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Research Article

SOME ASPECTS OF THE CONVECTIVE BOUNDARY LAYER STRUCTURE OVER COMPLEX TERRAIN IN TROPICAL SEMIARID REGIONS OF RAYALASEEMA

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ABSTRACT

This study documents the dynamics and evolution of elevated stable layers (ESL) over complex terrains around Gadanki valley in tropical semiarid region of southern India during different seasons. The data used in this study were obtained from L-band lower atmospheric wind profiler radar (hereafter LAWP or WPR), Joss-Waldvogel Disdrometer (JWD), optical rain gauge (ORG) and Automatic Weather station (AWS). The analysed boundary layer structure shows a strong influence of the underlying terrain. Until noon, a nearly terrain following capping inversion developed. However, advective processes proved to play an important role in the boundary layer structure over the hilly terrain. So, the large-scale air flow caused suppression of the convective boundary layer growth at the mountain ridge by forcing the capping inversion towards the elevation of the terrain. The advection of cold air by up-slope winds lowered the heating rate near the ground and was able to generate an inversion above the up-slope wind layer. In the late afternoon, the terrain following structure of the capping inversion diminished and the capping inversion tended to form. This study illustrates the importance of understanding the synoptic and mesoscale meteorological processesassociated with convective boundary layer evolution in topographic regions of different seasonal climatic variability.

INTRODUCTION

The structure and dynamics of the convective boundary layer (CBL) are fairly well understood, but the presence of topography alters certain features. In the Gadanki valley region, there is, at times, significant directional wind shear above 0.7 *zi*in the convective boundary layer. Despite vigorous convective mixing, appreciable vertical scalar gradients are observed. In the extreme, cross-valley horizontal advection and along-valley channeling leads to multiple afternoon inversions within and above the GadankiValley (Fig. 1). These differential advection effects have not been extensively documented nor are they accounted for in mesoscale forecasting, air quality models and interference on terrestrial and satellite radio communication links. Daytime convective boundary layer structure has been found to exhibit considerable horizontal variability, a phenomenon attributed to the underlying topography. This variability was observed to greatly influence vertical mixing and horizontal transport of air masses above and below the CBL, but no evidence of multiple BL structures such as that observed over the Gadanki Valley has been offered.

Date base and general climate

The L-band wind profiler radar LAWP system was installed on 28 August 1997 and has been working quite satisfactorily since 15 September 1997. For detailed Gadanki wind profiler description and data availability, refer to Reddy *et al.* [2002]. For the present study, Observations with the Gadanki LAWP were carried out fairly continuously from 01 October 1997 to 30 September 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. Disdrometer, optical rain gauge (ORG) and Automatic weather station (AWS) at NARL.

During the winter (December – February) and pre-monsoon months (March - May), surface temperature contrast does set up cross -equatorial flow and convergence of warm and moist air to the continent near the surface. It is capped by a subsidence and southward flow of dry and colder air above the boundary layer. As a result, the `potential convective instability builds up during the winter and pre-monsoon months to a high value but cannot be realized due to the inhibition from the subsidence above the PBL. The change in the sign of meridional gradient of TT makes the circulation conducive for symmetric instability that forces frictional boundary layer convergence, overcomes the inhibition and

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explosive development of off-equatorial convection over India and the Bay of Bengal takes place. Therefore, change in the sign of the meridional gradient of the TT may be used as a thermodynamic definition of onset of SAM (After the onset, the large scale flow at lower levels (above PBL) produces a large scale cyclonic vorticity (the monsoon trough) through interactions with the mountains to the north. This large scale low level cyclonic vorticity helps organize convection and helps maintain the northern TCZ over the continent.

The role of terrain in the Gadanki Valley

The scientific requirements dictated that the Indian MST (Mesosphere-Stratosphere Troposphere) Radar should be located preferably below 15 degrees North 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)]. The observation site is about 100, 200 and 500 km from the major cities, Chennai (Madras) to the southeast, Bangalore to the southwest, and Hyderabad, respectively.

