Wind profiler radar for understanding the tropical convective boundary layer during different seasons

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This paper elucidates tropical continental boundary layer structures and their evolutions during different seasons over Gadanki, Southern India. Gadanki-LAWP (Lower Atmospheric Wind Profiler Radar) has proved to be an excellent tool for studying convective structures and boundary layer depth with good temporal (~ 10 min) and vertical resolution (150 m). We used LAWP reflectivity, Doppler velocity and spectral width data in time versus altitude to characterize general behaviour of convective boundary layer based on the “morning” and “evening” transition. From a wide variety of observed patterns, three categories are identified: (i) Descent, (ii) Ascent, and (iii) Inversion Layer (IL). Long-term Gadanki-LAWP observational results show the Ascent cases occur on relatively warm and moist days with strong turbulence and weak capping inversion [maximum occurrence in monsoon], descent days occur [pre-monsoon] on warm dry convection days and IL days occur [winter] on dew/fog and drier days with subsidence inversion and/or advection of warm air from the Bay of Bengal.

Keywords: Wind profiler radar, Boundary layer, Precipitation

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1 Introduction

The atmospheric boundary-layer (ABL) is the layer of air directly influenced by the underlying surface and is up to two kilometers deep under convective conditions. Several studies have investigated complex interactions between the air and the ground using observational, theoretical and numerical approaches. Past studies confirmed that the convective boundary layer (CBL) is the source of heat, water vapour, momentum, and pollutants. It is now widely recognized that the dynamics of CBL in tropics are very important to understand the global climate, and meteorological nowcasting, including the prediction of boundary layer evolution and pollution dispersion. The real-time monitoring of wind profiles can provide information in connection with air pollution and safety in high-risk areas such as chemical and nuclear plants.

Unfortunately, simple parameterization of CBL height in terms of surface meteorological data is often insufficient, especially, in tropical region. In India, for several years, the CBL height has been measured by acoustic sounders, towers and radiosondes. Sodar and towers work well for low boundary layer heights at night or during strong subsidence episodes, but their height coverage is limited. Radiosondes can measure CBL (twice a day) with coarse temporal and spatial resolutions. Ground-based remote sensing instruments such as lower atmospheric wind profiler radar (LAWP) can be used for understanding the ABL evolution, because it can provide information with good temporal and vertical resolution. The daily cycle of CBL growth and collapse can be seen clearly in time-height displays of the reflectivity profiles of LAWP.

In recent years, LAWP has been utilized to investigate CBL evolution at Gadanki over hilly terrains in southern India in the semi-arid region. Long-term LAWP observations of CBL evolution over Gadanki, Reddy et al. found that with a few exceptions the drier period has a higher CBL height compared with the wet period. Kusuma analysed the measurements made during the field experiment Convection in Asian Monsoon system (CAMS-98) to identify the cloud and the boundary layer processes within precipitating and non-precipitating cloud systems of the SW monsoon. Kishore and Jain made an attempt to study the evolution of CBL in non-precipitating, pre-monsoon and monsoon convective
days using the May-August 1999 convection campaign data. Praveena and Kunhikrishnan, have used extensive dataset of the LAW to estimate ventilation coefficient (VC), an index of air pollution potential over Gadanki. They made a detailed study on daily, monthly and seasonal variations of VC and found that VC is high during noon hours, leading to less pollution potential during noon hours. They also found that seasonal variation of VC revealed low values during winter and high values during monsoon season.

However, many aspects of the complex structure and dynamics of the tropical continental CBL during different seasons over Gadanki have not yet been clarified. The objective of this paper is to characterize the diurnal and seasonal variations of different structures and dynamics of the ABL over the hilly terrain in Gadanki valley region. The complex structure of the boundary layer observations in the continental region are needed to initialize mesoscale models and for air pollution modeling.

2 Observational site and database

The scientific requirements dictated that the Indian MST (Mesosphere-Stratosphere Troposphere) Radar should be located preferably below 15 °N latitude. Hence, after careful consideration of the various constraints, a site at Gadanki village (13.5 °N, 79.2 °E, 361 m above sea level), near the temple town of Tirupati in the Chittoor district of Andhra Pradesh was selected for locating the National Atmospheric Research Laboratory (NARL) [Fig. 1(a)]. A major road passes near the observation site, with a usage of a few hundred heavy vehicles each day. The observation site is about 120 and 200 km from the nearby major cities, Chennai (Madras) to the south-east and Bangalore to the south-west, respectively. The local and general topography is rather complex with a number of hills and a very irregular mix of agricultural, small-scale industrial and rural population centers. The NARL is situated in a small valley called “Gadanki Valley” extending to northeast to about 25 km from Pakala to Tirupati [Fig. 1(b)]. For most of its length the valley is about 12-3 km wide. The hilly terrains surround the observational site from 1 to 50 km distance. The average height of the hills is about 550 m, with a maximum height of about 1050 m.

