CHAPTER – 5

INLAND BOUNDARY LAYER CHARACTERISTICS OVER A TROPICAL STATION USING UHF RADAR
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5.1 Introduction

The local features of the atmosphere mainly control the Atmospheric Boundary Layer (ABL) characteristics over an inland station. A knowledge of the ABL characteristics is important as it plays a vital role in various atmospheric processes such as convection triggering, turbulent transport (e.g., latent heat, pollutants, momentum etc.) and the development of Low Level Jetstream (LLJ) during monsoon periods. Understanding the turbulence and other boundary layer parameters is necessary for several applications in numerical weather prediction, chemical modeling and also the dynamics of the lower atmosphere. Turbulent dissipation and diffusion are the processes through which transport of heat energy, momentum and mass take place in the atmosphere close to the surface of the earth and it can affect the energy budget. Turbulence also influences the diffusion of pollutants from near earth surface to higher heights (Ramana, et al, 2004; Praveena and Kunhikrishnan, 2004). So, the knowledge of turbulence parameters is essential for understanding of the dynamics of ABL. One of the important features of the ABL is its diurnal variation since it controls the transport process of the ABL parameters.

5.1.1 ABL structure during clear sky day

The ABL structure during clear air conditions over land can be classified as daytime Convective Boundary Layer (CBL) and is also called Mixed Layer (ML), Nocturnal Boundary Layer (NBL) and Residual Layer (RL). The CBL exists from sunrise to sunset and boundary layer reaches its maximum depth around afternoon hours. Since convection is dominant mechanism, there is usually wind shear across the top of the CBL that contributes to the turbulence generation. The tropical regions export momentum to extra-tropical regions through the turbulent activities of the CBL. The tropical regions warm up continuously due to combined effect of insolation and heat exchange at earth-air interface. Diurnal variation of meteorological parameters in the tropical ABL is much stronger than in the extra-tropical ABL particularly over land, causing significant diurnal oscillations in wind
speed and convective activity. The properties of the tropical ABL are substantially different from the conditions of the subtropical ABL. Tropical regions are characterized as the hottest region of the globe and form large fields of convective clouds of all sizes. Strong solar fluxes, land-sea contrasts and Hadley cell circulation causes tropical ABL region more dynamic and due to this reason, the tropical convective clouds have unique characteristics such as maximum vertical extent and diurnal and seasonal variations.

5.1.2 Wind structure in the ABL during southwest monsoon

Wind plays a vital role in atmospheric transports of heat, mass, moisture and pollutants from one place to another. These transport processes play an important role in changing local weather. The winds and their variability in ABL are important in various fields like meteorology, atmospheric physics, environmental protection, agriculture, wind energy utilization, and air traffic control etc. Accordingly, the characterization of wind and its variability are extremely important and hence detailed observations of winds are necessary with high temporal and spatial resolution.

One of the important features that occur regularly in an irregular way over the Indian peninsula is the presence of the southwest monsoon with a strong southwesterly wind in the lower layers of the troposphere. The core of this strong southwesterly wind is around 850 hPa and this strong low level wind called low level jet stream (LLJ) (Joseph and Raman, 1966; Findlater, 1966, 1967; Desai et al., 1976), carries ample of moisture from South Indian Ocean and Arabian Sea sufficient to precipitate over continental areas, as they account for the majority of the annual total rainfall. Monsoon is a synoptic phenomenon and strongly coupled with warm oceans around, which needs proper exploration for predicting the variability of the Indian monsoon rainfall, the LLJ is one of the factors and needs a full understanding on the basis diurnally, daily and monthly.

5.2 Lower Atmospheric Wind Profiler (LAWP)

The lower atmospheric wind profiler (LAWP) is an L-band Ultra High Frequency (UHF) wind profiler was installed at Gadanki (13.5°N, 79.2°E), Andhra Pradesh, India. The location map of the LAWP is given in Fig.5.1. The LAWP was established over Gadanki in collaboration with the Ministry of Posts and
Telecommunications/Communication Laboratory, Japan for investigating ABL dynamics and precipitation cloud systems. The LAWP is coherent, phased array, Doppler radar operating at 1357.5 MHz with a peak power aperture product of $10^4$ Wm$^2$ (Reddy et al., 2001) capable of providing continuous high-resolution wind measurements in the first few kilometres of the atmosphere. Fig. 5.2 shows the antenna and transmitter assembly unit of the LAWP.

