CHAPTER VII

Horizontal and vertical winds, wind shear and turbulence during pre-monsoon thunderstorms from Doppler wind lidar and UHF radar measurements

7.1. Introduction

Thunderstorm, resulting from vigorous convective activity, is an important weather phenomenon in the atmosphere which is associated with various other meteorological phenomena like rainfall, hail and lightning. In the tropical latitudes, organization of several thunderstorms in mesoscale convective systems like squall lines is of great interest from meteorological point of view. Study of the life cycle of a tropical thunderstorm and atmospheric dynamics associated with it, is necessary to understand the short-duration heavy precipitation that it produces. Knowledge of atmospheric dynamics would also provide detailed understanding of the very physical processes that lead to development of such intense tropical convective events.

Thunderstorm development depends on three basic components, namely, moisture, instability and some form of lifting mechanism. The main stages of development of a thunderstorm include cumulus stage, mature stage and dissipating stage (Byers and Braham, 1949) which together may take place in about 60 – 90 min time period depending on the intensity of convection. Greater the atmospheric instability, stronger will be the thunderstorm updrafts and greater will be the potential for it to become a severe thunderstorm. Further, once the instability in a cumulus cloud is sufficient for an updraft to form, the development and the type of thunderstorm that forms is dependent on the strength of vertical motions of the atmosphere. Although they are short lived, they can be intense with strong updrafts and downdrafts and with local heavy rain. Also as vertical wind shear increases, storms with persistent updrafts will
Horizontal and vertical winds, wind shear and turbulence during pre-monsoon thunderstorms from Doppler wind lidar and UHF radar measurements

occur. Some previous studies (Newton and Newton, 1959; Asai, 1964; Robe and Emanuel, 2001) showed that vertical shear of horizontal wind plays important role in convective development. Weisman and Klemp (1982) suggested that in a given buoyant environment, weak vertical wind shear generates short-lived single-cell thunderstorms, weak to moderate shear generates multi-cell thunderstorms and moderate to strong shear generates super-cell thunderstorms. So it is essential to have high resolution measurements of altitude profiles of winds (both horizontal and vertical) to study the dynamical behavior of the atmosphere during evolution of a thunderstorm.

Over the Indian region, thunderstorm is an important weather phenomenon particularly during pre-monsoon (March–May) and post-monsoon (October–November) seasons. Thunderstorms with higher frequency occur during the pre-monsoon season when the atmosphere is highly unstable due to high temperatures prevailing at lower levels. Being mesoscale systems, they are source of abundant rainfall on ground catering to various water needs as well as being a cause of natural disasters. Extensive research has been carried out in the past few decades over the Indian region to investigate various aspects of pre-monsoon thunderstorms (eg., Koteswaram and Srinivasan 1958; Koteswaram and De 1959; Sadhukhan and De, 1998; Sadhukhan et al., 2000; Mukhopadhyay et al., 2005; Ghosh et al., 2008). Some long-term studies on thunderstorm activity, its occurrence frequency during different seasons and its association with seasonal rainfall over several Indian stations have been reported in literature (Williams, 1961; Manohar et al., 1999; Kandalgaonkar et al., 2005). Case studies of thunderstorm events from radiosonde/rawin ascent observations have been made by Chaudhary et al. (2010) to find out the effect of vertical wind shear and instability on strength and longevity of thunderstorms. Pre-monsoon convective atmosphere over a northeast Indian station (Kolkata) has been investigated using radiosonde data and various thermodynamic indices and parameters to assess the skill of these indices in forecasting the occurrence of pre-monsoon thunderstorm activity over the region (Tyagi et al., 2011).

Wind profilers can provide observations of vertical motion through a column within convection and together with information on horizontal winds, has been used to explore the relationship between air motions within the convective storm and
microphysics (May and Rajopadhyaya, 1999; Rao et al., 2006; 2008; Kirankumar et al., 2008). Larsen and Rottger (1987) have compared observations of thunderstorm reflectivities and Doppler velocities measured with VHF and UHF radar. Chilson et al. (1993) have used dual-frequency Doppler radar to observe the thunderstorm associated with tropical wave and made measurements of vertical winds as well as to study the nature of precipitation. May et al. (2002) showed potential of the combined wind profiler and polarimetric radar measurements in studying the vertical motion and complex microphysical characteristics of shallow tropical thunderstorm that formed on sea-breeze front. The structures of vertical velocity, horizontal divergence and turbulence associated with tropical Mesoscale Convective System (MCS) have been examined by using MST radar observations over a tropical Indian station (Gadanki) by Rao et al. (2001) and Kishore Kumar et al. (2005). Observational results obtained from UHF wind profiler during the life-cycle of a pre-monsoon thunderstorm have been used to examine time-height variations in the vertical velocity, echo power, and vertical wind shear by Deshpande and Ernest Raj (2009). However, space-time resolution in all the above measurements is not fully adequate to capture the small scale motions and dramatic changes that are associated with such short-lived intense convective events.

