Chapter I

Introduction

1.1 Background

Wind is the horizontal movement of air in response to pressure differences. Through winds the atmosphere attempts to balance the uneven distribution of pressure over Earth’s surface. Their strength depends on the strength of the gradient in pressure. Winds are always flowing from higher pressure to lower pressure regions. The steeper the pressure gradients involved, the faster and stronger will be the winds. The movements of the wind also play a major role in correcting the imbalances in radiational heating and cooling that occur over Earth’s surface. On an average tropics receive more radiant energy than they lose and poles lose more radiant energy than they receive. Global wind systems transport energy from tropics to pole ward in order to maintain the energy balance. The global wind system also gives rise to the ocean currents, which are another significant factor in equalizing the energy imbalance. Besides serving a vital function in the advectional (horizontal) transport of heat energy, winds also transport water vapor from the air above bodies of water, where it has evaporated, to land surfaces, where it condenses and precipitates. This allows greater precipitation over land surfaces than could otherwise occur. Further winds can be used as alternate energy resource in the place of fossil fuels, because of the less contribution to pollution and being renewable. Winds vary widely in velocity, duration, and direction.

Wind systems can be classified according to their horizontal extent and time scale of their persistence. They are planetary wind systems, synoptic scale wind systems, meso-scale wind systems and micro-scale wind systems.

1.1.1 Planetary scale wind systems

a) Surface wind systems

The planetary or global wind system is a response to the global pressure patterns and also plays a role in the maintenance of those same pressures. This wind system is the major means of transport for energy and moisture through Earth’s atmosphere. Global
wind pattern can be explained by the general circulation model of the atmosphere. It consists of seven pressure belts or zones, one is centered at the equator and other six distributed equally in both hemispheres. Equator belt is known as equatorial low. The areas of subtropical high pressure, is generally located between latitudes 25° and 35° in Northern and Southern hemispheres. The sub-polar low is located between 55 and 65 degree latitudes in both hemispheres and finally the polar high is located in both hemispheric poles.

The characteristics of convergence and divergence are very important to our understanding of global wind patterns. Surface air diverges from zones of high pressure and converges on areas of low pressure. Surface winds originate in areas of high pressure and blow towards the areas of low pressure. Idealized model of global atmospheric circulation includes six wind belts, or zones, in addition to the seven pressure zones that are mentioned above and is shown in the figure 1.1. Two wind belts, one in each hemisphere, are located where winds move out of the polar highs and down the pressure gradients toward the sub-polar lows. As these winds are deflected to the right in the Northern hemisphere and to the left in the Southern, they become the polar easterlies. The remaining four wind belts are closely associated with the divergent winds of the subtropical highs. In each hemisphere, winds flow out of the poleward portions of these highs toward the sub-polar lows. The air that flow from subtropical high to sub-polar region will deflect to the right in the northern hemisphere and to the left in southern hemisphere and becomes southwesterly and northwesterly in northern and southern hemispheres. They are commonly known as subtropical westerly. They tend to be less consistent in direction than the trades, but they are usually stronger winds and may be associated with stormy weather. The westerlies occur between about 35° and 65° N and S latitudes. In the southern hemisphere westerlies attain more consistency and strength as compared to the northern hemisphere because of the lesser density of the land mass. Other two wind systems one each in both hemispheres will flow from the subtropical high to equatorial low and due to coriolis force get deflected and form tropical easterlies. In the northern hemisphere it is named as North easterlies and in the southern hemisphere it is known as South easterlies and can be identified between latitudes 5° and 25°.
b) Upper Air Winds and Jet Streams

