Chapter 1

Introduction

"Of each particular thing, ask: What is it in (and by) itself? What is its nature?"
-- Marcus Aurelius (121 to 180 AD)

1.1. Introduction

The *Atmospheric Boundary Layer* **(ABL)** is the part of the atmosphere where the direct effect of the Earth's surface is noticeable. Frequently, the term planetary boundary layer (PBL) is used synonymously (*Garratt, 1991; Arya, 2001*). According to *Stull (1988)*, ABL defined as "the part of the troposphere that is directly influenced by the presence of the Earth's surface, and responds to surface forcings with a time scale of about an hour or less". The surface forcings (energy balance at the surface, frictional drag, terrain induced flow modifications, etc.) are not the same around the globe. Therefore, the ABL depth/height is quite variable in both space and time because of the variability in the following factors.

1. Geography (low-latitude, mid-latitude poles, continental, marine, etc.)
2. Surface (land, ocean, soil type, soil moisture, etc.)
3. Dynamics (large-scale vertical motion and horizontal advection of heat and moisture) and
4. Biological (forest, agricultural, desert etc.)

The knowledge of ABL and atmospheric state variables (temperature (T), humidity (q), wind speed and direction) within the ABL is highly essential for fundamental and applied research in meteorology and improving weather forecasts. The ABL is the source region for most of the weather phenomena, such as fronts, cyclones, and thunderstorms that greatly affect human activities. It plays a vital role in the exchange of heat, momentum, moisture and natural (e.g., Carbon dioxide (CO_2) and other greenhouse gases) and anthropogenic (e.g. pollutant emission) contaminants from the Earth's surface to the free atmosphere above the ABL. Therefore, its location as a buffer region between the biosphere and free troposphere makes this layer very relevant to air quality issues and to the global climate problem. Moreover, it is the region where we live and almost all interactions between the atmosphere and us take place. The processes within the ABL influence the human life directly and indirectly via its influence on the rest of the weather.

1.2. Transport processes in the boundary layer

Given the importance of boundary layer in weather and climate research and in our life, it is vital to understand the flows and transport processes of heat, momentum, moisture and matter within the ABL. Atmospheric flows and changes in the ABL are, mainly, due to changes in 1) the mean wind, 2) turbulence and 3) waves. Each can exist in the boundary layer separately or in the presence of any other. Transport quantities such as fluxes of heat, moisture, momentum and energy are dominated in the horizontal by the mean wind and in the vertical by turbulence.

Turbulence is a key process in the ABL. Turbulent flow consists of chaotic motions (eddies) of different sizes superimposed on each other. Eddies exist in different sizes, continuously cascading from large-scale to small-scale and finally dissipate as heat due to viscosity. Turbulence is more effective in transporting quantities than molecular diffusivity. Molecular diffusivity is effective only in lower few centimeters of the troposphere. Through efficient diffusion of air pollutants released near the ground, atmospheric turbulence prevents the fatal poisoning of life on Earth. Turbulent communication between the surface and the air above it is quite rapid, that allows the boundary layer to respond to changing surface forcings. Turbulence is a response to the instabilities in the flow then tends to reduce these instabilities. Turbulence is homogeneous, when it is statistically the same at every point of the turbulent flow. Many ABL flows are considered to be highly turbulent. Turbulent Kinetic Energy (TKE) is a measure of the intensity of turbulence. The turbulence in ABL is generated, mainly, by two processes.

1. **Convective or Thermal Turbulence:** This process occurs during daytime only. The solar heating of the ground during a sunny day causes thermals (~1-2 km) and/or Plumes (~100 m). The plumes rise and expand adiabatically until a thermodynamic equilibrium is reached at the top of the atmospheric boundary layer.
2. **Mechanical Turbulence:** Frictional drag on the air flowing over the ground develops wind shear near the Earth's surface, which often becomes turbulent. But there may also be wind shear due to baroclinicity and meso-scale processes such as sea breezes. Also, obstacles like trees and buildings deflect the flow causing turbulence.

Sometimes one process dominates the other and it depends on the stability of the atmosphere. The ABL is said to be *unstable* whenever the surface is warmer than the air, such as during a sunny day with light winds over the land, or when cold air is advected over a warmer water surface. In such conditions, i.e., when buoyant convection dominates, the ABL is said to be in a state of *free convection*. The boundary layer is said to be *stable* when the surface is colder than the air, such as during a clear night over land, or when warm air is advected over colder water surface. The boundary layer is said to be *neutral* during windy and overcast conditions. In those conditions, i.e., when mechanical process dominates, the boundary layer is said to be in a state of *forced convection*. To summarize, during night-time the amount of TKE results from a *competition* between wind shear, which tends to produce turbulence, and buoyancy, which tends to suppress turbulence. During daytime both processes *cooperate* in producing turbulence.

The energy of turbulent eddy follows the Kolmogorov energy spectrum, which can be described as the dissipation of mechanical to internal energy. It occurs by direct cascade of turbulence through a series of Fourier modes of the velocity field, in which large-scale eddies subdivide into small-scale turbulent eddies until they disappear by means of heat dissipation through molecular viscosity (Figure 1.1). In the buoyancy subrange i.e., the energy input region, buoyancy or gravitation is the restoring force for the adiabatic displacement of the air parcels in the vertical. This energy cascading starts at the outer scale wave number with an eddy size of the order of outer scale length L_0 i.e., the size of the largest turbulent eddy of the inertial range and continues until those eddies dissipates to the inner scale length l_0, a transition scale between the inertial and the viscous ranges, creating smaller and smaller structures which produces a hierarchy of eddies. Energy loss is significant in the energy dissipation region. Thus, all the energy is transmitted to the viscous sub-range through inertial sub-range without any significant loss.

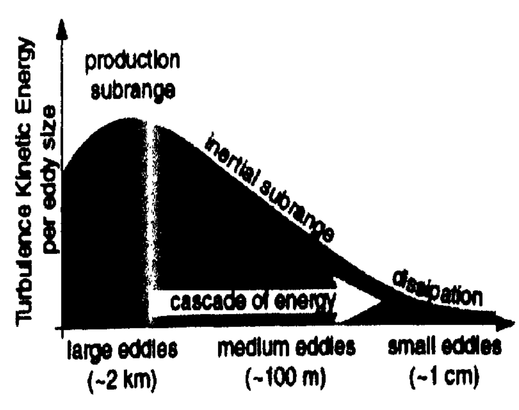

Figure 1.1: The spectrum of turbulence kinetic energy. Production of TKE is at the large-scales. TKE cascades through medium-size eddies to be dissipated by molecular viscosity at the small-eddy scale. (Source: Wallace and Hobbs, 2006).