The Gadanki-LAWP system was installed on 28 Aug. 1997 and has been working quite satisfactorily since 15 Sept. 1997. For detailed Gadanki wind profiler description and data availability, refer to Reddy et al. For the present study, observations with the Gadanki-LAWP were carried out fairly continuously from 01 Oct. 1997 to 30 Sept. 2000. A total of 775 days of wind profiler data are available until September 2000 for analysis. During the observational period, non-availability of the data for several days was mainly due to system failure, system maintenance, and severe weather hazards. A convection campaign has been carried out during May-August 1999 using VHF/UHF wind profiler radar, radiosonde, Disdrometer, optical rain gauge (ORG) and Automatic Weather Station (AWS) at NMRF. During this period, radiosonde observations have been made during 19 July to 14 Aug. 1999. A total of 24 radiosonde flights were launched with one...
flight every day at about 1600 hrs LT [+ 0530 hrs UT]. On special atmospheric event days, the radiosonde was launched twice or thrice a day.

The climate around Gadanki is warm, humid, or hot according to the season and the location of the area. According to India Meteorological Department, the seasons are classified as pre-monsoon (March, April and May), summer/south-west (SW) monsoon (June, July, August and September), North-east (NE)/post-monsoon (October, November and early December) and winter (late December, January and February). Moreover, Gadanki receives its maximum solar flux during the month of May and several localized convection occurs within the boundary layer before onset of the SW monsoon over this region. Gadanki receives a good amount of rainfall during May and from the south-west (SW) monsoon as well as the north-east (NE) monsoon.

3 Estimation of CBL depth from wind profiler: An intercomparison with radiosonde data

The vertical extent of CBL can be defined in different ways – the height where vertical gradient of the potential temperature or virtual potential temperature has a maximum; the crossover point of buoyancy flux profiles; the region of enhanced radar reflectivity due to strong humidity gradients and turbulence. The enhancement in radar reflectivity is in accordance with numerical experiments which show maximum refractive index structure constant in the inversion layer or in the regions where temperature and humidity gradients are large. In the present study radar reflectivity [range corrected signal-to-noise ratio (SNR), dB] is used to identify the top of the boundary layer. Convective boundary layer height/mixing depths (hereafter convective boundary layer depth or boundary layer depth) as determined using wind profiler are based on evidence that the profile of the refractive index structure function parameter exhibits a peak at the top of the boundary layer. The technique is based on experimental and theoretical evidence, indicating that the profile of structure intensity parameter, $C_n^2$ exhibits a peak at the inversion, capping the mixed layer. The wind profiler SNR at a given range is directly proportional to structure intensity parameter, $C_n^2$.

An algorithm was developed for estimation of the boundary-layer depth. First it computes the height of the maximum value in the range-corrected SNR profile for the vertical beam of the wind profiler over a 10 min period, and then takes the median of these values as the height of the boundary layer within an hour period. Alternatively, the median of the SNR profiles can be taken first, followed by finding the height of the maximum in the profiles, which provides more or less similar results. Contour plots of the SNR can be used to find the CBL height by view, and also indicate whether the measurement is reliable or not and how well defined the CBL is.

Figure 2 shows a time-height cross-section of reflectivity and spectral width observed with the Gadanki-LAWP during clear air day (on 13 Aug. 1999). From this figure it can be noted that evolution of the boundary layer directly depends upon the heating and cooling of the ground in response to the solar radiation. Strong reflectivity and turbulence observed during morning hours correspond to the morning transition or the morning rise of the inversion. The significant echo region appears in the lowest observational heights and ascends gradually, reaching a maximum height in the afternoon hours. This strong echo region marks the height of the daytime boundary layer or CBL. From Fig. 2 it can be noticed that (13 Aug. 1999 being a clear sky day) the top of the CBL reached its peak in the afternoon and stabilized afterwards. From Fig. 2(b) one can notice between 1500 and 2000 hrs LT, a uniform distribution of spectral width depicting a well mixed convective boundary layer. During the nighttime, a stable boundary layer develops, which is more complicated to understand than daytime CBL. Various processes taking place in the stable boundary layer make it complicated to interpret. Figure 2 also shows as an example of CBL height/mixed layer depth retrieval from backscatter data from the LAWP. The mixed layer height estimates were determined by the reflectivity maxima and are indicated by the ‘ovals’ in Fig. 2. This diurnal evolution of CBL height is usually valid on days without significant clouds or precipitation.

