Chapter 7

Summary and Future scope

The importance of atmospheric boundary layer (ABL) in understanding the weather and climate, dispersion of pollutants and interaction between the Earth's surface and atmosphere is becoming increasingly recognized. The processes that occur in ABL affect our lives directly through the dispersion of pollution or indirectly via its influence on the weather. The processes and factors that govern the ABL are highly variable and in turn engender complex spatiotemporal variations of ABL. As a result, the ABL exhibits a variety of variabilities, starting from micro-scale motions (turbulence) to diurnal and to seasonal variations. To understand these variabilities thoroughly, it is necessary to quantify these variations and also investigate the physical processes responsible for such variations. Therefore, an attempt has been made to understand the differences in the characteristics of the ABL between wet and dry spells of the Indian summer monsoon and an inland and a coastal station. Further, the afternoon transition and turbulence structure around the sunset have been studied using a unique data set, comprising that of instrumented meteorological towers and UHF wind profilers. The station data are augmented by IMDs gridded rainfall data set and global reanalysis meteorological fields. The important results obtained from this study are summarized below.

7.1. Characteristics of the ABL between wet and dry spells of the Indian summer monsoon

The rainfall during the Indian summer monsoon occurs in sporadic spells (known as wet spells/episodes) separated by lulls (known as break spells/episodes). During these episodes, the circulation patterns, soil condition and synoptic forcing would be different. It is not clear how the ABL, particularly the height and evolution, varies with differing soil conditions and circulation patterns. These issues have been investigated in Chapter 3.

1. Does the evolution of ABL is same during wet and dry episodes of the monsoon? If not, which physical mechanism/parameter is responsible for the observed variations?

Large differences are noted in the ABL height and its evolution between the episodes. The noon-afternoon ABL is found to be shallower during the wet episode than during the dry episode by 500-1000 m. It is also noted that the growth of the ABL is delayed by 2-4 h during the wet episode. Further, the growth of ABL is continued till evening during the dry episode, whereas the ABL collapses after 14-15 LT during the wet episode. The shallow and delayed ABL growth during the wet episode is mainly due to the weak buoyancy flux. Higher abundance of soil moisture (particularly in the topmost layers) during the wet episode than during dry episode partitions most of the net radiation into latent heat flux, leaving only a small part of radiation for sensible heat flux to drive convection and ABL growth.

2. *Does LLJ changes either in magnitude or height in different spells of the monsoon? How the amplitude of the diurnal cycle of LLJ changes between different spells of the monsoon?*

The magnitude, diurnal amplitude and to some extent direction (particularly during night) of LLJ do vary between the episodes. The LLJ is stronger during the dry episode than in wet episode. Relatively weaker winds during the wet episode are attributed to the migration of the LLJ to south of India from its mean position of 15° N (*Joseph and Sijikumar, 2004*). A large diurnal wind variability is noted in both episodes, but it is more pronounced during the dry episode. The LLJ seen at 1.5 km during the early morning, shifts progressively higher with time until afternoon, when it reforms at a lower altitude after the collapse of ABL. The LLJ peak, therefore, follows the ABL evolution and appears as if it caps the ABL.

7.2. Characteristics of the afternoon transition (AT) over a rural inland station

Though day-time highly convective and night-time stable ABL have been studied extensively, the transitions from convective to stable during the evening and back to convective in the morning were not documented properly. Therefore, the transitory nature of the ABL few hours before and after the time of sunset over Gadanki has been studied extensively in Chapter 4.

1. *Which state variable first identifies the afternoon transition?*

Among the surface state variables, the signature of transition is first seen in σ^2_{WS} and T data, both of which start decreasing monotonically ~100 min prior to the time of sunset. The r increase is the last signature of transition, while the reversal of ΔT variation from positive to negative falls in between these extremes. Aloft, both SNR and σ identify the start of the AT at the same time, 120-160 min prior to the time of sunset, depending on the height considered.

2. *Which state variable is best for the identification of AT?*

Among all state variables, the decrease in temperature at the surface and SNR aloft are strikingly apparent in all case studies, which makes them ideal for identifying the start time of the AT. Furthermore, the distributions of $Trans_{sunset}$ for T and SNR are somewhat consistent and narrower than that for other state variables. Although several earlier studies employed reversal of sign in surface heat flux as a criterion for transition (*Lothon et al., 2014*, and references therein), it is now well known that such a reversal does not always occur during the transition (*Busse and Knupp, 2012*). The formation of an inversion depends on several other factors and therefore the formation of inversion alone cannot be used to define the transition. A few studies used deceleration of low-level wind as a criterion for identifying the transition (*Mahrt, 1981*). The above criterion works well in the lower portion of ABL, but fails above the nocturnal boundary layer, where the wind accelerates in the frictionless fluid. Therefore, *T* at the surface and SNR aloft can be used to identify the start time of the transition, as also suggested by *Edwards et al. (2006)*.