1.3. Diurnal evolution/structure of the ABL

The boundary layer height (BLH) is highly variable in time and space, ranging from a few hundreds of meters in statically stable situations, to several km in convective conditions over deserts. Over land surfaces, the BLH is relatively high and shows strong diurnal cycle. In high pressure regions, the boundary layer has a well-mixed and well-defined structure that evolves with the diurnal cycle. The analysis of the ABL structure is not usually that straightforward in the case of low pressure. The cloud presence in low-pressure regions makes identification of BLH difficult. Over the ocean, due to high thermal capacity of the water body, the surface fluxes and the evolution of the Marine ABL (MABL) depend on several factors: mainly the geographic location (open-ocean, coastal waters, enclosed seas) and the synoptic conditions. Therefore the boundary layer thickness varies relatively slowly in space and time. Most changes in ABL over the oceans are caused by synoptic and meso-scale processes of vertical motion and advection of different air masses over the sea surface.

The general structure of the atmospheric boundary layer during fair weather conditions over the land is shown in Figure 1.2.

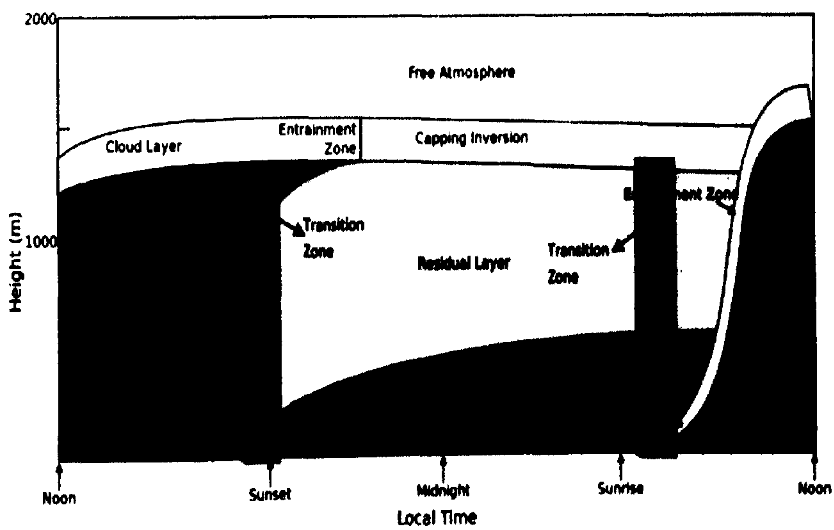

Figure 1.2: Schematic representation of the diurnal variation of ABL (Source: Stull, 1988).

The three major layers of ABL are,

- Unstable mixed layer (ML).
- Stable stratified nocturnal boundary layer (SBL).
- Neutral residual layer (RL).

and other minor layers are,

- Surface layer (SL) or constant flux layer (CFL).
- Micro layer or interfacial layer
- Entrainment zone (EZ)
- Transition zone or transition boundary layer (TBL).

1.3.1. Surface layer

The *Surface layer* is the region at the bottom of the ABL, covering 5-10% of ABL, where turbulent fluxes of heat, momentum and moisture are nearly constant (does not vary by more than 10% of their magnitude at the surface, regardless of whether it is part of a mixed layer or stable boundary layer). This layer extends from the Earth's surface to typically ~50-100 m in the tropics. The SL is characterized by a super-adiabatic lapse rate in temperature, moisture decrease with height, and strong wind shear (wind speed generally increases logarithmically with altitude in this layer) (see Figure 1.3). The Coriolis effect is small and is usually ignored. In other words, it can be identified by strong gradients in meteorological parameters. The unstable surface layer consists of small-scale structures, such as buoyant vertical plumes, convergence lines, sheets of rising air, and dust devils. A thin layer called a *micro-layer* or *interfacial layer* has been identified in the lowest few centimeters of air, where molecular transport dominates over the turbulent transport.

1.3.2. Mixed layer

The mixed layer constitutes the major part (heart) of the ABL. It is characterized by intense vertical mixing, which makes potential temperature and humidity to be nearly constant with height. The other tracers like aerosols and trace gases also remain constant with altitude in this layer. Mixing can be generated mechanically by shears (forced convection), or convectively by buoyancy (free convection). Buoyantly generated ML's tend to be more uniformly mixed than mechanical ones, because the anisotropy in convection favors vertical motions, while anisotropy in shear favors horizontal motions. A mixed layer dominated by buoyant turbulence is called a *convective boundary layer* (CBL) or *convective mixed layer.*

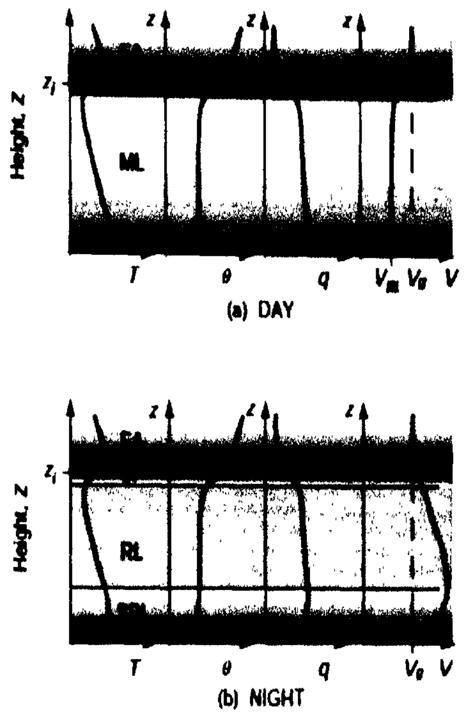

Figure 1.3: From left to right, an illustration of vertical profiles of temperature, potential temperature, specific humidity and wind speed in the ABL during day time (top panels) and during night time (bottom panels) (Source: Wallace and Hobbs, 2006).

The CBL, also called daytime ABL, exists during sunrise to sunset. When clouds are present in the mixed layer, it is further subdivided into a *Cloud layer* and a *Sub-cloud layer*. On initially cloud-free days, however, mixed layer growth is related to solar heating of the ground. Starting about 30 minutes after the sunrise, a turbulent ML begins to grow in depth and reaches its maximum depth in the late afternoon. Even though convection is the dominant mechanism within the ML, usually wind shear across the top of the ML also contributes to the turbulence generation. CBL is characterized by intense mixing in a statically unstable situation where thermals of warm air rise from the ground. The turbulence tends to mix heat, moisture, and momentum uniformly in the vertical. A typical daily evolution of the CBL over the land with continental climate on a clear sunny day (*Seibert et al., 1998*) is described below.