The circulation of the upper air winds is a far less complex phenomenon than surface wind circulation and because of less frictional drag, the flow will be stronger also. In the upper troposphere, an average westerly flow, the upper air westerlies, is maintained poleward of about 15°–20° latitude in both hemispheres. Between 15° and 20° N and S latitudes are the upper air easterlies, which can be considered the high-altitude extension of the trade winds. These upper air westerlies form as a response to the temperature difference between the tropical and polar air. Air will flow from equator to poles and turns eastward because of the effect of coriolis force. The net result is a broad circumpolar flow of westerly winds throughout most of the upper atmosphere. This flow is stronger in winter as compared to that in summer since during winter higher temperature gradient exists between tropics and pole. The temperature gradient between
tropical and polar air is not uniform, and is mostly concentrated where the tropical air meets the polar air, that is in the polar front. This region is the origin of polar easterly jet stream. It is having an average width of 100 km and a thickness of about 2-3 km. Another Jet stream, the subtropical westerly Jet stream, flows above the sinking air of the subtropical highs in the lower-middle latitudes. This Jet is also stronger in winter than in summer and shifts northwards during the summer months.

1.1.2 Synoptic scale wind systems

Synoptic scale systems are having the horizontal length of about 1000 km or more. There are number synoptic scale systems which persist for weeks to few months, which have an affect on the Indian subcontinent. Tropical cyclone associated wind systems and the Indian summer monsoon are well known synoptic systems which have great effect on the human well being. A brief description focusing on the monsoon system, and in particular the Indian summer monsoon, is provided below.

The term monsoon appears to have originated from the Arabic word mausam which means season. With change of season there is also generally a change of wind direction; hence the word ‘monsoon’ also came to be associated with wind directions. In a true monsoon climate, seasonal wind shifts typically cause a drastic change in the general precipitation and temperature patterns. Monsoons have been subject of considerable research work for more than a century. According to Ramage (1971) the main characteristics of monsoon regions are as follows:

- The prevailing wind direction shifts by at least $120^\circ$ between January and July.
- The average frequency of the respective prevailing wind directions in January and July exceeds 40%.
- The mean resultant wind speed in at least one of the months exceeds $3 \text{ ms}^{-1}$.
- Fewer than one cyclone-anticyclone alternation occurs every two years in either month in a 50 latitude-longitude region. This monsoon region includes parts of the African continent, South Asia and North Australia.
**a) Asian Summer Monsoon**

During the northern hemispheric summer season, ITCZ migrates to its northern most position (30° N) over South Asia, establishing the monsoon trough. There the pressure patterned meridional circulation in summer is further accentuated by the presence of huge mountain mass over South Asia, the Himalayas, leading to the establishment of the southwest monsoon. The supply of atmospheric water vapour is crucial in this context. In boreal summer, there is large evaporation in the south Indian Ocean trade wind area and the cross equatorial monsoon air-stream carries this water vapour into South Asia, thus fueling the monsoon rainfall. The parameters of broad scale monsoon system described by Krishnamurti and Bhalme (1976) are schematically shown in Figure 1.2. Mainly two wind systems are associated with monsoon apart from three pressure systems (monsoon trough, Mascarene high, Tibetan high). They are Tropical Easterly Jet stream (TEJ) and Monsoon Low Level Jet (MLLJ).

**Figure 1.2**: Synoptic components of Indian summer monsoon
**Low Level Cross Equatorial Jet:** This is the well known northern summer Low Level Jet (LLJ). The LLJ has its origin in the south Indian Ocean north of the Mascarene High as an easterly current, it crosses the equator in a narrow longitudinal belt close to the east African coast as southerly current (with speeds at times even as high as 100 knots), turns into Arabian Sea as a westerly current and passes through Indian sub-continent to the western Pacific Ocean. The LLJ is the main conduit for transporting moisture generated over the Indian Ocean into the monsoon area.