3. *Does the start time of AT exhibits any seasonal variation?*

The start time of the transition as defined by different state variables shows some seasonal variation, with late transitions during the northeast monsoon season. Though there is some seasonal variation in the start time of the AT relative to sunset time, the order in which the signature of the AT is seen in different state variables (first in *T*, and σ^2_{WS} followed by *T* and *r*) remained nearly the same in all seasons.

4. *Does the AT vary with height? If so, which physical mechanism is responsible for the observed height variation in the start time of transition?*

Interestingly, the start time of the AT exhibits a clear height dependency; i.e., the signature of the transition is seen first in profiler attributes (~160 min) followed by sodar attributes (~120 min) and finally in surface state variables (~100 min), suggesting that the transition follows a top-to-bottom evolution (*Angevine, 2008*). The fact that the first signatures of the transition are seen at higher altitudes by profiler/sodars than at the surface suggests that forces other than the buoyancy could also play an important role during the transition. With continuous waning of sensible heat flux (and surface forcing) during the AT, both the vertical extent and the strength of thermals decrease steadily, triggering the descent of the ABL or the transition. However, the surface heating is good enough to maintain the state variables and delay the decrease in *T* and σ^2_{WS} (considered to be the signatures of the transition). The entrainment ratio increases considerably during the morning and evening transitional periods, primarily due to the weak sensible heat flux. Therefore, the entrainment flux appears to be playing a major role during the transition period (and in the night) during which the sensible heat flux continuously weakens.

7.3. Nature and origin of the Post-Sunset Turbulence (PST)

The nocturnal boundary layer is known to be stable with occasional weak and sporadic turbulence due to dynamic instability and 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? For the first time, an attempt has been made to address several key questions regarding PSTs: their occurrence, start time and duration statistics and their dependency on height and season.

1. *How often turbulence episodes (enhanced turbulence) occur during the NBL? Does PST occurs at all altitudes within the ABL or has any preferential height(s)?*

   PST episodes are not rare, rather present in nearly 40-60% of observations, indicating that there is a possibility for the occurrence of PST once in two fair weather nights. The occurrence shows height dependency with relatively higher occurrence at higher altitudes (60% in the height region 900-1500 m and ~50% in the height region of 300-600 m) and lower occurrence at the surface (~38%).

2. *At what time, the PST starts and how long it persists?*

   The PSTs are first observed at the surface and then in sodar data and finally in radar data, indicating that it follows bottom-to-top evolution. On average, the PST_{sunset} occur ~1 h 10 min after the time of sunset at the surface, ~1 h 40 min after the time of sunset in height region of 300-450 m and ~2 h 10 min after the time of sunset in the height region of 900-1500 m. The distribution of PST_{susnet} is narrow for σ (900-1500 m), indicating the consistency in the start time of PST, whereas the distribution is wider in the height region of 300-450 m. The PST is not an instantaneous process; once occurs, persists for some time. The persistency varies from few minutes to several hours and also show height dependency. On average, PSTs persist for ~2 h at the surface-600 m and ~3 h at higher altitudes (($\geq$ 900 m). It means, the PSTs have a tilted plume structure.

3. *Is there any seasonal variation in the occurrence, in the start time of PST and in the persistency?*

   The occurrence shows seasonal dependency with higher occurrence in summer at all levels. The feature of higher occurrence of PSTs at higher altitudes is seen in all seasons. The occurrence statistics suggest that hot and dry (cool and moist) conditions are most favourable (detrimental) for the occurrence of PSTs. At the surface, distribution of PST_{sunset} is narrow, indicating that the start time of PST is nearly the same. But PST_{sunset} shows some seasonal variation with early PST_{sunset} during warm seasons (60 min after the sunset) and little late PST_{sunset} during cold season (70 min after the sunset). In the height region of 300-450 m, PST_{susnet} is ~1 h 30 min after the sunset, but the distribution is much wider compared to that of at the surface. PST duration is shorter in southwest monsoon season (~1 h 40 min, 1 h 50 min, 3 h 10 min) than in other seasons (~2 h, 2 h 10 min, 3-5 h) at all heights (surface, sodar - 300 m, radar - 900 m, respectively).

4. *What is the source for the observed PST?*

Mechanisms that could explain this unexpected behavior of ABL in the absence of solar forcing is primarily associated with background conditions. Temperature is higher during the post sunset turbulence day than on a normal day by 4-5 °C. Not much variation is seen in the mixing ratio before the initiation of turbulence, but it increases by 14% after the initiation of turbulence. Both wind speed and wind variance increases considerably just at the time of initiation of turbulence. Sudden increase in mixing ratio indicates incursion of moisture (strong turbulence reduces the mixing ratio). Although wind direction varies during the transition, but it's variation is nearly similar on post sunset turbulent day and normal day.

7.4. Inland ABL vs. Coastal ABL

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 to be different from that of an inland ABL. This study tries to understand the similarities and differences in the characteristics of ABL over coastal and inland stations.