1. Starting with the breakup of the nocturnal inversion in the morning a shallow CBL is formed near the ground. It grows gradually until the nocturnal inversion has been completely eroded.
2. It is followed by a fairly rapid growth of the CBL through the slightly stable residual layer up to a level of the capping inversion from the previous day.
3. Thereafter the growth of the mixed layer is reduced as it penetrates into the stable stratified free atmosphere. At this stage large-scale vertical air motions (subsidence) that even might dominate over the penetration process and causing the mixed layer to decrease, can have a considerable influence on the evolution of the mixed-layer.
4. Eventually the thermally driven turbulence and vertical mixing decays, which is followed by the formation of a shallow stable layer near the ground, which converts the CBL into the elevated residual layer for the following day.

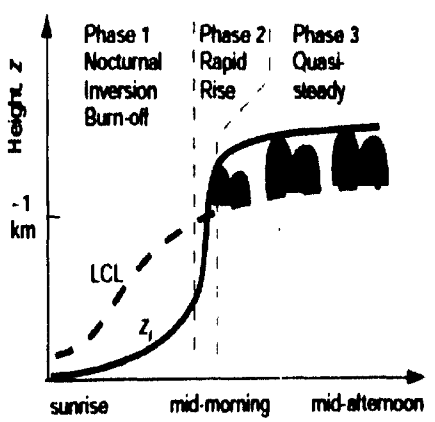

Figure 1.4: Growth phase of shallow convection within boundary layer (Source: Wallace and Hobbs, 2006).

1.3.3. Stable boundary layer

Stable Boundary Layer or Nocturnal Boundary layer (SBL or NBL) forms whenever underlying surfaces are colder than the air above it and is usually exists from sunset to sunrise. It can also be formed by the advection of warmer air over a cooler surface or during mid- and high-latitude winters. This is characterized by statically stable air with weaker, sporadic turbulence. The sporadic nature of turbulence allows the upper portions of the boundary layer to decouple from surface forcings (*Stull, 1988*).

The structure of the SBL is mainly determined by two external forcings: the wind speed and the net long-wave cooling of the surface. The latter depends mainly on the cloudiness. The most stable boundary layer occurs when weak wind prevails on a clear sky night. In this case, the SBL consists of only a shallow layer, which is characterized by a strong inversion. While the strong wind and shear induces turbulence, presence of clouds reduces the radiative loss to space, both these processes makes the SBL weakly stratified. In a stably stratified atmosphere the negative buoyancy acts as a sink for the turbulent kinetic energy and a sensitive balance exists between production and destruction of turbulence. The general level of turbulence is low; other effects such as gravity waves, advection and subsidence may also influence the structure.

SBL winds can have very complex characteristics. In lowest few meters, wind direction is determined by the local topography; wind speed often becomes light or calm and is governed by buoyancy, friction and entrainment. The winds aloft may accelerate to super geostrophic speeds, i.e. wind speed can increase with height, reaching a maximum near the top of the stable layer, called as the *low level jet* or *nocturnal jet* (LLJ). The statically stable air tends to suppress turbulence, while developing nocturnal jet tend to generate turbulence. As a result, turbulence sometimes occurs in relatively short periods that can cause mixing throughout the SBL. It has a poorly defined top that smoothly blends into the RL above and its height measured as the height where turbulence intensity is a small fraction of its surface value.

1.3.4. Residual layer

Between the SBL and the free atmosphere (FA), a neutrally stratified layer exists. The residual layer is the left-over of CBL, and has all the properties of the recently decayed CBL. The RL appear from about 30 min. before the sunset, i.e., at the time of cessation of the buoyantly active thermals, allowing turbulence to decay in the formerly well mixed layer, resulting a layer of air called the *Residual layer* with an initial mean state and concentration of variables same as those observed in recently decayed CBL. The RL is neutrally stratified, i.e., nearly equal turbulent intensity in all directions. This layer mostly exists for a while in the morning before being entraining into the new CBL. The residual layer does not have direct contact with the ground. Passive tracers dispersed into the daytime mixed layer will remain aloft in the RL during night.

1.3.5. Entrainment zone

The entrainment zone (EZ) is the region of statically stable air at the top of the ML, where entrainment of free tropospheric air downward and overshooting thermals upward coexists. The thickness of EZ can become wide, covering about 10-30% of the depth of the ML. The top of the entrainment zone is defined as the highest altitude that a thermal can reach. The bottom is more difficult to define, because there is no sharp boundary. The bottom is usually taken as that altitude where about 5 to 10% of the air on a horizontal plane has free troposphere characteristics. An alternative definition of the EZ is that region where the buoyancy flux is negative. Large temperature gradients are seen across the ML top (within EZ), because thermals will not penetrate as far and entrainment will be slow. In fact, the EZ is often called the capping inversion, during the day it acts as a lid damping out vertical motions.

1.3.6. Transition zone/boundary layer

The ABL shows a marked diurnal cycle, during the day, with fair weather conditions, a convective boundary layer exists. In contrast, during the night, a stable boundary layer appears. The evolution from a convective boundary layer to a stable boundary layer and vice versa happens through two transitional processes (see Figure 1.2). The former transition is defined as afternoon transition (AT); which is initiated when the surface sensible heat flux becomes negative. The later transition represented as morning transition (MT) is initiated when the surface sensible heat flux becomes positive and a shallow entraining ML grows into the surface inversion. These transitional boundary layers are ubiquitous in nature. The AT is not an instantaneous process, takes several minutes to few hours and involves balanced interplay of weak forcings including the radiation and entrainment. Several intriguing processes occur during the AT. The major characteristics of AT are progressive shutdown of surface heating, stabilization closer to the Earth's surface and transition from thermal turbulence to dynamical turbulence. Further, AT plays a key role in several weather phenomena, such as fog formation, small-scale frost forecast, air quality issues, transport and diffusion of trace constituents and wind energy production. During the AT, the r jump is often large enough to cause saturation at the surface and largely determines the time when fog will occur. (*Fitzjarrald et al., 1989*). During the AT, temperature variability may determine whether the surface will cool below freezing. The transition seen in moisture and temperature is also expected to happen for other scalars with surface fluxes.