Fig. 5.1 The location of the LAWP (Gadanki) with map of India

Fig. 5.2 Antenna and transmitter assembly unit of the LAWP
However, the development of wind profilers has revolutionized the boundary layer studies with their excellent height and temporal resolutions (Gage and Balsley 1978; Balsley and Gage, 1982). The UHF wind profilers are better suited for boundary layer observations (Ecklund et al., 1988; Rogers et al., 1993a; Gage et al., 1994; Gossard et al., 1998). One such, UHF radar, known as Lower Atmospheric Wind Profiler (LAWP), is located at Gadanki to carry out studies on atmospheric boundary layer.

5.2.1 Technical details

The phased antenna array consists of 576 circular microstrip patch antenna elements arranged in a 24 x 24 matrix over an area of 3.8 m x 3.8 m. The LAWP technical and processing details are given in Table No.1. The total array is organized into four quadrants. A total peak power of 1000 W is delivered to the antenna array by a parallel array of four outputs from Power Amplifier (PA), each feeding 250 W to one quadrant (12 x 12 elements) of the array. The Transmitter (Tx) unit, preceded by PA, generates an output power of 175 W, which is sufficient to drive the PA. The PA generates the required final output power by a division-amplification-combining technique. The output power is fed via the beam changer switch and hybrid circulator. The power distribution across the array is tapered to obtain better side lobe suppression. The array produces a pattern having a beam width of 4° and directive gain of 33 dB. However, due to the ohmic loss of 4 dB, the effective gain of the array is only 29 dB. The beam can be tilted by 15° (fixed) towards north and east (two principal planes) from the zenith by electrical steering, that is by injecting a progressive phase difference between the successive elements. Phase shifters are used to steer the beam in the north plane. For the east beam, required phases are injected through the appropriate lengths of the feeder lines. The same antenna array is used for all the three beams.

The echo signal received by the antenna array from the atmosphere is delivered to the receiver via circulators. The receiver is a phase coherent heterodyne type having a quadrature detector at the final output and delivers the video outputs to the signal processor. The receiver has an overall gain of 50-120 dB depending upon the gain setting of automatic gain controller amplifier (AGC). The dynamic range of the receiver is about 66 dB. The quadrature (I & Q) outputs of the receiver are limited
to a peak-to-peak voltage of 10 volts and given to the Signal Processor Unit (SPU). The SPU consists of an Analog to Digital Converter (ADC) and a coherent accumulator.

<table>
<thead>
<tr>
<th>Location</th>
<th>Gadanki (13.5°N, 79.2°E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna (Phased Array)</td>
<td>3.8m X 3.8m</td>
</tr>
<tr>
<td>Operating Frequency (f)</td>
<td>1357.5 MHz</td>
</tr>
<tr>
<td>Radar wave length (λ₀)</td>
<td>0.22 m</td>
</tr>
<tr>
<td>Transmitted peak power (P₀)</td>
<td>1000 Watts</td>
</tr>
<tr>
<td>Effective aperture (A₀)</td>
<td>10 m²</td>
</tr>
<tr>
<td>Beam width</td>
<td>4°</td>
</tr>
<tr>
<td>No. of beams*</td>
<td>3(E15, Zenith and N15)</td>
</tr>
<tr>
<td>Gain (G)</td>
<td>33 dB</td>
</tr>
<tr>
<td>Receiver band width (B₀)</td>
<td>1.58 x 10⁶</td>
</tr>
<tr>
<td>Receiver path loss (α₀)</td>
<td>4 dB</td>
</tr>
<tr>
<td>Transmitter path loss (α₀)</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>Cosmic temperature (T₀)</td>
<td>10 K</td>
</tr>
<tr>
<td>Receiver temperature (Tᵣ)</td>
<td>107 K</td>
</tr>
<tr>
<td>Maximum duty ratio</td>
<td>5%</td>
</tr>
<tr>
<td>Pulse width</td>
<td>1 – 2 μsec</td>
</tr>
<tr>
<td>Inter Pulse Period (IPP)</td>
<td>programmable</td>
</tr>
<tr>
<td>Range resolution (Δr)</td>
<td>150/300 m</td>
</tr>
<tr>
<td>Coherent Integration (N₀)</td>
<td>100</td>
</tr>
<tr>
<td>No. of FFT points</td>
<td>64 – 1024 (programmable)</td>
</tr>
</tbody>
</table>