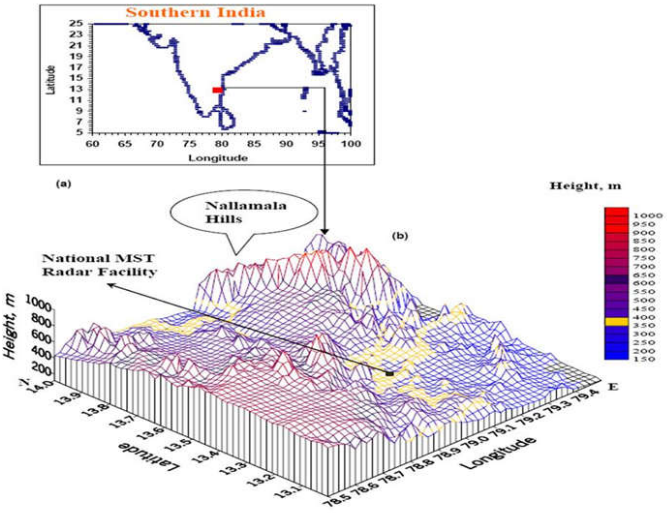

Figure 1 (a) Location of the National Atmospheric Research Laboratory (formerly known as National MST Radar Facility), Gadanki and (b) main topography of Gadanki area

Around the experimental site, Gadanki, 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 extends to northeast wards about 25 km from Pakala to Tirupati [please Refer Fig. 1.3. and Fig.1]. For most of its length the valley is about 12 - 3 km wide. The hilly terrains are surrounded 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. About 18 km from Tirupati, in the Rangampet forest on the Tirupati-Madanapallee Road, lies the Kalyani Dam. The dam is the main water source for Tirupati and Tirumalai. The river Swarnamukhi is also important river in Chittoor district of Andhra Pradesh. It joins the Bay of Bengal after flowing for about 155 km through Nellore district. Though it is not perennial, it plays a major role in water table control, facilitating rainwater infiltration and, thus, is significant for the agriculture sector of Chittoor and Nellore districts.

Convective boundary layer evolutions during Monsoon periods

The meteorological conditions over Indian sub-continent have been defined by India Meteorological Department (IMD). According to it, the seasons over India are divided into winter (January and February), pre-monsoon/summer or dry season (March, April, and May), monsoon/South-West (SW) monsoon or wet period (June, July, August, and September), and post-monsoon/North-East (NE) monsoon (October, November, and December). The SW and NE monsoon are also known as summer-monsoon and winter-monsoon respectively. Figure 2(a) shows the time-height cross-section of reflectivity (SNR) observed with the Gadanki-LAWP during the period July 21-31, 1999. It must be noted that such remarkable diurnal PBL variations were also existed on the other clear days of dry and wet seasons. On cloudy days such features were weak or disappeared. On precipitation days strong echoes caused by rainfall appeared, which were entirely different and distinguished from [Fig.2(a) on 21 & 22 July 1999, a bright band/melting layer could be observed around 4.5 km] the typical behavior of clear-air echoes observed on remaining days.

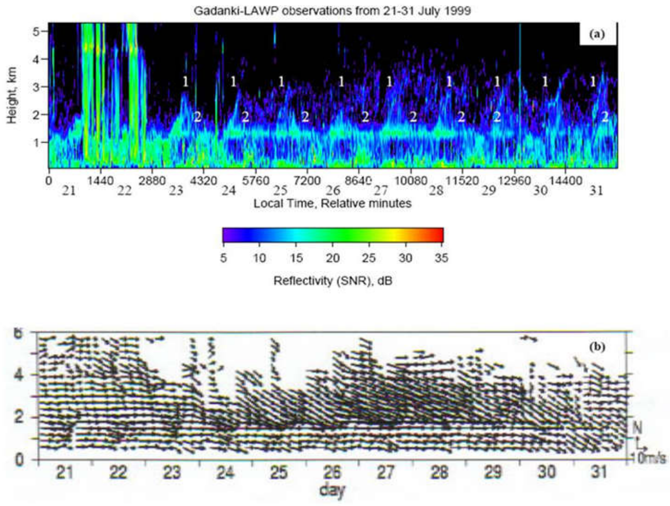

Figure 2 Time-height cross section of the Gadanki-LAWP (a) Reflectivity (SNR) and numbers indicate the heights of strong echoes and their respective types observed with LAWP. (b) Zonal-meridional winds averaged every one hour observed with the Gadanki-LAWP during 21-31 July 1999 in wet season.