**Tropical Easterly Jet:** A strong easterly flow of air south of the Tibetan High, a tropical easterly jet stream (TEJ), develops in the upper troposphere at around 150 hPa during the monsoon season. This jet has winds of 80-100 knots and has its axis approximately around 10°N and 100°E. Normally, TEJ is in an accelerating stage from south China Sea to south India and decelerates to the west. Upper divergence associated with TEJ is regarded as favorable for convection upstream of 70°E. Subsidence occurs downstream. The fact that the tropical easterly jet only occurs in the summer suggests that its development is related to the seasonal cycle of surface heating and convective heating in the area over which jet lies.

b) **Tropical Cyclones**

They are low pressure systems that form over warm tropical waters and have gale force winds (sustained winds of 63 kmh⁻¹ or greater and gusts in excess of 90 kmh⁻¹) near the centre. Technically they are defined as a non-frontal low pressure system of synoptic scale developing over warm waters having organized convection and a maximum mean wind speed of 34 knots or greater extending more than half-way around near the centre and persisting for at least six hours. The gale force winds can extend hundreds of kilometres from the cyclone centre. If the sustained winds around the centre reach 118 kmh⁻¹ (gusts in excess of 165 kmh⁻¹), then the system is called a severe tropical cyclone.
1.1.3 *Meso-scale wind systems*

Meso-scale meteorology is the study of atmospheric phenomena with typical spatial scales between 10 and 1000 km. Examples of meso-scale phenomena include land-sea breeze, mountain-valley breeze, nocturnal jet, thunderstorms, gap winds, downslope windstorms, and squall lines etc. Some of the wind systems are described in the following paragraphs.

a) *Land Breeze–Sea Breeze*

The land breeze–sea breeze cycle is a diurnal (daily) one in which the differential heating of land and water plays a major role. During day time land heats more quickly and air above becomes warmer as compared to the nearby sea. Air above the land expands and rises and this creates a low pressure over the land. Simultaneously high pressure forms over the sea and air starts flow from sea to land. This is called sea breeze. During night time the reverse happens. Land and air above it cools more quickly than nearby ocean and air above it. So high pressure will be developed over the land, and over the ocean low pressure develops. So the air starts flow from land to ocean. This air movement is called land breeze.

b) *Mountain Breeze-Valley Breeze*

The mechanism for the formation of mountain breeze–valley breeze is similar to land-sea breeze cycle. During the day time air above the slopes of the mountain heats more quickly as compared to the air above the valleys. So the air will flow from valleys to the slopes and is called as valley breeze. During nighttime the conditions reverse and the flow will be from slopes to the valley and is termed as mountain breeze.

c) *Nocturnal Low level Jet*

The term "low-level jet" (LLJ) is commonly used in meteorological literature to describe a wide variety of wind features found over nearly every continent on earth (Bonner, 1968; Uccellini and Johnson, 1979). At nighttime under clear-sky conditions and weak synoptic winds, a wind maximum close to the ground can exist, often referred to as nocturnal LLJ. Some authors (Li and Chen, 1998) used the term to describe any
low-level wind maximum while others (Bonner, 1968) took care to define appropriate wind shear criteria and threshold values of the wind maximum before applying the term ‘low-level jet’. Andreas et al. (2000) following Stull (1988), defined nocturnal LLJ as a maximum in the vertical profile of the wind speed that is at least 2 ms\(^{-1}\) faster than wind speeds above and below it within the lowest 1500 m of the atmosphere. Because of the widespread LLJ occurrence and its diversity in physical characteristics, the term LLJ is subjected to wide interpretation. Further, the LLJ has significant impact on the development of severe weather (Frisch et al., 1992; Zhong et al., 1996) as it serves as a major moisture transport mechanism and initiates shear instabilities for storm development.

d) **Thunderstorm associated wind systems**

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.

1.1.4 **Micro-scale wind systems**

Atmospheric systems with spatial scales less than 1 km are considered to be in the category of micro-scale wind systems. Turbulent eddies and whirls of air etc. are some examples in this category.