* The number after letter E and N is in degrees indicates the oblique angle from zenith.

Table. 5.1 System specification for LAWP unit
The ADC has 12-bit resolution and samples the analog input at the interval set at the Data Processing Unit (DPU). The SPU performs the coherent accumulation on the ADC output data. The constituted coherent data is then transferred to the DPU for further processing. The DPU performs Fast Fourier Transform (FFT) on the received coherent data. The on-line computer displays the frequency spectra (North, East and Zenith beams), signal strength, wind speed and direction. The data is further processed to compute moments before being transferred to the off-line computer via Ethernet for archival. Finally the data of incoherent, spectral moments and velocity field is archived on magneto-optical disks and eventually transferred to compact disks (CD-ROM). The LAWP spectral data is processed on-line. It can also be processed in off-line. The on-line data processing algorithm makes use of single peak detection for producing the moments and three-wind vector (u, v and w) by simply picking the strongest peak outside the clutter bounds. Quality control procedures are used to obtain the hourly horizontal winds. This data processing method works well for most of the time, however, there are the occasions when there are unrealistic wind data or when the consensus averaging method fails.

5.3 General geographical and meteorological conditions

The experimental site, LAWP is located at the National MST Radar Facility (NMRF), now it is renamed as National Atmospheric Research Laboratory (NARL), Gadanki (13.5°N, 79.2°E), about 370 m above the mean sea level. The terrain around Gadanki is complex, with many hills (average height of hills is about 750 m) within 10 km radius and a mixture of agricultural and population centers, the topography of this site can also influence the ABL features and it is about 120 km to North-West of Chennai on the east coast of Indian peninsula. Three-dimensional view of the main topography around Gadanki is shown in Fig.5.3.

According to India Meteorological Department (IMD), the onset of the southwest monsoon occurs at Gadanki around one week after the onset over Kerala. India experiences two monsoons namely southwest and northeast monsoons.
They account for the majority of the annual rainfall. The two monsoons are different in the sense that in summer, warm equatorial maritime air predominates over a major portion of the country. In winter, the air masses recede south and are replaced by cool tropical continental air. The normal mean surface day temperatures over Gadanki during January, April, July, and October are around 23°C, 30°C, 30°C, and 28°C, respectively.

5.4 Scope of the study

The ABL over the tropical regions are more complex due to the intense convective activity associated with tropical convergence zone called ITCZ. This region is regarded as the source region for several weather activities. The ABL structure changes spatially and temporally and hence knowledge of the variation on different time scales is most essential. A knowledge of ABL in different seasons, which are characteristics of the Indian sub-continent, is still lacking, especially in the southwest monsoon season. In the above perception, an investigation of ABL is carried out using high resolution data obtained from the LAWP during the southwest
monsoon period. The data has a better quality in height and time to bring out the research results. The LAWP is an L-band UHF radar to observe the atmospheric boundary layer continuously and this high-resolution radar is first of its kind in India. The key objective of the present study is to understand the diurnal evolution of the ABL during monsoon season and variation of LLJ since this feature is important during monsoon. The other characteristics and dynamical processes associated with boundary layer during the southwest monsoon such as variation of the vertical wind shear, ABL height using the signal to noise ratio method etc. are also studied.