Along with observations, numerical modeling has also made substantial advances in recent times in modeling of convective clouds and mesoscale convective systems. These models have been suitably customized for simulation/prediction of active mesoscale systems like severe thunderstorms over the Indian region (eg., Mohanty et al., 2004; Litta et al., 2007; Vaidya, 2007). Some recent studies include use of a high resolution WRF-NMM (Weather Research Forecasting – Non-hydrostatic Mesoscale Model) model to simulate severe thunderstorm events (Litta and Mohanty, 2008; Rajeevan et al., 2010; Litta et al., 2012).

High spatio-temporal resolution measurements of horizontal and vertical winds, from near-surface to a few kilometers above, using a Doppler wind lidar as well as UHF radar/wind profiler, during development and mature stages of some tropical thunderstorms are analyzed here to provide observational insight into the changes that place. Results of some case studies are presented and discussed in this Chapter.
7.2 System description and Data

The WindCube-200 wind lidar put into operation at Pune (18°32’N, 73°51’E, 559 m Above Mean Sea Level), India is capable of retrieving the 3D components of the wind (east-west, north-south, vertical) in the lower troposphere (from 100 m to around 6000 m above surface level) at every 50 m height interval. Details of the Doppler wind lidar system have been provided in Chapter-II. High resolution horizontal and vertical wind measurements made using the above wind lidar over Pune on four thunderstorm days (21 April, 09 May, 14 May and 27 May) during the pre-monsoon season of 2014 are analyzed in this Chapter to examine the dynamical conditions that exist during the development of typical pre-monsoon thunderstorms over the station. Horizontal and vertical wind profiles obtained at 5-min intervals in the altitude range from 100 m to 3000 m above surface (59 altitudes at 50 m height interval), have been used for the analysis. Further, horizontal wind shear, convergence, and turbulent intensity have also been computed from these measurements to gain a better understanding of the processes that take place during evolution of a convective event.

The ability of UHF radar to measure horizontal and vertical air motions and hydrometeor fall velocity through precipitating and non-precipitating systems has been utilized to analyze one case of thunderstorm event that occurred in the late afternoon hours on 03 June 2008 over Pune. Vertical profiles of vertical beam Signal-to-Noise Ratio (SNR), horizontal and vertical wind speed, spectral width obtained at 6-min intervals in the altitude range from 1050 m to 4350 m (at 300 m height interval) as well as those profiles of some computed parameters like vertical shear of horizontal wind and convergence have been used to examine the time-height variations that take place during a local thunderstorm event. Results obtained from these thunderstorm cases are presented and discussed in following Section.

7.3 Results and discussion

7.3.1 Case studies using Doppler wind lidar observations

7.3.1.1 Time-height variation of horizontal wind

In order to have a complete diurnal time-height evolution of horizontal and vertical winds, Doppler wind lidar data from 00:00 hrs to 23:00 hrs Local Time (LT) on
21 April 2014, 09 May 2014, 14 May 2014 and 27 May 2014 have been used. Local thunderstorm event in afternoon hours accompanied by thunder, lightning, gusty winds and heavy rainfall occurred over the lidar observing site on these four days. Although surface level convection during the hot pre-monsoon season starts soon after sunrise, the full development, mature and dissipation stages of a tropical thunderstorm forming over the Indian sub-continent generally takes place in the local after-noon or late evening hours. The local time when precipitation (rainfall) started occurring on ground on these four days is 1855 hrs, 1530 hrs, 1830 hrs, and 1340 hrs respectively, as determined from a Disdrometer placed close to the lidar system. Time-height contour plots of lidar-derived horizontal winds on these four thunderstorm days are shown in Figures 7.1a, 7.1b, 7.1c, and 7.1d. Vertical data gaps (blank regions) in all the contour plots on all the four days are indicative of duration when rainfall occurred. This is the limitation of the optical remote sensing system (lidar) when the optical signal gets attenuated due to rain drops. It is observed that on all the thunderstorm days presented here, there is significant time-height variability in horizontal wind especially 2-3 hours before rainfall occurrence. There are pockets of either high or low wind speeds. Variations on 14 May 2014 (Fig. 7.1c) show very interesting behavior. The nocturnal low level jet (NLLJ) discussed in Chapter VI is very prominent in the late nighttime around 800 m altitude. Its existence ceased soon after local sunrise and after 11:00 hrs LT, horizontal winds showed large time-height variability. Wind speeds throughout the 100 m – 1500 m height region were high (~ 10 ms⁻¹, hourly averaged) at least one hour before occurrence of rainfall, that is, during the mature stage of thunderstorm. Time-height variation of Carrier-to-Noise Ratio (CNR), an indicator of backscattered signal strength, on 21 April 2014 is shown in Figure 7.2, as a typical example. One can see that in the local post-sunrise hours the boundary layer growth starts as on a normal day. But once intense convection and cloud formation associated with thunderstorm development started, this boundary layer evolution gets inhibited. Higher echo strengths (CNR) in the layers close to ground ceased to exist by 11:00 hours, which otherwise would have continued to grow in strength and in altitude until afternoon hours.
Figure 7.1a: Time height variation of horizontal wind on 21 April 2014