Boundary layer height can be determined from radiosonde data by inspecting the potential temperature profile and finding the altitude of the temperature inversion capping the boundary layer. Typically, in a well-mixed boundary layer, the potential temperature is nearly constant with height. At the top of the mixed layer, in the inversion layer, the potential temperature increases with altitude. In the free troposphere above the inversion layer, the atmosphere is usually stably stratified, i.e. the potential temperature increases with altitude, but the positive lapse rate is smaller than in the inversion...
layer. We chose the “middle” altitude of the inversion layer as an estimate for boundary layer depth. In cases where the potential temperature sounding was inconclusive in terms of locating the inversion layer we looked for a significant decrease in the water vapour mixing ratio sounding to find the inversion layer. As an example, Fig. 3 shows a potential temperature sounding recorded in the late afternoon (~ 1600 hrs LT) on 13 Aug. 1999. The sharp increase in potential temperature in the inversion layer is clearly visible. In this case, the boundary layer was determined to be 2.2 km deep. LAW observed CBL depth between 1600 and 1700 hrs LT is 2.25 km, which is in good agreement with radiosonde observations.

Simultaneous observations of Gadanki–LAWP and radiosonde data have been utilized by Kishore and Jain for CBL depth comparison, who reported good agreement between the two measurements. The same database has been used for this study also. The scatter plot of the boundary layer depths derived from the wind profiler and radiosonde (Fig. 4) show a reasonably good agreement between the two methods.

The observed discrepancies are expected because, radiosonde provides a “snapshot” of the state of the atmosphere as they ascend. Therefore, the mixing height determined from radiosonde data represents a point measurement in space and time.

Wind profiler radar, on the other hand, yield temporal and spatial averages of boundary layer
height. This has to be kept in mind when comparing mixing height estimates from radiosonde with those of wind profiler radars. A particular radiosonde may fly through an updraft or downdraft, thus yielding significantly higher or lower values for mixing height than the remote sensors. However, these analyses suggest that the wind profiler derived CBL depth can be utilized for understanding the boundary layer dynamics. The wind profiler radar techniques work well under a variety of atmospheric conditions. However, there are certain circumstances that place limitations on this technique. Enhancements of wind profiler radar reflectivity can also be caused by scattering from clouds, precipitation, insects, birds, or ground clutter and may be mistaken as the reflectivity peak associated with the boundary layer top. For the present study, these situations are identified by the visual inspection of the time-height cross-section of the reflectivity records and these data are discarded for estimation of the CBL depth.

4 Evolution of the CBL structures during different seasons

Wind profiler offers the unique ability to directly measure vertical motion profiles through precipitating and non-precipitating cloud systems. The wind profiler reflectivity provides a detailed record of the evolution of CBL throughout the day. We adopted similar scheme proposed by Grimsdell and Angevine and also added another category of the CBL evolution based on Gadanki-LAWP long-term data. In the present study, CBL evolution during the period of precipitation also is included. However, those data were excluded when estimating the CBL depth. We established that the following conditions had to be met for their inclusion in the CBL study.

(a) The reflectivity pattern shows growth of the CBL during the morning transition that indicated the presence and growth of boundary layer thermals.

(b) During the afternoon, a discernible and coherent pattern should be seen in the reflectivity figure. The spectral width shows a similar pattern, indicating that the reflectivity is related to turbulent activity within the CBL.

As was previously mentioned, much variation was observed in the behaviour of the CBL during the morning, afternoon and early evening, in contrast with the consistency seen during the nighttime. The definition of the three categories and the assignment of particular days to those categories based on two-dimensional patterns were necessarily subjective. Although it may be possible to describe these patterns with a small number of objective parameters, we did not do so; as such pattern recognition is a notoriously difficult problem.

The three categories were named descent, ascent and inversion layer (IL), based on the behaviour of the profiler reflectivity in each category. The defining characteristics of the categories are as follows.

**Descent** — The reflectivity pattern shows growth of the CBL during the morning transition that indicated the presence and growth of boundary layer thermals. The reflectivity is strong throughout the CBL depth during the morning transition hours, with correspondingly large spectral width (not shown here), implying the presence of strong convection. From late afternoon to evening (i.e. in the evening transition hours – between 1600 and 1800 hrs LT), the maximum height reached by the strong reflectivity steadily decreased, while the signal strength remained constant and the spectral width remained small.