5.5 Data processing

The schematic diagram for processing LAWP data is given in Fig.5A and the details of the processing are given herewith. Usually the data is processed using the software called ADP (Atmospheric Data Processor) and the details of the ADP are given in Anandan et al (1996; 2004). The complex time series of the samples are subjected to the process of FFT for on-line computation of the Doppler power spectrum for each range bin of the selected range window. The Doppler spectra are recorded and transferred for off-line processing. The ADP involves the following steps: the dc contribution, which arises either from non-fading clutter or un-cancelled dc system biases or both, is eliminated by replacing the spectral point at zero frequency value with the average of two adjacent points (3 point dc removal) or with the four adjacent points (5 points dc removal). The data sets are further edited to remove interference band, if any, which might run through the entire range window and are subtracted out by estimating them in a range bin where they dominate the real signal. The spectrum contains background noise and it needs to be removed as a first step to compute the moments. The average noise value for each range bin is estimated by following the objective method of Hildebrand and Sekhon (1974). The mean noise level thus calculated is subtracted from all the range bins of the spectral frame. For each range bin, the signal peak is identified using ADP. The spectral window is determined by noting all the contiguous points that are above dc level. The three low order moments (0th, 1st and 2nd) are computed using numerical integration by using the expressions adopted by Woodman (1985).
Received Signal

→ Ranging
  (Sampling)

→ Coherent Integration
  (Time - domain averaging)

→ Spectral analysis
  (Fast Fourier Transformation)

→ Incoherent integration
  (Spectral averaging)

→ D C Removal

→ Spectral cleaning

→ Noise level estimation

→ Spectral moments
  (Echo power, Doppler shift and spectral width)

→ Wind vectors
  (U, V and W)

Fig. 5.4  Schematic diagram for data processing in LAWP
5.6 Computation procedures

5.6.1 Moments

The 0th moment represents the total signal power in the Doppler spectrum or total signal strength.

\[ M_0 = \sum_{i=m}^{n} \overline{P}_i \]  

(5.1)

The 1st moment represents the weighted mean Doppler shift.

\[ M_1 = \frac{1}{M_0} \sum_{i=m}^{n} \overline{P}_i f_i \text{ where } f_i = \frac{(i - N/2)}{(IPP \cdot n \cdot N)} \]  

(5.2)

The 2nd moment represents the variance, a measure of dispersion from central frequency.

\[ M_2 = \frac{1}{M_0} \sum_{i=m}^{n} \overline{P}_i (f_i - M_1)^2 \]  

(5.3)

where IPP is the inter pulse period, \( m \) and \( n \) are the lower and upper limits of the Doppler bin of the spectral window and \( \overline{P}_i \) and \( f_i \) are the power and frequency corresponding to the Doppler bin within the spectral window.

5.6.2 Signal to noise ratio (SNR)

Signal to noise ratio (SNR) can be calculated as,

\[ SNR = 10 \log \left( \frac{M_0}{N \cdot L} \right) \]  

(5.4)

where \( N \) and \( L \) are the total number of Doppler bins and average noise level respectively. The product \( N \) and \( L \) give the total noise power over the whole signal spectral window.

5.6.3 Height and wind components

For representing the observation in physical parameters, the Doppler frequency and range bin have to be expressed in terms of corresponding radial velocity and height.

\[ H = \frac{(c \cdot v \cdot \cos \theta)}{2} \]  

(5.5)
Velocity \[ V = \frac{c \cdot f_D}{(2 \cdot f_c)} \text{ in } \text{m/s} \quad (5.6) \]

where \( c \) is the velocity of light in free space \((2.98 \times 10^8 \text{ ms}^{-1})\), \( f_D \) is Doppler frequency in Hz and \( f_c \) is the carrier frequency and \( t_R \) is time delay of the pulse return.