From 23 - 31 July 1999, two distinct types of strong echo regions were found apart from the smaller scale variations. It is very hard to interpret the small-scale fluctuations. In the morning around 0700 LT, a significant echo layer (Type 1) appeared at the lowest observation height (300 m) and gradually ascended up to 4 km height until about 1600 LT. Such a layer structure was smeared in the evening and identified along with top of the PBL (or the mixing layer). 23-31 (8 days) July 1999, were the typical clear days (without any precipitation at the ground) in the wet season. On clear days, another type of thin-layered echo (Type 2) was observed more or less continuously between 1 – 2 km. Figure 2(b) shows the Gadanki-LAWP measured horizontal winds during 21-31 July 1999, averaged for 1-hr and plotted as wind vectors. The horizontal winds show clear diurnal variation in the boundary layer and clear detachment from the free atmospheric winds on clear days. The predominant wind direction was westerly in the PBL whereas in the free atmosphere the winds were blowing from north westerly.

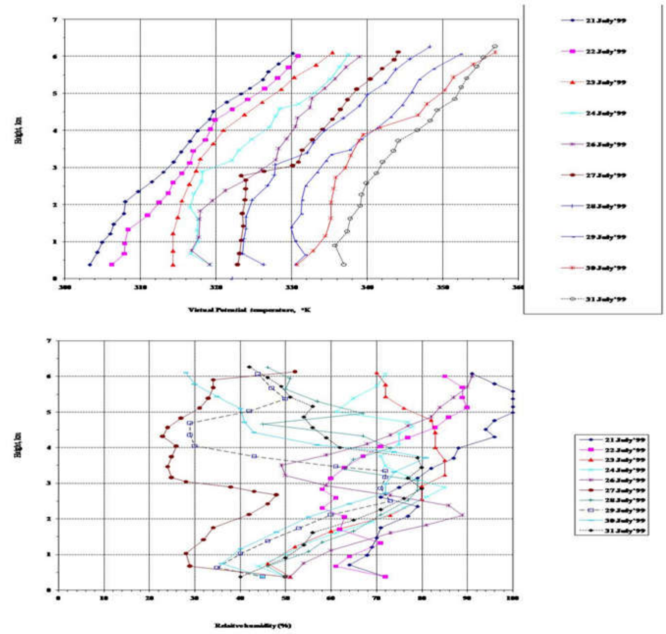

Figure 3 Vertical profiles of (a) virtual potential temperature [Each profile is shifted by 3^{O}K] and (b) relative humidity observed from radiosondes launched at the NMRF during 21-31 July 1999 (except July 25,1999) around 16:00 Local Time.

Figure 3 shows the vertical profile of the (a) virtual potential temperature and (b) relative humidity observed with radiosonde around 1600 LT during 21-31 July 1999 (except July 25, 1999). On 21 and 22 July 1999 the boundary layer was weakly stable due to rain condition. We found that the type 1 echo layer appeared near the top of mixing layer defined by an almost constant virtual potential temperature. By considering the echoing mechanisms of the radio waves, we suppose that the strong turbulence and vertical fluctuations inside the mixing layer (not shown here) and the striking gap in the vertical distributions of humidity and temperature contribute to the generation of the strong echo layer observed by the LAWP. During 23-31 July 1999, high refractivities were located around 2 km in the form of elevated layer. The elevated layer was the trade-wind inversion, visible to the radar because of the strong gradient of refractive index at that level. The refractive index depends on temperature and humidity but the gradient at the inversion was dominated by the sharp decrease of humidity with altitude [Fig.3(b)]. The strong echoes at low altitude were also explained by humidity fluctuations, because the surface is a moisture source and gradients are strong near the source. During 8 days the inversion was nearly always detectable as a layer of locally high reflectivity. Wind profiler observations in the sub tropics showed that the type 1 echo layer very few occasions ascend typically up to 2 km in the late afternoon hours when clear sky conditions prevailed. On average, the sub-tropics boundary layer depth researches 1 km by mid afternoon, which is significantly shallower than the typical tropical boundary layer. Also the type 1 echo layer diurnal variations in the tropical PBL were quite different from the other LAWP observations in the sub-tropics but similar to the equatorial region. The type 2 echo layer was similar to that observed with the 915-MHz LAWP at the height of the trade wind inversion in Hawaii, United States.