1.2 **Measurement of winds in the atmosphere**

Wind plays a vital role in atmospheric dynamics and energetics. It transports heat, mass, moisture and also gaseous and particulate pollutants from one place to another. This transport process in turn affects the local weather as well as the climate. Horizontal and vertical velocity plays an important role in the dynamics of the atmospheric circulation systems on all scales. Hence the characterization of wind and its variability is extremely important. Detailed observations of winds are necessary with high spatial and temporal resolution. Basically wind measurement was classified in to
two broad categories. They are in-situ and remote sensing measurements. They have their own inherent advantages and limitations too. A brief description of these measurement methods is provided below.

1.2.1 **In-situ measurement**

The direct sensing technique includes surface measurements (instrumented shelters) and sensors mounted on various platforms, such as fixed platforms (mast, towers) and moving platforms (aircraft, balloons). In-situ sensors are traditional instruments for surface and lower boundary layer studies, providing accurate and high resolution information required for a quantitative work, but are costlier and limited to lower heights. Platforms such as towers are convenient for carrying out surface layer studies. Common wind speed measuring instrument in the surface layer are anemometers and wind direction measuring instrument is the wind wane. Wind anemometers are basically of three types. They are cup anemometers, sonic anemometers and hot wire anemometers. Each one is used according to the requirement of the experiment.

Balloon systems play an important role in the atmospheric wind studies. The first radiosonde, commonly referred to as weather balloons, was flown in 1927. At present, they are the most commonly used method for obtaining vertical or altitude profiles of atmospheric parameters. Radiosondes can provide information on temperature, humidity and pressure as they ascend through the atmosphere, with the information transmitted back to a ground station via a telemetry system. Wind profiles can be measured by utilizing a secondary system for tracking the motion of the balloon. Initial tracking methods involved manual theodolites, while more modern tracking systems utilize ground based Doppler radars or navigation systems such as the GPS (Global Positioning System). The GPS, an alternative to the ascending radiosonde is a space-based three dimensional positioning velocity and time system which is operated by the dropsonde, which is usually released from an aircraft and descends slowly through the atmosphere on a parachute. Both the radiosonde and dropsonde provide accurate, high vertical resolution data. However, they provide only a “snapshot” of the atmosphere and it takes about one hour duration to get one vertical profile of winds in the troposphere.
The need for in-situ data to corroborate measurements obtained by remote sensing methods has driven resurgence in the use of tethered balloons and kites. The first temperature soundings of the atmosphere were accomplished in 1748, by taking a thermometer on a kite. With the advent of radiosondes, aeroplanes and telemetry systems, the use of such tethered devices was reduced. However, recent campaigns involving tethered kites and balloons have highlighted the excellent vertical resolution that can be obtained with such systems (Balsley et al., 1998; Muschinski et al., 2001).

1.2.2 Remote Sensing measurement

Remote sensing systems have the advantage of being able to make multiple measurements from a range of heights simultaneously. However, as compared to in-situ techniques, vertical resolution of the measurement is quite coarse. The number and type of systems used for remote sensing of the atmosphere are large and varied, therefore only a brief overview will be given here. The remote sensing technique can be categorized into two types based on source of radiation. They are active and passive remote sensing. Passive remote sensing uses natural radiation as the source for atmospheric observation. Interferometers, radiometers, spectrometers and photometers are some examples of passive remote sensing systems. In active sensing techniques, energy will be transmitted and interaction of this energy with atmosphere is studied. Examples of active remote sensing systems include optical lidar or laser radar, acoustic radars or sodars, radars and RASS (radio acoustic sounding system).

Radars are the most common form of active remote sensing systems. Radars range from large Medium Frequency (MF) systems for observing the ionosphere (Vincent and Lesicar, 1991), through to small Ultra High Frequency (UHF) cloud radars operating in the frequency range 30-100 GHz. The UHF and VHF wind profiling radars are used throughout the world for meteorological observations, typically operating as Doppler radars (Ecklund et al., 1990). UHF radars have also been successfully installed on ships (Carter et al., 1992). Fully transportable UHF systems have been developed (Hashiguchi et al., 1995), enabling observations to be carried out in a wide range of situations and conditions. UHF and VHF radars are able to obtain rainfall distributions, as they are both sensitive to precipitation (Rajopadhyaya et al., 1999). VHF radars have
been used extensively to observe the troposphere for two to three decades. Initially, VHF radars used for wind profiling, measured the winds using Doppler techniques (Gage and Balsley, 1980). Application of spaced antenna methods provided an alternative method of operation (Rottger and Vincent, 1978).