**Ascent** — During the morning, the reflectivity pattern shows CBL growth similar to that on the descent days. Moreover, CBL is continuously ascended after midday also. During the evening transition hours, mostly CBL will be ascended or disappeared.

**Inversion layer (IL)** — LAWP reflectivity pattern shows CBL evolution similar to the descent days but throughout the day persistence of an inversion layer (mainly due to subsidence) between 1.5 and 3.5 km with strong reflectivity and also existence of the nocturnal multiple elevated layers (a few days in the daytime also).

Figure 5 shows time-height distribution of reflectivity (different structures of the CBL evolution)
Fig. 5 — Time-height cross-section of the C Catholic profiler (vertical beam) range-corrected reflectivity (SNR) during day-convexion days during different seasons [left three panels for descent type, middle three panels for ascent type, right three panels for inversion layer (IL) type].
Fig. 6 — Same as Fig. 5, but for 'wet' convection days during different seasons. Left two panels descent: and Left bottom panel is disdrometer estimated rain rate and reflectivity; Middle two panels Ascent type and rain rate obtained from the optical rain gauge; Right two panels for Inversion Layer (IL) type. Disdrometer estimated rain rate and reflectivity is depicted in the bottom panel for the IL category.
observed during different days in each category during dry periods. The very fine vertical streaks seen in these figures are due to the time resolution of the LAW. These figures highlight the variability present within the categories, but also show that despite this variability, the basic features described above still can be seen. As an example from the descent category, on 02 Mar. 1998 and 20 Apr. 1999, the strong reflectivity [Fig. 5 (left two panels)] observed during the morning hours corresponds to the morning transition or the morning rise of inversion. This strong reflectivity region appears in the lowest observational heights and ascends gradually, reaching a maximum height in the afternoon hours. These observations show that strong reflectivity region marks the height of the daytime boundary layer. So, this can be considered as the top of the boundary layer. The observations of this echo associated with morning transition in this study are similar to those observed by other wind profiler radars in clear air days elsewhere. On 23 Apr. 2000 the daytime convective boundary layer reaches typical depths of up to 4 km. This usually appears in the months of March and April over this region, because diabatic processes within a dry convective boundary layer are rather significant, and tend to be dominated by sensible heating/cooling. As a result of the dry conditions and large sensible heat fluxes, large diurnal temperature range typically exists. In addition, differential mesoscale heating and cooling owing to regional-scale terrain and land-surface contrasts may affect the characteristics of the boundary layer.

On IL layer days [Fig. 5 right three panels], both temperature and humidity were lower. Also during winter seasons, formation of fog/dew in the early morning period (minimum temperature [Fig. 7(b)] observed) is common, because all four sides of LAW site are covered with hillocks. Most of the IL days occurred when crops became senescent and surface moisture sources therefore reduce significantly. These conditions are suitable for formation of subsidence inversion during the winter months, usually about 2 to 4 km deep. These subsidence inversions may persist for many days under a dome of high pressure. Most of the IL days were influenced more strongly by high pressure systems and also a consistent difference in wind direction and wind speed. On IL days, the wind comes from north or north-east (average wind speed < 6 m/s), whereas during descent days winds come from westerly (average wind speed < 13 m/s). Previous studies over Gadanki suggest that during SW monsoon, low-level jet plays a major role on precipitating clouds.

Figure 6 [left two panels] shows the evolution of CBL on descent days during the SW monsoon period. On these days, a shallow CBL confined to 1.5 is observed most of the days. It is well known that during the SW monsoon, boundary layer will be rich in moisture. So, most of the radiation from the surface will be utilized for the evaporation processes, which results in a shallow CBL. Enhanced soil moisture probably contributes to increase in the latent heat fluxes and thus decreasing the surface sensible flux locally and suppress to increase in the latent heat locally and suppress to increase in the latent heat. Disdrometer derived rain rate (mm/h) and Radar Reflectivity, dBz confirms the mesoscale convective system passage over LAW.

On ascent days [middle two panels of Fig.6] during wet convection days (on 09 and 10 May 1999), in the morning transition hours, the CBL growth is more or less similar to descent days. The striking feature of ascent days is that the CBL grows continuously in afternoon hours with an increasing trend up to 1500 hrs LT, after which precipitation was observed over the wind profiler site. On these days, vertically rising plumes with velocity ~ 2 m/s [not shown here] are noticed. These plumes play an important role in transporting more humid air to the upper heights, which aids the convection triggering. The ORG estimated rain rate (no Disdrometer data because of power failure) derived rain rate (mm/h) confirms the mesoscale convective system passage over LAW.