From CBL observations one can conclude that the double-layered structure is a characteristic feature observed during active phase of monsoon irrespective of year.

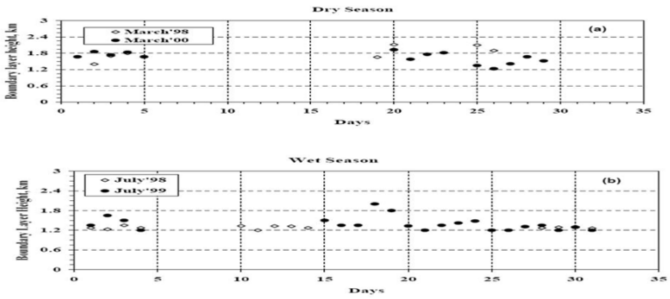

Figure 4 Boundary layer heights from Gadanki-LAWP measurements. Heights shown are the average over 1200-1500 local time for each day: (a) dry season and (b) wet season.

Figure 4 shows the midday boundary layer height for all the days with well-formed convective boundary layer. The height shown for each day [***Table1***] was the average of three hours in early afternoon (1200-1500 LT). The boundary layer heights were determined for each hour by subjective examination of the results of a peak-finding algorithm using SNR from the Gadanki-LAWP. The results suggest that CBL height during dry period varied between 1.2 and 2.0 km and whereas in wet period the boundary layer height varied between 1.05 and 1.70 km (except on 18 and 19 July 1999). The boundary layer height is determined by a variety of factors and is not simply related to any local surface meteorological variables, but we can see some broad relationships. The dry period/pre-monsoon is the beginning of summer hot and very humid in southern India. During this period maturation of the crops and consequent cessation of evapo-transpiration occur. No measurable rain fell during dry season, so soil moisture was probably quite low. It is an ideal situation to form the convective boundary layer in this region. With the onset of the South West (Summer) monsoon the cloudiness, humid conditions associated with the monsoon season high potential evapo-transpiration appear. Hence, in wet season most of the net solar radiation evaporates moisture rather than heating the surface, and therefore contributes little to buoyant forcing. In dry period, during convective days smooth diurnal variation in wind was observed up to 2 km and winds were northeasterly and southeasterly. Whereas in the wet period, the winds were mostly westerly and frequent occurrence of low-level jet between 1 to 2 km heights associated with the monsoon flow. We found that, with a few exceptions, the wet period had a higher boundary layer compared with the dry period. These observational results were more are less similar to those observations over the Deecan plateau regions using aerological data. The characteristic variations in the thermodynamic parameters of the ABL at Pune showed suppression of the mixed layer, absence of inversion/stable layers and decreased convective instability in the lower layers during the period of active monsoon conditions.

Table 1 LAWP Observations Analysed for Convective Boundary Layer Information

Season	Year	Days	Number of Days
SW	1998	2–4, 19, 20, 25, and 26 March	8
NE	1998	1–4, 10–14, and 28–31 July	11
SW	1999	1–6, 20–23, and 25–31 March	15
NE	1999	1–10 and 14–31 July	23

Multiple mixed layer events

Preliminary analysis of LAWP data over Gadanki during winter period (December to February) more frequently and maximum occurrence of Elevated stable layers (ESLs) and less frequently multiple inversions layers or multiple mixed layers are noticed in the hillyregion. The qualitative analysis reveals two principal mechanisms operating separately or in tandem lead to the development of the multiple mixed layer structure: 1) The presence of early morning mist/fog which reduces the total available buoyant energy for boundary layer growth; and 2) advection of warmer air from the over the Valley.