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?*

The mean ABL height is lower over the coastal station (~1.65 km) than over inland station (~1.95 km) throughout the day. The ABL is not only shallower at coastal station but its rapid growth is delayed by 1-2 h. The diurnal variation of ABL is quite pronounced at both stations. Relatively, the diurnal range of ABL height is small over the coastal station. The time at which ABL reaches its maximum height in a day is different at different stations, i.e., 1.95 km at 14 LT over an inland station and 1.65 km at 12 LT over a coastal station. The ABL height difference between the stations is largest during the afternoon period, mainly due to the difference in the growth of ABL height and the delay in the collapse time of ABL over these stations. The shallow and delayed ABL growth over the coastal station is mainly due to the weak sensible heat flux governed by abundant soil moisture. Abundance of soil-moisture (nearly 2.5 times higher at the coastal station than at inland station) at the coastal station converts most of the net radiation into latent heat flux, rather than sensible heat flux and thereby reducing the height of the ABL and also delays the rapid growth of ABL.

Larger SNR and smaller spectral width values are seen during the noon (11-13 LT), when thermals are very active and ABL reaches its maximum height, at coastal station than at inland station. It is somewhat surprising given that the inland region is characterized by strong winds and turbulence, one would expect high SNR over inland station. Possibly, the prevalence of humid air (*Mohan and Rao, 2012*) and humidity gradients, important for radar backscatter in the ABL, over the coastal region might have enhanced the SNR.

2. *What is the impact of sea-breeze circulation on the observed ABL characteristics over a coastal station?*

The ABL variation and its evolution differ completely from that depicted in Figure 6.2 on strong sea-breeze days. After the intrusion of sea-breeze, discerning ABL height and other characteristics becomes difficult. Strong sec-breezes were observed on some days during the campaign period, mostly in the early period of the campaign. Strong sec-breeze occurs due to the differential heating between the sea and land. Since 95% of the campaign falls in post-monsoon and winter seasons, such large differential heating (and strong sea-breezes) does not exist. Moreover, it is easy to discern the sea-breeze during the monsoon season, because both synoptic monsoon flow (westerly) and sea-breeze (easterly) flow are in opposite direction.

3. *How different are afternoon transitions over coastal and inland stations?*

On average, the signature of the AT is identified by SNR and σ are at the same time, 120-160 min prior to the time of sunset (at different levels) over the inland station, but this signature of the AT is delayed by nearly 20-30 min (150-180 min prior to the time of sunset) at the coastal station. The top-to-bottom evolution of the start time of AT observed at Gadanki (Chapter 4) appears to be a common feature at all the stations, as it seen even at the coastal station (Kalpakkam).

4. *Does PST occur over a coastal station? If so, how different it is from that of over an inland station?*

The PSTs are omnipresent over both stations with an occurrence of 50%. Also, the occurrence shows height dependency with higher occurrence at higher altitudes at both stations. The occurrence of PST is relatively higher at inland station than at coastal station at all chosen levels. The start time of PST shows a height variation with progressive delay with altitude, following bottom-to-top evolution. The duration of PST is found to increase with altitude at both the stations. The start time of PST is delayed over inland station by 15-20 min. at all heights. Though the duration of PST is nearly equal at inland and coastal stations, but the day-to-day variability is quite large over inland station compared to that of coastal station. Though larger values of SNR are observed at the coastal station during the day time (Figure 6.3), the SNR is nearly equal during the PST period over the two stations. In contrast, the turbulence intensity is stronger over inland station than over coastal station at all heights.

7.5. Future scope

The investigations carried out in the present study not only yielded many interesting results, but also raised many scientific questions, which can be taken up as a future work. The results presented in this thesis stimulate multitude of studies as discussed below.

- During the afternoon transition a delay exists between the instant when the buoyancy flux goes to zero and the time when the local gradient of the virtual potential temperature indicates a sign change. We need to quantify the delay in different seasons and situations (clear sky, cloudy sky, convection day, strong and weak synoptic forcing, etc.) and understand which process causes this delay?
- The study conducted here on revealed several intriguing characteristics of afternoon transition, like top-to-bottom evolution, the role of entrainment, etc., Given the role of the morning transition in the evolution of day-time ABL, there is a need to understand the

behavior of morning transition from the surface to the top of ABL using tower, sodar and WPR measurements.

- Though it is clear that warm and dry conditions favour the occurrence of PSTs, it is not clear which mechanism is exactly responsible for the occurrence of PST. The local katabatic flow can cause, but the wind direction on days with and without the PSTs do not change much, indicating that it along may not be responsible. It warrants a detailed study further to identify the source of PSTs.
- The intriguing observations found in the present study needs to modeled. As a first step, the advanced meso-scale models, like WRF, needs to be used to check whether or not the model is able to reproduce the observations, like the occurrence of PST, top-to-bottom evolution of evening transition, delayed growth in ABL during wet spells and over coastal stations, by experimenting with all parameterization schemes.