Presently importance of the optical remote sensing technique, namely the laser radar or lidar (Light Detection and Ranging) is increasing in the wind measurement field because of the lower cost of operation and higher vertical and horizontal resolution and temporal resolution. Doppler wind lidars are being recognized as more efficient, accurate and capable of making observations in the lower troposphere with high space and time resolutions.

1.2.3 Study of wind systems and related atmospheric phenomenon using Wind profilers and Wind lidars

Several atmospheric phenomena can be better understood if measuring systems are designed to observe them with finer resolution in time and space and on continuous basis. Wind profiler is one such system for wind measurements which helped to investigate the dynamical state of the atmosphere in detail. Wind profiler principle is that in clear air, it measures the backscattering of the UHF/VHF radar signal from turbulent variations in the refractive index and measure the Doppler shift of the return. 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 radar is an excellent tool in making high-resolution measurements of atmospheric winds, associated vertical shears of horizontal winds, momentum flux and various atmospheric turbulence parameters.

Vertical velocity of the air is a very important meteorological parameter since it plays significant role in the dynamics of atmospheric circulation systems on all scales. Clouds and precipitation are influenced by upward vertical velocities. Main advantage of wind profilers is that they provide direct measurements of vertical motions with good time and height resolution over a range of altitudes in the troposphere at a particular site (Balsley et al., 1988; Gage et al., 1991; Huaman and Balsley, 1996, Jagannadha Rao et
Such direct, long-term measurements of vertical motions are unique. These measurements are very important in explaining the heat balance in the tropical atmosphere because the vertical motions give the component of adiabatic heating and cooling that largely balances diabatic heating and cooling (Gage et al., 1992). The possible capability of wind profilers to provide accurate estimates of the momentum and heat fluxes might be their most important contribution yet to the field of atmospheric dynamic studies, especially when those measurements can be ingested into circulation models. With the advent of VHF/UHF radar, which can measure wind components with fine vertical resolution, the momentum fluxes can be estimated directly from the vertical and zonal components of the wind. In the troposphere and lower stratosphere, there have also been several attempts at deriving the momentum fluxes with wind profilers (Fukao et al., 1988; Fritts et al., 1990; Nastrom and VanZandt, 1991). Vincent and Reid (1983) used pairs of opposite beams (i.e., coplanar beam directions which are pointed in opposite directions at the same zenith angles) to estimate the momentum flux components. Fukao \textit{et al.} (1988) determined the momentum flux in the upper troposphere and lower stratosphere using three and four beam methods. They showed that the momentum flux due to long-period fluctuations is caused primarily by synoptic-scale or meso-scale disturbances, while short-period flux may primarily be related with intense vertical air motion.

Remote wind sensing using lidar was introduced in the mid 1960s with the advent of Doppler lidar concepts (Forman et al., 1965) and since then these methods have vastly improved (Rothermel et al., 1998). Doppler techniques are powerful because the Doppler shift can be reliably determined either within or above the planetary boundary layer (Grund et al., 2001). The coherent Doppler lidars have the best possibilities for such investigations in the clear atmosphere as well as in cloudy conditions because of the high spatiotemporal resolution of the measured characteristics. These lidars are used for measurements of the wind field (Köpp et al., 1984; Hall et al., 1984; Keeler et al., 1987; Hawley et al., 1993; Frehlich et al., 1994; Banakh et al., 1995; Werner et al., 2001; Reitebuch et al., 2001; Smalikho., 2003) and the aircraft wake vortices (Köpp 1994, 1999; Constant et al., 1994; Hannon and Thomson, 1994; Brockman et al., 1999; Harris et al., 2000, 2002; Vaughan and Harris, 2001; Keane et al., 2002; Köpp et al., 2003;
Doppler lidar has important contributions in the cloud study (Intrieri et al., 1995). Moreover, the Doppler lidars are powerful tool in measuring the marine boundary layer (Pichugina et al., 2011).