Enough care has been taken to avoid this precipitation data while determining the CBL height. The Deepening of the CBL is observed in the late afternoon in the present case, whereas it is observed exactly at the midday on the dry convection days. Several more examples of the CBL evolution during wet convection days from the Gadanki-LAWP reflectivity patterns are shown by Reddy et al. and Praveena et al.
Figure 7(a) and Table 1 show that the different daytime CBL structure has been found to exhibit considerable vertical variability during different seasons; a phenomenon attributed to the underlying topography and varied land surface-atmosphere interactions. Information from the surface weather maps (issued by India Meteorological Department), Disdrometer, optical rain rage and Automatic weather station [Fig. 7(b)] data are examined to see whether there are any differences in the measured variables that could explain the observed differences in reflectivity between the three categories. Difference in temperature and humidity affects energy partitioning within CBL. A shallow CBL confined to around 1.4 km (Table 1 and Fig. 7(a)) is observed during monsoon season. In moist conditions, more energy is partitioned into latent heat flux, leading to convection. This effect is consistent with the formation of a capping inversion that was present in the descent case; usually, its occurrence is maximum in SW monsoon period [Fig. 7]. It is also a fact that the average CBL depth of descent days was low [max. occurrence in monsoon (average CBL height ~1.4 km)]. Occurrence of IL type CBL (average CBL depth ~ 2.6 km) evolution is maximum during winter, which could be due to the presence of early morning dew/fog that reduces the total available buoyant energy for the boundary layer and/or advection of warmer air from the Bay of Bengal through north-easterly/easterly wind over the Gadanki valley. During the month of May occurrence of Ascent type CBL evolution is more pronounced due to dry-to-wet transition occurrence around this region. The striking feature in the Ascent type is that the CBL (average CBL depth ~ 2.38) is continuously growing after 1200 hrs LT also. Depending on the background meteorological conditions, the CBL evolution may disappear or there may be an increasing trend up to 1500 hrs LT, after which precipitation was observed over the wind profiler site. The Optical Rain

<table>
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<tr>
<th>Season/Climate</th>
<th>Number of days CBL evolution</th>
<th>Mean noontime CBL height, km</th>
<th>Occurrence percentage of different CBL structures</th>
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</thead>
<tbody>
<tr>
<td>Summer/Pre-monsoon (March to May)</td>
<td>223</td>
<td>2.68 ± 0.52</td>
<td>Descent: 39, Ascent: 33, Inversion Layer: 20</td>
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<tr>
<td>Dry to Wet transition (May)</td>
<td>47</td>
<td>2.38 ± 0.42</td>
<td>Descent: 06, Ascent: 20, Inversion Layer: 06</td>
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<tr>
<td>South-West Monsoon (June to September)</td>
<td>97</td>
<td>1.42 ± 0.33</td>
<td>Descent: 40, Ascent: 44, Inversion Layer: 22</td>
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<tr>
<td>SW to NE transition (October)</td>
<td>20</td>
<td>1.49 ± 0.35</td>
<td>Descent: 05, Ascent: 04, Inversion Layer: 06</td>
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<tr>
<td>North-East Monsoon (October to Early December)</td>
<td>66</td>
<td>1.51 ± 0.39</td>
<td>Descent: 16, Ascent: 13, Inversion Layer: 19</td>
</tr>
<tr>
<td>Winter (Late December to February)</td>
<td>102</td>
<td>1.68 ± 0.37</td>
<td>Descent: 12, Ascent: 11, Inversion Layer: 44</td>
</tr>
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</table>
Gauge/Disdrometer and AWS precipitation measurements are shown in Fig. 7(b). The deepening of the CBL is observed in the late afternoon in the Ascent type, whereas it is observed exactly at the midday for the descent type [average CBL depth ~ 2.68] during dry convection days.

5 Summary and conclusion
Convective boundary layer height/mixing height measurements using wind profiler radar and radiosonde data were generally in good agreement lending credence to the wind profiler estimates of the CBL height/depth. Extensive observations of the CBL revealed well-distinguishable features over Gadanki in winter, pre-monsoon, SW and NE monsoon during dry and wet periods. From a wide variety of observed patterns, three categories are identified: (i) Descent, (ii) Ascent, and (iii) Inversion Layer. Wind profiler data shows that frequent appearance (during May month and monsoon) of the Ascent cases occur on relatively warm and moist days with strong turbulence and weak capping inversion, descent days occur (pre-monsoon) on warm dry days and IL days occur [winter] due to subsidence and/or advection associated with the passage of cold front in the Gadanki valley.

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References