In the GadankiValley, cross-valley horizontal (winds) advection and along-valley channeling leads to a complex (multiple elevated stable layer) structure in the convective boundary layer [e.g. Figure 5 (a) and Figure 6 (a)]. This horizontal wind variability greatly influences vertical mixing and horizontal transport of air masses above and below the CBL. These differential advection effects have not been extensively documented nor are they accounted for in mesoscale forecasting or air quality models. Gadanki-LAWP data demonstrates that three principal mechanisms are responsible for the complex CBL structure observed (December and March period) within and above the Gadanki Valley [see Figure 4.2(a) and 4.3(a)]: 1) channeled flow within the valley; 2) advection of warmer and drier air from higher elevation land adjacent to the valley; and 3) fog formation or pooling of cooler air on the valley floor during the overnight hours.

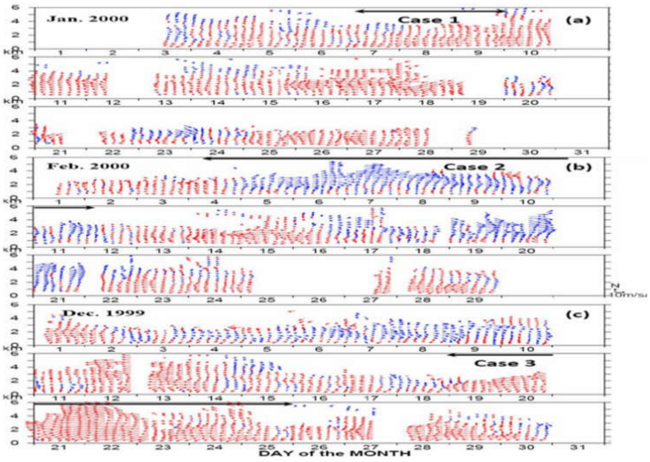

Figure 5 4-hrly averaged Day-to-Day variation of horizontal winds observed during (a) January 2000, (b) February 2000 and (c) December 1999 months. Vectors are directed upward for northward (southerly) component and towards the right for eastward (westerly) component.

With the movement of a fresh air mass into the Gadanki Valley region following a depression over Bay of Bengal and this frontal cloud system passage, these processes work together to establish an elevated inversion that is maintained by warm air advection aloft and reduction of convective processes at the surface through the presence of fog or cold pools.

Three cases described above illustrate the combined influence of valley channeling, fog, and overlying forcing (i.e. advection of warmer air and elevated mixed layers from off the Catskill Plateau) on the formation of multiple mixed layers within and above the GadankiValley. Valley channeling serves to maintain low-level ambient conditions (temperature and humidity); fog occurrence diverts energy that would normally initially be used to drive mixed layer growth to dissipating the fog; and finally, warm air advection aloft helps to strengthen the established fossil inversion, allowing for the development and persistence of the multiple mixed layers. Further analysis and modeling studies should reveal additional information regarding the dynamics and mechanisms responsible for the formation and maintenance of the Gadanki Valley CBL structure.

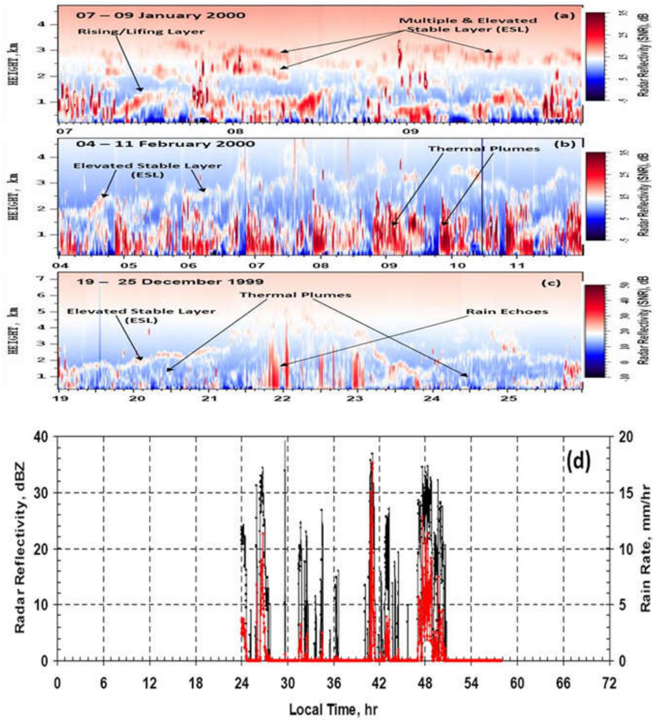

Figure 6 Gadanki-LAWP vertical beam observation of the radar reflectivity. 10-min averaged time-height cross section of radar reflectivity shows CBL evolution different atmospheric/weather conditions. (a) Multiple Elevated Stable layers (b) Elevated Stable Layer (ESL) and thermal plumes and (c) ESL during passage of Convective precipitating cloud system Panel (d) represents the disdrometer derived Rain integral parameters.