Doppler lidar has great potential for measuring the mean and turbulent velocity structure of the atmospheric boundary layer (ABL). Its ability to map out the fine scale velocity fields would immediately provide insight into the coherent structure of the turbulence. Several atmospheric phenomena like nocturnal low level jet (Banta et al., 2002; Banta et al., 2003; Mahrt and Vickers, 2002) and thunderstorms are studied in detail by these lidars. Study of turbulence requires high resolution data sets and Doppler lidar fulfills this need almost in a successful manner. Wind lidars have been used to study relation between turbulence and shear during the passage of low level jet in the nocturnal hours. Moreover detailed studies of turbulence such as ‘Intermittency’ and its relation with wave instability was carried out by using wind lidars (Sun et al., 2004; Blumen et al., 2001; Balsley et al., 2002; Sun et al., 2011).

1.3 Site Description

Extensive observations of vertical profiles of horizontal winds collected at two tropical Indian stations namely, Pune (18° 32′ N, 73° 51′ E, 559 m Above Mean Sea Level) and Mahbubnagar (16° 41′ N, 77° 56′ E, 445 m Above Mean Sea Level) have been used to investigate various lower tropospheric phenomena in this thesis to meet the objectives of the proposed study. Figure 1.3 shows the topographical map of Southern Peninsular region of India with the Arabian Sea on the west and Bay of Bengal on the east. Pune is a typical continental tropical Indian station (urban) located about 200 km inland to the east of the Arabian Sea coast and on the lee side of the Western Ghats (mountain ranges) which run near-parallel to the west coast. This station is under the influence of westerly/south westerly winds during the southwest monsoon months (June - September) and during the other months, especially in winter (December - February) surface level winds are predominantly easterly/south easterly. South westerly winds blowing from the marine region (Arabian Sea) during monsoon season have a strong westerly component over the Indian continental region and they bring in moisture laden air masses/clouds which results in rainfall over land. Hot summer conditions with
stronger surface winds prevail during pre-monsoon season (March - May) over the region. The post-monsoon season (October – November) is of shorter duration when there is a transition from wet/humid monsoon conditions to dry, relatively colder and calm winter conditions. Thus surface temperatures, atmospheric conditions including winds at the surface as well as in the troposphere vary systematically from one season to the other and hence reflect on the seasonal variability of most of the lower atmospheric phenomena through physical and dynamical processes.

Figure 1.3: Terrain map of Indian sub continent showing geostrophical positions of Pune and Mahbubnagar
Mahbubnagar site is more in the central part of the peninsula on the eastern edge of the Deccan Plateau (shown in the map above). Observations have been made at this station as part of an intensive ground observational campaign (CAIPEEX-IGOC-2011) from June to October 2011. Jaya Prakash Narayan College of Engineering (JPNCE) at Palamuru, Mahbubnagar has been selected as the base location for the ground-based observations during IGOC (Integrated Ground Observation Campaign). The primary aim of this campaign was to investigate cloud-aerosol interactions by making ground-based as well as aircraft observations. However, the wind measurements made during this campaign were used here to investigate various features of the Monsoon Low Level Jet. Mahbubnagar has a typical tropical semi-urban environment. The observational location is on the southern slopes of the low lying mountain ranges (whose maximum height is 600 m above mean sea level) oriented in the northwest-southeast direction. Several of these mountain ranges create parallel valleys which join to an area with average elevation of 100 m above mean sea level. The land use category around the location is cropland. The actual observational location is in level terrain (average elevation is 440 m above mean sea level); however, there are few low lying hills in the north and in the south sector. South-westerly winds blowing from the marine region (Arabian Sea) and over the south Indian peninsula during the monsoon season (June-September) have a strong westerly component over this region.