1.4. Instruments/techniques for probing ABL

Sensors used for ABL measurements fall into two broad categories; in situ sensors that are mounted on masts, towers, tethered balloons, kytoons, radiosondes and aircrafts and remote sensors, including ground-based instruments, like sound detection and ranging (SODAR), radio detection and ranging (RADAR - wind profiling radars, Doppler weather radars), light detection and ranging (LIDAR), radio acoustic sounding system (RASS) (see *Clifford et al., 1994; Emeis et al., 2008*), and air-borne sensors (aircraft-mounted and satellite-based (global positioning system radio occultation (GPS RO) and cloud-aerosol lidar and infrared pathfinder satellite observation (CALIPSO)).

To investigate the lower part of ABL, sensors mounted on masts, towers are frequently used. These towers have ranged in size 5-300 m and support a very comprehensive suite of instrumentation. The air-borne in situ measurements made with kytoons, radiosondes and aircrafts are generally expensive and they are made either on routine basis (for ex., 2/4 sondes per day) or in campaign mode. ABL observations by remote sensing techniques have been increased considerably in the last decade or so. Remote sensing of the ABL variables can be done actively and passively. Active techniques involve transmission of acoustic or electromagnetic radiation in to the region of interest and measuring the backscattered fraction that is returned to the instrument. The return energy is due to natural or artificial targets such as rain, dust, turbulence. In contrast, passive techniques involve the measurement of radiation naturally emitted from the atmosphere, e.g., as in infrared radiometry. Ground-based active remote sensors allow continuous sensing of the atmosphere and thereby studying the evolution of vertical structure of the ABL, but the constraints on minimum range and spatial resolution limit their utility for surface layer measurements. Used in combination, however, the two types of sensors provide a complete description of the ABL.

Pros of in situ sensors are their higher sensitivity, simplicity and accuracy, whereas remote sensors scan large volumes, provide overhead measurements and can operate continuously. Cons of in situ sensors are movement of the sensor or platform by flow and stabilization of platform in turbulent flow, on the other hand, remote sensors are costly and complex in operation and also are not able to measure certain ABL parameters. Among remote sensors, ground-based sodar, radar and lidar are widely popular and are extensively used in ABL research. Sodar is a relatively simple, not very expensive system that provides profile data with high temporal and vertical resolution, suitable for routine monitoring of ABL. One disadvantage is the limited sounding range (500-1000 m). Sensitivity to environmental noise and noise pollution are additional shortcomings for the operation of a sodar. Lidar allows the direct measurements of aerosol and trace gas profiling, but it is not always straight forward, because the detected profiles are often contaminated by advective transport of aerosols or trace gases. Wind-profiler is relatively expensive and complex system, but provides wind and turbulence profiles with good time and height resolutions.

Satellite measurements have the advantage of being able to sample meteorological variables in inaccessible regions, like oceans and forests. Recently, satellite measurements, like GPS RO and CALIPSO are also being used to generate global maps of the boundary layer altitude (*VonEngeln et al., 2005; Ratnam and Basha, 2010; Guo et al., 2011; Ao et al., 2012; McGrath-Spangler and Denning, 2013*). The variables of greatest interest to boundary layer meteorologists are BLH, wind speed, temperature, humidity, and the turbulent fluxes of momentum, heat, mass, and radiant energy. The large variety of sensors that have been developed is staggering. Sensors/instruments that have been frequently used to measure the boundary layer variables in the present thesis are listed below.

Temperature : hygroclip, thermistor, thermo couple, sonic anemometer, radiosonde.

Humidity : hygroclip, thin-film capacitor, carbon humidity sensor, radiosonde.

Winds : wind-profiler, sonic anemometer, cup anemometer, wind vane, sodar, GPS.

Pressure : aneroid barometer

Radiation : pyranometer, prygeometer.

Rainfall : tipping bucket rain gauge

BLH : sodar, wind-profiler, radiosonde.

The working principle and full specifications of the above sensors are discussed briefly in Chapter 2

1.5. Past investigations on ABL (Literature review)

In last few decades major advances have been made in the understanding of PBL physics through theoretical studies, field campaigns, wind tunnel and tank experiments, numerical weather models and large eddy and direct numerical simulations. Extensive research has been done on idealized ABL's (in homogeneous and flat terrain) and the structure and dynamics of the ABL under these conditions is understood well (*Garratt, 1991; Arya, 2001; Pena et al., 2014*). Less attention has been paid to complicating factors which influence the ABL such as complex topography. Most practical applications involve complex surfaces and therefore require even intensive attention. The knowledge of ABL is also lacking concerning the spatial generalization of measurements (*Beyrich, 1997; Rotach, 2008*). Moreover, interactions between such terrain and the overlying atmosphere can cause different transport and mixing processes, which may result in a different ABL (*Lieman and Alpert, 1991*; *Kalthoff et al., 1998; DeWekker, 2002; Bianco et al., 2011; Medeiros et al., 2014*). Mostly, thermally induced wind systems influence the structure of the ABL over complex terrain. The following sub-sections briefly review the studies carried out on characteristics of ABL, in general, variability of the ABL, in particular.

The BLH, a key parameter in air quality control, pollutant dispersion, scaling laws, climate studies and weather and forecast models, is interpreted in different ways and estimated using different techniques. The BLH is estimated using surface fluxes and turbulence measurements and empirical relationships (*Garratt, 1982; Kaimal et al., 1982; Hojstrup et al., 1997; Liu and Ohtaki, 1997; Tombrou et al., 1998; Choi et al., 2011*; *Brummer et al., 2012*). Radiosondes (hereafter referred to as simply "sonde") provide ABL height information over a wide area and are used in operational BLH determination (*Joffre et al., 2001; Seidel et al. 2010; Liu and Liang, 2010; Schmid and Niyogi, 2012; Beyrich and Leps, 2012*). The most straight forward and widely used method for the determination of BLH is by identifying the large vertical gradient in virtual potential temperature, humidity/mixing ratio and refractivity (*Seibert et al., 1998*). *Seidel et al. (2010)* compared the retrieval of BLH by seven methods, using temperature and humidity profiles from 10 years at 505 sonde stations. Six methods are directly compared, they generally yield BLH estimates that differ by several hundred meters and are sensitive to vertical resolution of sonde data. Sonde BLH is taken as the true value, although variability may result from different criteria for different variables. Specific problems occur in the stable (nocturnal) boundary layer since no universal relationship seems to exist between the profiles of temperature, humidity or wind and turbulence parameters. The interpretation of profiles thus is not straightforward and several criteria have been used (see Table 1 in *Seibert et al., 1998*).

