen in the month of June. In July, wind speeds are less in comparison to that in June. Magnitudes are once again small in August and September. Thus monthly mean meridional wind profiles show time evolution of a southerly maximum during March-September period and northerly maxima during October-December period in the height range of 3 - 6 km.

3.3.3 Time-height evolution of monthly mean zonal wind – structure of Monsoon Low Level Jet (MLLJ)

The presence of a low-level westerly maximum in mean zonal winds observed during the SW monsoon months from June to September indicates the prevalence of MLLJ over this station. In order to see the time-height evolution of zonal component of wind in the tropical lower troposphere and also to examine its inter-annual variability, the individual monthly means for the 36-month period (June 2003 – May 2006) are taken to plot the time-height cross-section which is shown in Figure 3.5. The x-axis shows the month number starting from June 2003. Positive values of the contours (pink to red shaded areas) indicate that zonal winds are westerly. It is seen that there exists a systematic pattern of variation on monthly mean scale repeated year to year. Seasonal variation of zonal winds shows two altitude regimes with a transition around 4-5 km altitude. Both altitude regions show a clear alternating seasonal pattern of westerly and easterly winds. During southwest monsoon months (June-September i.e., month numbers 1-4, 13-16, 25-28 in the figure) winds are predominantly westerly in the lower troposphere with strong westerlies in the 1.5 to 3 km altitude range. The transition in this lower region from westerly to easterly takes place immediately after the month of September and easterlies continue to prevail in winter months also. Above 4 km altitude, there is opposite seasonal behavior. Here westerlies are observed in post-monsoon and winter months. Another interesting feature is that the low level westerlies during monsoon months sometimes seem to extend into the upper region. An inter-annual
variability in this seasonal behavior is also evident. The low-level westerly maximum (LLJ core) is relatively stronger and extended in period during the years 2003 and 2005, compared to that in 2004. Reports of India Meteorological Department (IMD) indicate that the years 2003 and 2005 are normal monsoon years and that 2004 is below normal year. Thus on a seasonal scale it can be said that strong and extended low-level westerlies can lead to a good/normal monsoon. The mid level (5 to 7 km) westerly maximum also exhibits an inter-annual variation. It is strong and narrow in duration during 2003-2004 winter season but is weaker in magnitude during 2004-2005 and 2005-2006 winter seasons. Time-height evolution of meridional winds (not shown here) also show alternating regimes of southerly and northerly winds in the lower troposphere, but less pronounced in magnitude.

Figure 3.5: Time-height cross-section of monthly mean zonal wind from June 2003 to May 2006
3.3.4 Association between westerly zonal wind and local rainfall

To examine the intra-seasonal variability in zonal component of wind in more detail on daily scale and also to see its relationship with monsoon precipitation, daily average zonal wind during the months of June – September for all the three years (2003, 2004, 2005) is taken and plotted as time-height cross-sections (contours) in Figures 3.6a, 3.6b and 3.6c. Daily total rainfall (mm) for Pune station is also shown as over-laid line plots in these contour figures to examine its association. Significant intra-seasonal as well as inter-annual variability can be seen in lower tropospheric zonal winds.

![Zonal Wind Contours](image)

**Figure 3.6a:** Time-height cross-section of daily mean zonal wind for the period 01 June to 30 September 2003 along with daily total rainfall (mm) over Pune station

During the monsoon season of 2003 there are several episodes of strong westerlies (Figure 3.6a) spread throughout the season. A low level westerly maximum is seen on almost all the days during the monsoon season, having a jet core in 2 - 4 km height range. The zonal wind speed in the jet core region reaches as high as 18 ms⁻¹ on daily mean scale during the year 2003. As mentioned above, this is associated with the large scale phenomena called Monsoon Low Level Jet (MLLJ) which has role in modulation of monsoon intra-seasonal oscillation.
Figure 3.6b: Same as in Figure 3.6a but for the period 01 June to 30 September 2004

Figure 3.6c: Same as in Figure 3.6a but for the period 01 June to 30 September 2005
Another interesting feature is that the vertical extent of the low level westerly maxima extends sometimes up to 6-8 km. On an average it extends up to 6 km with a speed of 10-12 ms$^{-1}$. During the monsoon seasons of 2004 and 2005 (Figures 3.6b and 3.6c), there are distinctly separate episodes of few days duration when strong westerly flow occurs over this region (for example three in 2005). It is noted that during all the three monsoon seasons, whenever there is strong westerly flow (strong MLLJ), precipitation/rainfall is recorded over the station (peaks in the rainfall curves). During 2003 even small peaks of rainy days coincide with strong westerly flow throughout the season. Heavy rain spell occurred from day number 52 to 58 when the zonal wind speeds in the 2.5 – 3.5 km altitude range was above 16 ms$^{-1}$. During the year 2004 two heavy rain spells occurred over Pune during 12 to 20 June and 28 July to 22 August accompanied by strong westerlies (speeds around 18 ms$^{-1}$). Again in the monsoon season of 2005, three heavy rain spells occurred (22 June to 02 July, 24 July to 10 August, and 9 to 20 September) and strong westerlies of magnitude on a daily mean scale as high as 20 ms$^{-1}$ are observed during these episodes. Thus rain spells/episodes during active monsoon conditions are due to the strong large-scale zonal flow, closely related the westerly MLLJ. However, one can also notice sharp rainfall peaks (of 2-3 days duration) during first half of June and last week of September which do not seem to be accompanied by strong westerlies. This may be due to the fact that monsoon flow is weak or is not yet set up in the region by first week of June and the precipitation that occurred during this period may be due to strong local convection (what are called pre-monsoon and post-monsoon thunderstorms). The normal onset date of southwest monsoon over Pune region is 6 June as per long-term climatology. During break phases of monsoon the MLLJ is weak or totally absent and sometimes localized rainfall can occur due to local convection.

3.4 Conclusions

Horizontal wind profile data obtained from a UHF wind profiler at the tropical Indian station Pune during the 3-year period, June 2003 – May 2006 has been utilized to study seasonal and inter-annual variability of winds in the lower troposphere. Zonal winds display a predominant systematic seasonal evolution in two altitude regimes
having a transition around 4-5 km altitude. In the lower region, during south west monsoon months (June to September) winds are predominantly westerly with a peak around 1.5 – 3 km range indicating the presence of Monsoon Low Level Jet. Change over from westerly to easterly in this height region takes place soon after the month of September (when SW monsoon mostly withdraws from the Indian sub-continent) and easterlies continue in winter months also. Above 4 km height, the behavior of winds is quite opposite in direction. Here westerlies are observed during post-monsoon and winter periods. Wind variability (standard deviation) appears to increase with altitude during all seasons in both zonal and meridional components. However, below 3 km altitude the variability in zonal winds is slightly higher during monsoon season which could be due to the intra-seasonal variations associated with monsoon. The low level westerly maximum (MLLJ) during monsoon season is strong during normal/good monsoon years. It is interesting to see that on a day-to-day scale, stronger westerlies (strong MLLJ) are closely associated with occurrence of precipitation/rainfall over the wind profiler station and this is consistently observed during all the three years.