Figure 7.1b: Time height variation of horizontal wind on 09 May 2014
**Figure 7.1c:** Time height variation of horizontal wind on 14 May 2014

**Figure 7.1d:** Time height variation of horizontal wind on 27 May 2014
7. Horizontal and vertical winds, wind shear and turbulence during pre-monsoon thunderstorms from Doppler wind lidar and UHF radar measurements

7.3.1.2 Time-height variation of vertical wind

Wind profilers (based on both optical/laser and radio remote sensing) alone can provide virtually continuous observations of vertical motions through an atmospheric column especially within convection. Thus they provide a very important insight into the nature of updrafts and downdrafts in a developing thunderstorm. Time-height variations of vertical wind speed \(w\) on the four thunderstorm days, namely on 21 April 2014, 09 May 2014, 14 May 2014 and 27 May 2014, are shown in Figures 7.3a, 7.3b, 7.3c, and 7.3d. Here positive values of vertical velocity indicate updrafts. It is interesting to note that on all the four thunderstorm event days, vertical velocity during thunderstorm development stage (3 to 4 hours before rainfall occurred) showed alternating updrafts and downdrafts extended to almost the entire height region. On 21 April 2014 (Fig. 7.3a) between 11:00 and 12:00 hrs LT vertical velocity was positive (upward motion), from 13:00 to 14:00 hrs LT it showed downward motion and around 15:00 hrs LT strong upward motion extending from surface to \(~1200\) m was recorded. From \(~16:00\) hrs LT weak downward motion prevailed until precipitation on ground was recorded \(~18:55\) hrs LT on this day.
Figure 7.3a: Time height variation Vertical velocity on 21 April 2014

Figure 7.3b: Time height variation Vertical velocity on 09 May 2014
Figure 7.3c: Time height variation of Vertical velocity on 14 May 2014

Figure 7.3d: Time height variation of Vertical velocity on 27 May 2014
On 09 May 2014 (Fig. 7.3b) similar alternating upward and downward motions are recorded during thunderstorm development, but these motions were confined mostly to 100 – 800 m height region. Precipitation on ground was recorded around 15:30 hrs LT on this day. On 14 May 2014 (Fig. 7.3c) upward motions were noticed to be relatively stronger. Very strong upward motions extending up to 2000 m were detected between 15:00 and 17:00 hrs LT on this day while precipitation on ground was recorded around 18:30 hrs LT. On 27 May 2014 (Fig. 7.3d) vertical motions were generally weaker and precipitation occurred relatively much earlier (~ 13:30 hrs LT) on this day. Thus the recorded vertical motions on the four cases showed that during developing stage of thunderstorm, alternating upward and downward motions are prevalent in the entire vertical column of the atmosphere.