The advances in ground-based remote sensing instruments made it possible to monitor the BLH continuously. The other advantage of these remote sounders is that they do not cause any modification to the investigated flow, which make them valuable tools for probing the ABL. In recent years, remote sensing data from sodar (*Beyrich and Weil, 1993; Beyrich, 1994, 1997; Beyrich and Gryning, 1998; Asimakopoulos et al., 2004; Satudt, 2006*), lidar (*Lammert and Bossenberg, 2006; Baars et al., 2008; Pearson et al., 2010; Milroy et al., 2012; Granados-Munoz et al., 2012; Pena et al., 2013; Summa et al., 2013; Luo et al., 2014*) and wind profilers/RASS (*Hashiguchi et al., 1995; Bianco and Wilczak, 2002; Heo et al., 2003; Bianco et al., 2008*) have been used extensively to detect the BLH from continuous profiles of reflectivity, turbulent intensity and particle concentration at different wavelengths. In addition, several other instruments were also used to detect the BLH, including microwave radiometer (*Guldner and Spankuch, 2001; Cimini et al., 2013*) and Ceilometer (*Eresmaa et al., 2006; Munkel, 2007; Giuseppe et al., 2011*). Satellite remote sounders, such as GPS RO and CALIPSO, provide a new opportunity for developing a global BLH data set (*VonEngeln et al., 2005; Sokolovskiy et al., 2006; Guo et al., 2011; Ao et al., 2012; McGrath-Spangler and Denning, 2013*). Models do retrieve BLH, but they do not predict the BLH directly, rather infer from the bulk Richardson number (*Vogelezang and Holtslag, 1996; Baklanov et al., 2011*). Several intercomparison studies have been carried out to understand the strengths and limitations of each technique by considering the BLH obtained by one technique as reference (often sonde-derived BLH is considered as the reference) (*White et al., 1999; Cohn and Angevine, 2000; Emeis and Schäfer, 2006; Emeis et al., 2008; Tsaknakis et al., 2011; Haeffelin et al., 2012; Wang et al., 2012; Haeffelin et al., 2012; Compton et al., 2013; Collaud et al., 2014; Banks et al., 2015*). For instance, BLH obtained by sonic anemometer (*Contini et al., 2008*), profiler (*Angevine et al., 1994; Beyrich and Görsdorf, 1995; Grimsdell and Angevine, 1998*), lidar (*Hennemuth and Lammert, 2006; Sawyer and Li, 2013*), ceilometer (*Emeis et al., 2012*), lidar and model (*Garrett, 1981; Korhonen et al., 2013*) are compared with radiosonde-derived BLH.

Several field campaigns have been conducted, wherein both in situ and remote sensing instruments are extensively used to understand ABL characteristics over the land, ocean and ice. The campaigns conducted for understanding continental ABL are only reviewed here. These campaigns include the Atmospheric Radiation Measurement Program (ARM)'s Southern Great Plain (SGP; *Stokes and Schwartz, 1994*), Cooperative Atmospheric Surface Exchange Study (CASES-97; *LeMone et al., 2000)*, CASES-99 *(Poulos et al., 2002)*, First International Satellite Land surface Climatology Project Field Experiments (FIFE; *Sellers et al., 1992*), Upper Missouri River Basin Pilot Project (UMRBPP; *Smith and Farwell, 1997*), Verification of the Origins of Rotation in Tornadoes EXperiment (VORTEX; *Rasmussen et al., 1994*), Biosphere Effects on Aerosol and Photochemistry EXperiment (BEARPEX; *Choi et al., 2013*) and Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST; *Lothon et al., 2014*). SGP measurements provide the best data set for studying BLH variations, especially diurnal cycle and seasonal changes, and LLJ's. Observations in both CASES and FIFE were made over plain surfaces under fair-weather conditions at a high temporal (1-3 h) resolution. The CASES campaign tried to identify the sources and to quantify the physical characteristics of atmospheric phenomena during the NBL, including the transition periods. On the other hand, FIFE campaign focused on the physical processes active in the daytime boundary layer and the relationship between the surface forcing and spatiotemporal variation in the structure of the ABL. UMRBPP campaign was conducted in a complex terrain to understand the influence of topography on ABL. VORTEX campaign facilitates a comparison of BLH in different synoptic conditions (severe and fair weather conditions). The BLLAST campaign emphasizes more on the physical processes occurring during the transitional periods, primarily during the late evening transitions. The BLH over complex, forested terrain is estimated based on the power spectra and the integral length scale of cross-stream winds obtained from a three-axis sonic anemometer during the two summers of the BEARPEX experiment. The BLH values estimated with this technique show very good agreement with observations obtained from balloon tethersondes and rawinsondes under unstable conditions ($z/L < 0$) at the coniferous forest.

Extensive literature is available on structure, dynamics of ABL characteristics and physical processes associated to the development. There have been many atmospheric boundary layer evolution studies using a variety of observations and models (*Deardorff et al., 1980; Banta, 1984; Kalthoff et al., 1998; Angevine et al., 1994; Shaw et al., 2005; Conzemius and Fedorovich, 2006; Tombrou et al., 2007; Bianco et al., 2011; Haman et al., 2012*). Further, few researchers studied the role of different dynamical processes on its development. For instance, the role of entrainment processes (*Sorbjan, 1996*; *Davis et al., 1997; Sullivan et al., 1998*; *Conzemius and*

Fedorovich, 2007; Canut et al., 2012), wind shear (*Moeng and Sullivan, 1994; Fedorovich et al., 2001; Pino et al., 2003, 2006; Pino and Vilà-Guerau de Arellano, 2008)*, and large-scale subsidence (*Stensrud, 1983; Fochesatto et al., 2001; Blay-carreras et al., 2014)* on the development and evolution of the CBL. Other related the ABL processes and the evolution of ABL to surface conditions (*King et al., 2006; Tanaka et al., 2007; Endo et al., 2008*), soil moisture (*Findell and Elthair, 2003; Wai and Smith, 1998; Zhou et al. 2013*), prevailing wind conditions and circulations (*Dewekker, 2002; Demko, et al., 2010*), entrainment fluxes (*Betts, 1992; Betts and Ball, 1994; Barr and Betts, 1997*) and baroclinicity (*Arya and Wyngaard, 1975; Zhou et al., 1985; Rizza et al., 2013*). Understanding such variations and deciphering the source of variations are important for various reasons. Few studies focused on the impact of ABL on the budgets of chemical constituents and their diurnal evolution, for ex., on CO_2 budget (*DeArellano et al., 2004; Casso-Torralba et al., 2008*), isoprene budget (*DeArellano et al., 2009*), SO_2 episodes (*Prtenjak et al., 2009*) and air chemistry (*Fast et al., 2000*).