After computing the radial velocity for different beam positions, the absolute velocity (\( u, v \) and \( w \)) can be calculated. To compute \( u, v \), and \( w \) at least three non-coplanar beam radial velocity data are required. If higher number of different beam data is available, then the computation will give an optimum result in the least square method. Then the light of sight component of wind vector \( \mathbf{V} = (V_x, V_y, V_z) \) is

\[ V_i = V_i = V_x \cos \theta + V_y \cos \theta_y + V_z \cos \theta_z \quad (5.7) \]

where \( i \) is the unit vector along the radar beam and \( X, Y \) and \( Z \) directions are aligned to East-West, North-South and Zenith respectively. Applying least square method (Sato, 1989)

\[ e^2 = (V_x \cos \theta + V_y \cos \theta_y + V_z \cos \theta_z - V_{in})^2 \quad (5.8) \]

where \( V_{in} = f_{in} \cdot \frac{\lambda}{2} \). To satisfy the minimum residual \( \frac{\partial e}{\partial V_k} = 0 \) where \( k \) corresponds to \( X, Y \) and \( Z \).

\[
\begin{bmatrix}
V_x \\
V_y \\
V_z
\end{bmatrix} = 
\begin{bmatrix}
\sum_i \cos^2 \theta_{xi} & \sum_i \cos \theta_{xi} \cos \theta_{yi} & \sum_i \cos \theta_{xi} \cos \theta_{zi} \\
\sum_i \cos \theta_{xi} \cos \theta_{yi} & \sum_i \cos^2 \theta_{yi} & \sum_i \cos \theta_{yi} \cos \theta_{zi} \\
\sum_i \cos \theta_{xi} \cos \theta_{zi} & \sum_i \cos \theta_{zi} \cos \theta_{yi} & \sum_i \cos^2 \theta_{zi}
\end{bmatrix} \cdot 
\begin{bmatrix}
V_{in} \cos \theta_{xi} \\
V_{in} \cos \theta_{yi} \\
V_{in} \cos \theta_{zi}
\end{bmatrix}
\quad (5.9)
\]

Thus on solving this equation we can derive \( V_x, V_y \) and \( V_z \) which corresponds to \( u, v \) and \( w \) components of velocity.

5.7 Diurnal variations

The data taken from the LAWP during non rainy days of the southwest monsoon is a good quality data set. The measured wind values were found to be in general agreement with those of the measured values of radiosonde and MST radar (Mesosphere, Stratosphere, Troposphere) during the period of 26th and 29th July 1999 (Praveena, et al 2003) and LAWP and MST were compared by Reddy et al,
2001. A typical example of simultaneous measurements of wind speed with LAWP, MST radar and radiosonde observations are given in Fig.5.5. The present study is based on the above data during the southwest monsoon period. We considered all non rainy days of the months of May, June, July, August and September for the years 1999 and 2000. The non rainy days in the above years during the months are given Table 5.2 and the days are collected from NARL. We generalise the characteristics of the ABL dynamics by considering a few days from each month of the year 1999 during southwest monsoon period. The representative days selected for the study are 6th May, 23rd June, 25th July, 14th September and 8th August of the year 1999. In addition the above, the dynamic behaviour of the ABL is studied in the case of active and weak phases of the southwest monsoon using the LAWP data and NCEP/NCAR reanalysis data set (Kalnay et al., 1996). The active days are selected from the daily rainfall and 850 hPa zonal wind following the procedure of Joseph and Sijikumar, 2004. The days selected are good agreement in both the methods and the active phase is from 15th July to 20th July and weak phase is from 12th August to 15th August in the year 1999.

![Comparison of wind speed measured by LAWP, MST radar and radiosonde on 26 July 1999 (1030 IST) and 28 July 1999 (1615 IST)](image-url)

Fig.5.5 Comparison of wind speed measured by LAWP, MST radar and radiosonde on 26 July 1999 (1030 IST) and 28 July 1999 (1615 IST)
Table 5.2 Non rainy days considered for the analysis