Time series of wind lidar-derived vertical velocity (at 5-min interval) measured at four typical altitudes (100 m, 300 m, 500 m, 700 m) on the above four thunderstorm days are shown in Figures 7.4a to 7.4d. The vertical dashed line in the figures indicates the respective local time of onset of rainfall on ground on these days. During nighttime and post-sunrise hours vertical velocity was very small in magnitude. However, during the developing stage of the thunderstorm, the magnitude of vertical velocity increases manifold appearing as highly turbulent condition with updrafts and downdrafts. This is evident during all the four cases presented here. To compare the time variation of vertical wind on a non thunderstorm (NTS) day with those on a thunderstorm (TS) day, two pairs of days are selected and shown. Figure 7.5a shows these comparisons in time variations on 10 May (NTS day) and 09 May (TS day) and Figure 7.5b depicts these comparisons on 15 May (NTS day) and 14 May (TS day). It is evident that both the duration and magnitude of vertical velocity fluctuations on thunderstorm days are clearly much higher compared to those on non thunderstorm days. Whatever small magnitude fluctuations in vertical wind during forenoon hours are recorded on NTS days could be because of the daytime convection that naturally exists in the layers close to ground during the pre-monsoon season.
Figure 7.4a: Temporal variation of Vertical velocity at 100, 300, 500 and 700 meter heights on 21 April 2014

Figure 7.4b: Temporal variation of Vertical velocity at 100, 300, 500 and 700 meter heights on 09 May 2014
Figure 7.4c: Temporal variation of Vertical velocity at 100, 300, 500 and 700 meter heights on 14 May 2014

Figure 7.4d: Temporal variation of Vertical velocity at 100, 300, 500 and 700 meter heights on 27 May 2014
Figure 7.5a: Temporal variation of vertical velocities on a non thunderstorm day
(10 May 2014, upper panel) and a thunderstorm day (09 May 2014, lower panel)

**Figure 7.5b**: Temporal variation of vertical velocities on a non thunderstorm day (15 May 2014, upper panel) and a thunderstorm day (14 May 2014, lower panel)
7.3.1.3 Time-height variation of Turbulent Intensity

In order to study the nature of turbulence in the atmospheric layer from surface to about 3000 m during the development a thunderstorm, Turbulence Intensity (TI) parameter is calculated from the 5-min average profiles of horizontal wind speed derived from wind lidar on the four thunderstorm days mentioned above. The expression for calculating TI, also used in Chapter VI, is as following.

\[ TI = \frac{\sigma_V}{V_{\text{mean}}} \]  

(7.1)

Where \( \sigma_V \) represents the standard deviation of the horizontal wind speed, and \( V_{\text{mean}} \) designates the mean horizontal wind speed. Time-height variations of TI on the four thunderstorm days, namely on 21 April 2014, 09 May 2014, 14 May 2014 and 27 May 2014, are shown in Figures 7.6a, 7.6b, 7.6c, and 7.6d, respectively. TI values are low during local nighttime and interestingly TI seems to strengthen soon after local sunrise, initially in surface layers. As daytime convective boundary layer evolves, TI also builds up vertically. On all the four thunderstorm days TI is high in magnitude during the evolution of intense convection. Just before the occurrence of rainfall on ground, high TI values extend throughout the vertical column indicating highly turbulent atmospheric conditions. Thus the observations show that daytime convection and conditions leading to development of thunderstorm are closely associated with enhanced turbulence in the lower atmosphere.

7.3.1.4 Time-height variation Convergence and Horizontal wind shear

Convergence and Horizontal wind shear are calculated by using 5-min averaged data by using the below formulae

\[ Convergence = \frac{dW}{dz} \]  

(7.2)

\[ \text{Hor. windshear} = \frac{dU}{dz} \]  

(7.3)

Convergence and horizontal wind shear calculated above is then made into hourly values.
Horizontal and vertical winds, wind shear and turbulence during pre-monsoon thunderstorms from Doppler wind lidar and VHF radar measurements

Figure 7.6a: Time height variation of Turbulence Intensity on 21 April 2014

Figure 7.6b: Time height variation of Turbulence Intensity on 09 May 2014
Figure 7.6c: Time height variation of Turbulence Intensity on 14 May 2014

Figure 7.6d: Time height variation of Turbulence Intensity on 27 May 2014
Figure 7.7a: Time height variation of Convergence on 27 May 2014

Figure 7.7b: Time height variation of horizontal wind shear on 27 May 2014
Figure 7.7a shows time-height variations in convergence and Figure 7.7b those in horizontal wind shear as typical case during the thunderstorm event on 27 May 2014. Strong convergence is seen in the lower layers in the developing stages of thunderstorms. During the development of thunderstorm over the observing site, vertically alternating layers of convergence and divergence and divergence are observed, which contribute to strengthening and vertical growth of the local convective processes. At the same time, horizontally time-stratified layers of strong positive and negative wind shear are also observed between 100 m and 700 m altitude.