During the night, a shallower stable boundary layer with less turbulence intensity exists near the surface (*Nieuwstadt, 1984*). The structure of the NBL and its characteristics (winds, turbulence) has been studied by several researchers. They include, role of the Richardson number (*Mauritsen and Svensson, 2007; Ferrero et al., 2011; Basu et al., 2014*), radiative and turbulent fluxes (*Ha and Mahrt, 2003; Garratt, 1981; Edwards, 2009*), surface heterogeneity (*Doran et al., 1995; Zhong et al., 1995; McCabe et al., 2007; Stoll, 2007; Reen et al., 2014*), large-scale subsidence (*Carlson and Stull, 1986; Mirocha and Kosovich, 2010*), baroclinicity (*Kim and Mahrt 1992*) on the structure of NBL. Though NBL is generally stable, occasional bursts of turbulence has been noted by several researchers and these turbulence episodes are attributed to a variety of processes, including LLJ (*Banta et al., 2002, 2003, 2007; Ohya et al., 2008; Van de Wiel et al., 2010; Kutsher et al., 2012*), drainage flows (*Mahrt et al., 2001; Soler et al., 2002*), density currents and katabatic flows (*Papadopoulos and Helmis, 1999; Monti et al., 2002; Shapiro et al., 2012; Shapiro and Fedorovich, 2014*), coherent structures and small-scale motions (*Cuxart et al., 2002*), meso-scale motions (*Mahrt et al., 2007*), gravity waves (*Ralph et al., 1993; Meillier et al., 2008; Sorbjan et al., 2013*), solitary waves (*Cheuang and Little, 1990; Coleman et al., 2011*), inertial oscillation and nocturnal jets (*Van de Wiel et al., 2010*). The nature and source of turbulence depends primarily on the geographical location (coast, hilly terrain, etc.).

The ABL experiences two transitional phases on every day, morning and evening, and such transitions are important for various reasons (*Angevine, 2008; Lothon et al., 2014; Wildmann et al., 2015 and references therein*). Morning transition (MT) has been the subject of several earlier studies, for ex., its characteristics (*Angevine et al., 2001; Lapworth, 2006; Bange et al., 2006; Angevine, 2008)* and the role of diurnal temperature cycle (*Ketzler, 2014*), gravity waves (*Lapworth, 2014)* and shear (*Beare, 2008)* on MT. The relevance of the RL during the MT has also been studied by (*Fochesatto et al., 2001; Gibert et al., 2011*). There is a renewed interest on afternoon/evening transition for obvious reasons. Several field campaigns are being conducted to understand the characteristics of AT, using a variety of data sets obtained from in situ and remote sensing instruments (*Mahrt, 1981; Grant, 1997; Acevedo and Fitzjarrald, 2001; Angevine, 2008; Busse and Knupp, 2012; Wingo and Knupp, 2015; Sastre et al., 2015*), air-craft measurements (*Bonin et al., 2013*), meso-scale model fields (*Brazel et al., 2005; Beare et al., 2006; Edwards et al., 2006; Sorbjan, 2007; Nadeau et al., 2011*), combination of instruments and models (*Sastre et al., 2012*).

In literature, Barbados Oceanographic and Meteorological EXperiment (BOMEX; *Holland et al., 1970*) was the first international boundary layer experiment conducted during May to July 1969, in which all surface and ABL parameters including air sea fluxes are characterized. Atlantic Trade wind EXperiment (ATEX; *Dunckel et al., 1974*) was also conducted in 1969 to study the development of the ABL in the trade wind region. Venzulean International Meteorology and Hydrology EXperiment (VIMHEX) was conducted during May-September 1972 at Carrisal, Venezula to study the boundary layer characteristics with strong emphasis on hydrological features. Air Mass Transformation EXperiment (AMTEX; *Lenschow et al., 1976*) was another large-scale experiment conducted during 1974-1975 in Japan. It was found that the fluxes needed to understand in terms of co-spectra and the eddy processes, and a coupling became apparent among surface waves, fluxes, and turbulent eddies at the scale of the boundary layer. Two experiments conducted almost 20 years ago were remained as milestones in ABL research; 1) the Kanas experiment, which saw the first systematic application of tower-based sonic anemometry and 2) the Minnesota experiment, in which a string of turbulence probes were attached to the tethering cable of a balloon. Both provided a framework for describing the structure and turbulence in the ABL (*Kaimal and Wyngaard, 1990*). At Cabauw, Netherland, 213 m tower observations were used to understand the structure of SBL, inversion rise and early morning entrainment and dependence of sound wave propagation on ABL structure (*Ulden and Wieringa, 1996*). *Stull and Eloranta,* (*1983*) combined remote sensors, surface observations, balloon platforms and aircraft measurements made in Boundary Layer eXperiment (BLX-83) experiment to study the kinematics at the top of the daytime CBL, entrainment zone and relationship between individual thermals. Phoenix I (*Gal-Chen and Kropfli, 1984*) and Phoenix II (*Kaimal and Gaynor, 1983; Schneider and Lilly, 1999*) campaigns conducted at Boulder, Colorado during September 1978 and May-July 1984, respectively, focused on the diurnal evolution of ABL. A few campaigns focused on the evolution of ABL in different forest canopies, for ex., Amazon Boundary Layer Experiment (ABLE) in Amazon forest (*Harriss et al., 1987*) and Understanding Severe Thunderstorms and Alberta Boundary Layer Experiment (UNSTABLE; *Taylor et al., 2011*) in Alberta. From late morning through early afternoon, the ABL over the cropped area remained cooler, more moist, and shallower than the ABL over the forest.