### Variation of the zonal wind

The day to day variation of the zonal wind is prominent during the southwest monsoon season other than diurnal variation and can observe from the time series of area averaged zonal wind from NCEP/NCAR reanalysis data (Fig.5.11). As the encroachment of southwest monsoon, the variability of the wind is found to be high in both vertical and temporal domains. The height time intensity contour of the hourly averaged zonal wind is plotted and presented in Fig.5.6 from a to e. The Fig.5.6a, top panel of the figure represents the diurnal variation of the wind for 6th May representing month of May. This date is not included in the southwest monsoon season because the long term climatological mean of the monsoon onset over India is 1st June with a standard deviation of 8 days (Rao, 1976) and the date of onset during the year is 25th May. This date is considered to study the evolution of the monsoon onset and propagation of the monsoon surge. During early May, the westerlies with a speed of more than 5 ms\(^{-1}\) are seen in early morning hours (~6 am) at an altitude of 1 km and as the day progresses the wind structure in the lower levels weakens (and occasionally wind becomes easterly). Around 2 km and above the wind is easterly because prevailing wind direction during May is easterly. After the onset of monsoon influence of LLJ increases due to the advancement of monsoon surge. The structure of the boundary layer also gets modified with the activity of the monsoon. To get a
detailed structure of the monsoon boundary layer, we present diurnal variation of zonal wind structure on representative days from each month of the southwest monsoon (Fig.5.6 from b to e). During the month of June (23rd June) the zonal wind strength is high and the wind speed is more than 15 ms\(^{-1}\). This maximum speed is found in the early morning hours of the day over a long duration around 1.3 km. As the day progresses the strength of the LLJ weakens due to the convective activity and this shifts the westerly wind to a higher altitude about 2.8 km in the afternoon hours. This is due to the development of the convective boundary layer due to the enormous supply of solar radiation. This convective activity made the ABL to become unstable. Generally, the LLJ can be treated as the geostrophic wind because it blows just above the ABL. During night time, thermals are absent and hence frictional effect in the ABL is small. So, the ABL depth during night is small. As the day progresses, convective activity increases and ABL depth increases. Accordingly, LLJ shifts to the higher level.

From Fig.5.6b it is obvious that the deepening of the LLJ core as the development of the CBL. Fig.5.6c & Fig.5.6d represent the contours of wind speed to show the diurnal variation of the LLJ during July and August respectively. The diurnal variation of the wind pattern during July and August is similar to that of the June, but the intensity is higher than that of the June. The maximum core strength of the LLJ is found to be in the early morning hours and the speed is more than 22 ms\(^{-1}\). It is found that the CBL development pushes the LLJ core upward from its morning position and hence one feels that CBL causes the deepening of LLJ. This feature is noticed in all the cases. Further, when the CBL develops the LLJ wind speed exceeds 15 ms\(^{-1}\), indicates the active monsoon situation. The decrease of the wind speed of LLJ from early morning hours to evening hours may be due to the interaction of the upper air circulations. This mode of variations is noticed in all the days considered. The maximum wind speed is \(~25\) ms\(^{-1}\) at 8 am about 1.4 km in the month of July and August, but maximum wind strength during June is around 6 am and the value is around 18 ms\(^{-1}\). The LLJ core height during daytime exceeds 3 km in certain occasions.
Fig. 5.6 Diurnal variation of zonal wind component (ms⁻¹) from LAWP for the representative days (a) 6th May, (b) 23rd June, (c) 25th July, (d) 8th August and (e) 14th September of 1999.

The diurnal variation of the vector wind for each month along with its magnitude is given in Fig. 5.7 (a - e), which is similar to figure 5.6. Generally, onset of monsoon over this station (Gadanki) is around one week after the onset of monsoon over Kerala. LLJ forms over the region along with onset of monsoon. Due
to this reason, one can expect easterly or feeble westerly winds at the surface during May, since the onset of monsoon over the station is in the early June. It is seen that in May near the surface during daytime, wind is generally westerly may be due to the local influence and the wind turns easterlies with altitude. The winds above ABL are

easterly generated by the influence of trade winds prevailing over the region before the onset of monsoon. The westerly winds in the ABL are feeble. During the month of June the entire atmosphere become under the influence of LLJ and it has a

Fig. 5.7 Diurnal variation of vector wind from LAWP for the representative days (a) 6th May, (b) 23rd June, (c) 25th July, (d) 8th August and (e) 14th September of 1999.
noticeable change as the day progress. To study the diurnal variation of the wind during different months in the summer monsoon, vector wind in the lowest 3 km for a representative day in June, July, August and September are considered. Fig. 5.6 from b to e represent diurnal variation on these days. In monsoon months other than September, the wind pattern is more or less similar in nature but the difference is only in magnitude. It is found that the diurnal variation in wind strength is seen in all non rainy days, irrespective of the monsoon epochs, viz: active or weak phases of southwest monsoon. The wind direction in the ABL is almost westerly but the direction turns clockwise slightly with height indicating veering. In the month of September the wind is feeble indicating weakening of the southwest monsoon and the direction is also fluctuating with time. Even though the LLJ is weakened, the diurnal variation is prominent in the zonal wind component.