1.4 Objectives and organization of the thesis

Wind plays a vital role in atmospheric dynamics and energetics. It transports heat, mass, moisture and also gaseous and particulate pollutants from one place to another. This transport process in turn affects the local weather as well as the climate. Horizontal and vertical winds play important role in the dynamics of the atmospheric circulation systems on all scales. Hence the characterization of wind and its variability is extremely important.

This thesis gives deep insight into some important lower tropospheric atmospheric phenomena in the tropical Indian region, by using high resolution measurements of Radar and Lidar. The main objectives of this thesis are as follows:
1) Diurnal and seasonal variability in horizontal winds
2) Monsoon Low-Level Jet (LLJ), its strength and fine structure during different conditions of monsoon and its time evolution
3) Inter comparison of horizontal winds obtained from lidar and GPS radiosonde
4) High-resolution vertical wind structure during evolution/life-cycle of events of intense convection like tropical thunderstorms
5) Estimation of turbulence parameters and fluxes and their inter-relationship with winds

Work carried out is organized as follows. Chapter 2 describes the wind profiling remote sensing techniques used for probing the earth’s atmosphere. Scattering mechanism such as Bragg scattering, Rayleigh scattering, Fresnel scattering relevant to the radar remote sensing and Mie scattering to the lidar remote sensing of the atmosphere are discussed. Then the standard radar and lidar equations for the meteorological targets are discussed. Technical specifications of UHF profiler and the calibration and validation details are provided (Pant et al., 2005) and technical details of Doppler wind lidar are also described.

Variability in horizontal wind in the lower troposphere is discussed in detail in Chapter 3. Seasonal and monthly mean variations in the UHF radar derived zonal and meridional winds in the height range 1.05 - 8 km over Pune are discussed. Occurrence and intra-seasonal evolution of Monsoon Low level Jet (MLLJ) and its association with rainfall are explained by using daily mean data sets.

Chapter 4 discusses the inter comparison of wind profiles obtained simultaneously from wind lidar and GPS radiosonde over two tropical Indian stations, namely Pune and Mahabubnagar. Comparison has been done for horizontal wind and wind direction. Root mean square error, bias and spread have been calculated for the altitude profiles obtained from the two techniques (radiosonde and wind lidar) for quantitative comparison.

Investigation of the fine structure and time evolution of the monsoon low level jet (MLLJ) during the south west monsoon season is presented and discussed in Chapter 5. Detailed analysis of MLLJ parameters such as jet core height and jet speed are undertaken and explained. Influence of day time heating and shear generated below
the jet and associated turbulence on the time evolution of MLLJ is discussed. Study of the MLLJ characteristics during strong and weak jet conditions are also explained in this chapter.

Chapter 6 discusses the Nocturnal Low Level Jet (NLLJ) occurrence and its characteristics over Pune. Detailed analysis of jet parameters (jet speed, jet core height and jet direction) is undertaken and their seasonal and monthly mean variations are discussed. An attempt has been made to examine the role of horizontal temperature gradient, inertial oscillation and surface level stability in the formation of NLLJ over this station.

Doppler wind lidar and UHF radar/wind profiler measurements of horizontal and vertical winds in the lower troposphere during some cases of typical tropical thunderstorms have been presented and discussed in Chapter 7. Time-height variations of lidar-derived convergence, horizontal wind shear, and turbulence intensity are examined to understand the atmospheric dynamical response during the thunderstorm events. Time-height variations in radar-derived horizontal wind, wind shear and spectral width are also discussed.

Chapter 8 summarizes the main conclusions of the studies made and also presents the scope for future research based on the results discussed in the thesis.