Significant interest in the structure and properties of the NBL resulted in a number of field programs/experiments such as Stable Atmospheric Boundary Layer Experiment in Spain (SABLES-98; *Cuxart et al., 2000*), CASES-99 (*Poulos et al., 2002*), SABLES 2006 (*Viana et al., 2007; Yague et al., 2007*), Global Energy Water cycle EXperiment (GEWEX) Atmospheric Boundary Layer Study (GABLS) series (GABLS1 (*Holtslag et al., 2006*), GABLS2 (*Svensson et al., 2011*), GABLS3 (*Bosveld et al., 2014*)), Wave-turbulence INteractions in the stAble Boundary Layer (WINABL; *Nappo et al., 2014*), STAble Boundary layer eXperiment (STABX; *Marwan Katurji, 2015*). The whole objective of these campaigns are to understand the horizontal and vertical structure of turbulence during the formation and evolution of stable boundary layer, and the interaction of phenomena affecting the turbulence under different heterogeneous surfaces by using the combinations of in situ, remote sensing technology and modeling capability. Further several field experiments are conducted in recent years for better characterization and modelling of the transitions, CASES-97 (*Poulos et al., 2002*), Phoenix evening TRANSition FLow EXperiment (TRANSFLEX; *Fernando et al., 2013*), BLLAST (*Lothon et al., 2014*).

1.5.1. Past Investigations on ABL over India

Over the Indian domain, ABL studies are relatively sparse. Most of the available literature on ABL is based on a few field experiments in the last 5 decades. International Indian

Ocean Expedition (IIOE) was the first field experiment carried out in 1960's (http://www.incois.gov.in/portal/iioe/aboutus.jsp) over the Indian domain followed by Indo-Soviet Monsoon EXperiment (ISMEX) in 1973 (*Pant, 1978*). Both attempted to fill the gap in the existing knowledge on the marine ABL, in particular, the kinematic and thermodynamic structure of lower part of ABL over oceanic regions, such as Indian Ocean, Arabian Sea and Bay of Bengal. Under Indo-Soviet collaboration program, two monsoon experiments, namely 1) MONSOON-77 in 1977 (*Mohanty and Das, 1986*), 2) MONsoon EXperiment (MONEX) in 1979 (*Sethuraman et al., 1980*), have been conducted for understanding ABL features in two phases of monsoon (winter, summer). Another major field campaign has been conducted in the monsoon trough region, MONsoon Trough Boundary Layer EXperiment (MONTBLEX), in 1990 (*Goel and Srivastava, 1990; Parasnis, 1991; Sivaramakrishnan et al., 1992; Kusuma et al., 1991, 1995; Gera et al., 1996*). The above studies investigated the differences in ABL features between the active and break phases of monsoon period. LAnd Surface Process EXperiment (LASPEX) (*Pillai et al., 1998; Nagar et al., 2001; Murthy et al., 2004*) during 1997–98 at Sabarmati basin of Gujarat covering different seasons provided the vertical thermal and wind structure in ABL with the help of sonde and tower observations. Further, the thermodynamic structure as well as its time evolution is explored in the Bay Of Bengal Monsoon EXperiment (BOBMEX; *Bhat et al., 2001*), conducted during July-August 1999. It also revealed the vertical stability (Convective Available Potential Energy (CAPE) and Convective INhibition (CIN)) of the atmosphere in different phases of the monsoon.

In addition to the above major field campaigns, a few researchers utilized the routine observations and also conducted small field experiments to understand the ABL characteristics. For instance, the characteristics of turbulent fluxes at the surface (*Sivaramakrishnan et al., 1992; Verneker, 1995; Chatterjee et al., 1996; Kusuma et al., 1996a; Sadani and Murthy, 1996; Vishwanatham and Satyanarayana, 1996; Nagar et al., 2002; Dharmaraj et al., 2009; Alappattu et al., 2009; Chowdhuri et al., 2014*), the thermal and wind structure of the ABL and its kinematic characteristics (*Raman et al., 1990; Parasnis and Goyal, 1990; Pradhan et al., 1996; Kusuma, et al., 1996b; Rajkumar, 1996; Potty et al., 2001; Ramana et al., 2004; Dharmaraj et al., 2006; Ruchith et al., 2014a; 2014b; 2014c*) and vertical structure of the fluxes (heat, moisture and momentum) (*Kusuma et al., 1996b; Gopalkrishnan et al., 1998; Sathyanarayana et al., 2000; Mohanty et al., 2003*). A few researchers focused on the characteristics of coastal ABL

(*Colacino et al., 1982; Rao and Murthy, 2001; Gera et al., 2001; Subrhamanyam et al., 2003; Sam et al., 2007; Alappattu et al., 2008; Sandhya et al., 2011*). Further, the characteristics of LLJ (occurrence, evolution, peak and the role of surface BL) are examined with the help of sonde and remote sensing measurements (*Sam and Murhty, 2002; Joseph and Sijikumar, 2004; Prabha et al., 2008; Murthy et al., 2013; Sandhya et al., 2014; Ruchith et al., 2014a, 2014b*). A few studies explored the role of ABL on aerosol distribution (*Parameswaran et al., 1997, 2001a, 2001b; Pandithurai et al., 2008; Patil et al., 2014*), variation of ABL during the passage of cyclone/thunderstorms (*Deshpande and Raj, 2009; Murthy et al., 2011; Babu and Jayakrishnan, 2014*), effect of eclipse in modulating the ABL characteristics (*Sethuraman et al., 1990; Subramanyam et al., 2011; Jayakrishnan et al., 2013*).

At National Atmospheric Research Laboratory, Gadanki, a major experimental facility in India, the characteristics of ABL have been studied in detail using both in situ and remote sensing techniques. *Krishna Reddy et al. (2002)* studied the diurnal evolution of ABL in different seasons with good temporal (10 min) and vertical resolutions (150 m). *Krishnan et al. (2003)* and *Krishnan and Kunhikrishnan* (*2004*) studied the seasonal variation of ABL height and ventilation coefficient. They noted that the ventilation coefficient (VC) is strongly influenced by wind speed during the monsoon season, whereas in other seasons both ABL height and wind speed determine the value of VC. *Kishore and Jain (2006)* noted that the evolution of BLH, determined from vertical profiles of refractive index structure constant, is different in different seasons and can be used to monitor the convective instability (*Kishore and Jain, 2006*). Furthermore, utilizing the same wind profiler observations, *Kalupureddy et al. (2007)* characterized the diurnal and seasonal features of the monsoon LLJ with a focus on the diurnal variability of low-level winds. *Das et al. (2004)* have shown that the trapped humidity layers, just above the ABL, and the Kelvin Helmholtz Instability (KHI) are important for UHF radar backscattering. The characteristics of LLJ, like the occurrence, frequency, amplitude, etc., have been by *Rajaraman et al. (2011)*. Further, *Basha and Ratnam (2009) and Nath et al. (2010)* detected BLH using sonde and GPS RO observations and they found BLH is higher during the pre-monsoon followed by monsoon, post-monsoon and winter. Utilizing the GPS RO measurements, a robust method was proposed to determine the BLH (*Ratnam and Basha, 2010*). Further, *Ratnam et al. (2010)* examined the effect of annular solar eclipse of 15 January 2010 on the lower ABL using a suite of measurements. They noted a decrease in thermal plume level, a dip in the surface layer and subsidence during the peak time of eclipse. ***Shravan et al. (2012)*** noted that two types of NBL prevail over Gadanki, a steady NBL and disturbed NBL in the second half of the night. They are attributed to differences in surface forcing and wind fields (turbulence). ***Mohan and Rao (2012)***, observed significant changes in the BLH and other meteorological variables (temperature, humidity) between two contrasting spells of Indian summer monsoon.