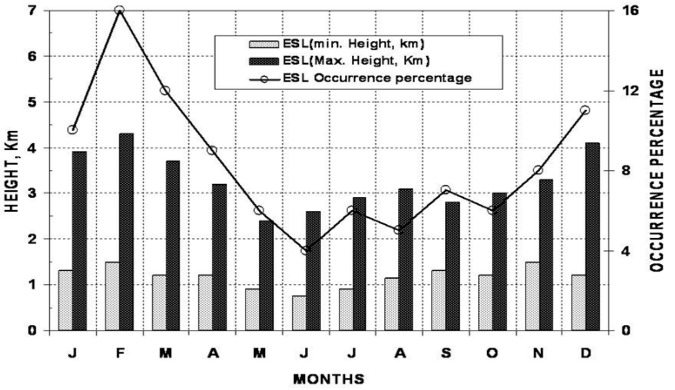

Figure 7 Monthly occurrence percentage of Elevated Stable Layer, its minimum height and maximum height over Gadankivalley region

Fig. 7 shows the monthly occurrence of elevated stable layers (ESLs) that often form the boundary between layers of differing stability or origin is likely to be a dominant feature of the atmospheric structure. Because elevated terrain can shield an interior basin from passages of weather-frontal systems and air mass changes, ESLs can become a semi permanent feature of the local meteorology, however, they can move vertically by hundreds of meters over short periods.

From the Wind profiler observations, the immediate effect of the afternoon and morning transitions on the residual cap might be important to horizontal circulations and vertical mixing. Differences in theisheight across the study region probably maximized during the morning and evening transition periods. Differential solar heating caused the primary capping layer in the western region to be higher during morning (when convective activity erodes the stable layer aloft) and lower during early evening (when radiative cooling and weak turbulent transport move the stable interface lower). The well-known mountain-valley circulation established in the surface layer enhances the vertical development (Figure 5). A counter circulation established during the early evening hours can then become important in vertical exchange. That is, pollution and/or moisture, mixed to larger heights in the western region during the morning, might be transported to the eastern region above the mixed layer by elevated circulations established the previous evening (Figure 8). In order to measure the effectiveness of this mechanism, detailed measurements of temperature, moisture, and/or tracer must be obtained at multiple sites with reasonable vertical resolution.

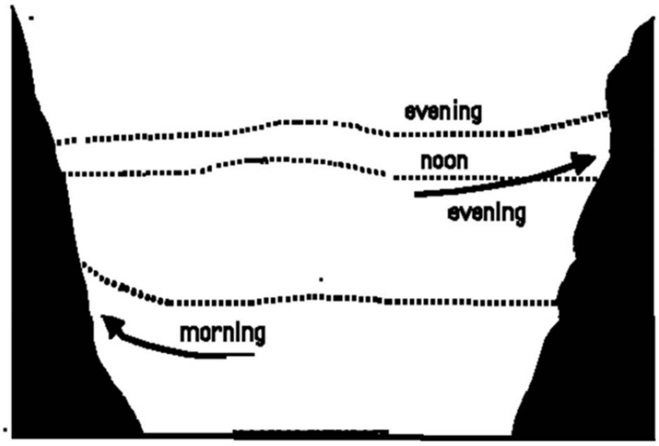

Figure 8 Mountain-valleycirculation established in the surface layer enhances the vertical development

SUMMARY AND CONCLUSIONS

The analyzed boundary layer structure shows a strong influence of the underlying terrain. Three events (foggy, fine weather, and synoptical scale disturbances) were chosen as a case study. The events analysis reveals two principal mechanisms operating separately or in tandem lead to the development of the multiplemixed layer structure:1) The presence of early morning fog which reduces the total available buoyant energy for boundary layer growth;and 2) advection of warmer air fromthe Deccan Plateauover the Valley.

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