### 7.3.2 Case study using UHF radar observations

The ability of UHF radar/wind profiler to directly measure vertical air motions and hydrometeor fall velocity through precipitating and non precipitating systems has been explored through an analysis of one pre-monsoon thunderstorm event which occurred in the late afternoon hours on 03 June 2008 over Pune station. Using the high resolution UHF radar data (altitude profiles at 6-min interval), the extent of enhancement in vertical velocities (updrafts and downdrafts), echo power, changes in spectral width, horizontal wind, and vertical shear of horizontal wind during developed stage of thunderstorm are examined and results presented.

Vertical profile (1.05 km to 16.0 km) of vertical pointing beam Signal-to-Noise Ratio (SNR in dB) averaged over an hour centered on 1700hrs LT is shown in Figure 7.8. High values of SNR are observed up to the height of 4 km with a sharp fall in echo strength above this height. This enhancement of reflectivity is associated with the radar bright band that occurs mainly due to the phase change of hydrometeors near the 0°C isotherm level. But being a case of convective event, this bright band is not seen clearly as seen in normal stratiform clouds may be because of its mixed convective and stratiform nature. Time-height variations of 6-min instantaneous values of horizontal wind speed, vertical shear of horizontal wind, vertical velocity, and spectral width observed in the height range from 1.05 km to 4.35 km on 03 June 2008 during the period 16:40 to 17:44 hrs LT are shown in Figures 7.9a, 7.9b, 7.9c and 7.9d respectively.
Strong horizontal winds with speeds as high as 30 ms\(^{-1}\) has been observed during mature stage of thunderstorm (Fig. 7.9a). Regions of strong horizontal winds seem to shift up to higher altitudes as the convection grows vertically in a thunderstorm. Analysis of horizontal wind shear indicates the presence of strong wind shear during maximum downdraft occurs (Fig. 7.9b). This shear is existing in all the height (1.05 - 4.35 km) levels. Vertical velocities (Fig. 7.9c) show abrupt updraft and downdrafts during the course of the thunderstorm with values ranging from 0 to 18 ms\(^{-1}\). Maximum downdraft is seen around 17:14 hrs LT and this intense downdraft is due to the occurrence of precipitation (hydrometeor fall velocity). Spectral width (Fig. 7.9d) was maximum just before the maximum precipitation occurred and was confined to 3.15 km - 4.35 km region. Thus interesting time-height changes take place during developed stage of a tropical thunderstorm and UHF radar is able to capture these changes.
7 - Horizontal and vertical winds, wind shear and turbulence during pre-monsoon thunderstorms from Doppler wind lidar and UHF radar measurements

Figure 7.9a: Time-height variations of 6 minute instantaneous values of horizontal wind speed on 03 June 2008 during the period 16:50-17:44 hrs LT

Figure 7.9b: Time-height variations of 6 minute instantaneous values of horizontal wind shear on 03 June 2008 during the period 16:50-17:44 hrs LT
**Figure 7.9c**: Time-height variations of 6 minute instantaneous values of precipitation fall velocity on 03 June 2008 during the period 16:50-17:44 hrs LT.

**Figure 7.9d**: Time-height variations of 6 minute instantaneous values of Doppler width on 03 June 2008 during the period 16:50-17:44 hrs LT.
7.4 Conclusions

Time-height variations of horizontal and vertical winds obtained from Doppler wind lidar and UHF radar during pre-monsoon thunderstorm events provide interesting results. There is significant time-height variability in horizontal wind especially 2-3 hours before rainfall occurrence with pockets of high and low wind speeds. The recorded vertical motions on the thunderstorm days showed that during its developing stage, alternating updrafts and downdrafts are prevalent through the entire vertical column of the lower atmosphere. It is also seen that both the duration and magnitude of vertical velocity fluctuations on thunderstorm days are much higher compared to those on non-thunderstorm days. Turbulence intensity is high in magnitude during the evolution of intense convection and also these high values extend throughout the vertical atmospheric column indicating highly turbulent atmospheric conditions. Alternating layers of positive and negative convergence (convergence and divergence) with horizontally time-stratified layers of strong positive and negative wind shear are observed which contribute to strengthening and vertical growth of the local convection. Thus high-resolution wind lidar and UHF radar observations show that daytime convection and conditions leading to development of pre-monsoon thunderstorm are closely associated with strong upward and downward motions (large vertical velocity fluctuations), enhanced and vertically evolving turbulence, alternating regions of convergence and divergence and strong wind shears in the lower atmosphere.