1.6. Scope of the thesis

Understanding of ABL processes and their variability remained an active area of research for several years through intense field campaigns and routine measurements. Earlier studies in India have elucidated the vertical structure and evolution of ABL over different surfaces (ocean, land, etc.) and advanced our understanding on ABL processes to a great extent. Nevertheless, most of these studies were carried out as part of monsoon experiments and therefore confined to regions dominated by monsoonal rain, such as monsoon trough region, Bay of Bengal, Arabian Sea, etc. Moreover, these studies were mostly based on limited (short-term) measurements made during intense campaigns. Further, most of these studies were carried out in isolation by focusing either on ABL variability near the surface using meteorological tower observations or on variability aloft using remote sensing devices. None of the above studies characterized the ABL parameters (winds, BLH, turbulence, etc.), processes and their variabilities in detail due to the lack of suitable observations (continuous measurements at the surface and aloft). Therefore, several key research problems on the variability of ABL remain unexplored.

- It is not clear how the ABL, particularly the height and evolution, varies with differing soil conditions and circulation patterns. These differing conditions within a season prevail during the summer monsoon season, in which the rainfall occurs in quasi-periodic pulses (known as active spells/wet episodes) separated by lulls (known as break spells/dry episodes).
- The day-time highly convective and night-time stable ABL have been studied extensively. Nevertheless, studies on the behaviour of ABL during the transitions (stable to turbulent during the morning and from turbulent to stable during the evening) are limited and mostly confined to mid-latitudes. The basic properties of transition, like how and when the transition starts, how long it persists, which scaling laws would work, etc., are also not known precisely.

- The nocturnal boundary layer is known to be stable with occasional weak and sporadic turbulence due to dynamic instability or density current. It is known from earlier studies in mid-latitudes that meso-scale circulations could trigger turbulence around the sunset. Do such turbulence episodes exist in the tropics? If so, what is the nature and source of such turbulence?
- Apart from surface forcing, the BLH and its evolution depends on several factors, like meso-scale circulations (land/sea breezes and valley/slope winds) and entrainment from the top of ABL, etc. One would, therefore, expect the characteristics of coastal ABL different from that of an inland ABL. Nevertheless, a comprehensive study describing the variability of ABL and its state variables from coast to inland has not been studied due to lack of suitable measurements.

Therefore, the aim of the thesis is to characterize the above mentioned variabilities of ABL (like, active to break spells, during evening transitions, episodes of turbulence in NBL and inland to coastal) and to understand the physical processes responsible for such variability. To address these issues, an integrated approach has been followed, wherein a suite of in situ and remote sensing instruments available at National Atmospheric Research Laboratory (NARL), Gadanki (13.45° N, 79.18° E, 360 m a.s.l.) and Indira Gandhi Centre for Atomic Research, Kalpakkam (12.30° N, 80.10° E, 5 m a.s.l.) have been employed. These data sets are augmented by gridded data sets of rainfall from India Meteorological Department (IMD) and Tropical Rainfall Measuring Mission (TRMM-3B42) and meteorological fields from European Centre for Medium range Weather Forecasting (ECMWF) and National Center for Environmental Prediction (NCEP) - National Centre for Atmospheric Research (NCAR) reanalysis.

The difference and similarities in ABL characteristics (evolution of ABL, height of ABL, winds, turbulence) between two contrasting episodes of Indian summer monsoon have been studied in Chapter 3 using a comprehensive data set covering 3 years of measurements at the surface and aloft. In particular, this study tried to address the following issues.

1. Does the evolution of ABL is same in wet and dry episodes of the monsoon? If not, which physical mechanism/parameter is responsible for the observed variations?
2. Does LLJ change either in magnitude or height in different spells of the monsoon? How the amplitude of the diurnal cycle of LLJ change between different spells of the monsoon?

The transitory nature of the ABL a few hours before and after the time of sunset over Gadanki has been presented in Chapter 4. This study addresses the following fundamental and important issues related to the afternoon transition.

1. Which state variable first identifies AT?
2. Which variable best identifies it?
3. Does the start time of AT exhibits any seasonal variation?
4. Does the start time of AT shows any vertical variation? If so, which physical mechanism is responsible for the observed height variation in the start time of transition?

The anomalous behaviour of turbulence during the post-sunset period (referred to as PST) has been studied at Gadanki in Chapter 5. This study tries to answer several questions on this intriguing problem.

1. How often turbulence episodes (enhanced turbulence) occur during NBL? Does PST occurs at all altitudes within the ABL or has any preferential height(s)?
2. At what time, the PST starts and how long it persists? Does it exhibit any seasonal dependency?
3. What is the source for the observed PST?

The similarities and dissimilarities in ABL characteristics (evolution, height of ABL, transitions, and turbulence) between an inland region (Gadanki ~90 km away from the coast line) and a coastal region (Kalpakkam ~5 km away from the coast line) have been studied extensively in Chapter 6. This chapter tries to answer the following questions.

1. How different is the evolution of ABL over the two observational sites (land and coastal)? What are the physical mechanisms that alter the evolution at these two sites?
2. How different are afternoon transitions in the coastal region from in an inland region?
3. What is the impact of sea-breeze circulation on the observed ABL characteristics over a coastal region?
4. Does PST occur over a coastal station? If so, how different it is from that of over an inland station?

Chapter 7 summarizes all important findings from the present study. It also poses new scientific problems emanated from this work for future research.