5.7.2 Variation of vertical wind shear

Wind shear is the sudden tearing or shearing effect encountered along the edge of a zone in which there is a violent change in wind speed or direction. It can exist in a horizontal or vertical direction and produces churning motions and consequently turbulence. Wind shear, encountered near the ground, is more serious and potentially very dangerous. One of the important reasons for generation of the low level wind shear is temperature inversion. Vertical shear is most common near the ground and can pose a serious hazard to aircrafts during take off and landing. In particular, observations suggest that a stable layer of air is unstable when the Richardson's number (the ratio of the stability over the wind shear) is less than 0.25. That is the mechanical wave production exceeds the buoyancy damping by a factor of 4. Also, the Clear Air Turbulence (CAT) is often observed in the vicinity of jet streaks, where the vertical wind shear is large. Clear Air Turbulence (CAT) is a zone of strong wind shear. Depending on wind shear, the intensity of CAT is divided into three main categories: light (L), medium (M), strong and severe (S) following Stull (1993). They are sub classified as follows
The wind shear, $s$ ($s^{-1}$) is computed from the $u$-component ($u$) and $v$-component ($v$) of the wind field obtained from the LAWP and the vertical distance, $dz$ is taken as the vertical interval of the observations in metre (150 m). The wind shear computed using the following relation

$$ s = \sqrt{\left(\frac{du}{dz}\right)^2 + \left(\frac{dv}{dz}\right)^2} \quad (5.10) $$

The diurnal variation of the wind shear for representative days during the southwest monsoon period are presented in the Fig.5.8 (a - e). The vertical wind shear values range from 0 to 0.048 $s^{-1}$. Even though the vertical interval ($dz = 150$ m) is somewhat large for the computation of vertical wind shear, the shear values obtained are reasonably well and hence the probability of CAT. Certainly, we can obtain better results if the vertical interval is less than that of the present one. The intensity of CAT is less during May and September than that during June, July and August. The wind as well as wind shear during June to August is more than the other months. Although September belongs to monsoon season, the wind strength weakens rapidly by the withdrawal of monsoon. During May and September the variation of wind direction with height is not in a regular pattern compared to the other months. During monsoon period, due to the influence of LLJ the wind direction is almost constant throughout the day. Even the intensity of the shear is low, a layer of high wind shear is found in the Entrainment Zone (EZ). The maximum shear zone is found in ABL during morning hours and it is due to the development of the convective boundary layer. The high values of shear zone in the EZ is found in almost all the
cases. During evening around 1900 hours the vertical wind shear values are almost zero, indicating that a sudden breakup of the boundary layer turbulence due to the dissipation of the CBL. On certain days, the high intensity of CAT is seen during mid-night hours and it may due to the increase of the wind strength. This increasing of wind strength may attribute to the nocturnal LLJ.

Fig. 5.8 Diurnal variation of vertical wind shear (s') for the representative days (a) 6th May, (b) 23rd June, (c) 25th July, (d) 8th August and (e) 14th September of 1999.
Generally, the intense CAT is found just below the LLJ core and it can be noticed from the figures of zonal wind and vertical wind shear. During the period of study the CAT ranges from 0 to 0.41 s⁻¹, 0.039 s⁻¹, 0.036 s⁻¹, 0.037 s⁻¹ and 0.5 s⁻¹ on 6th May, 23rd June, 25th July, 8th August and 14th September respectively. The maximum intensity of CAT is in a range of medium level, so it is not much hazardous to aircrafts but is capable of generating turbulence for triggering various convective activities.

### 5.7.3 Atmospheric boundary layer depth

![Fig.5.9 Diurnal variation of signal to noise ratio (reflectivity) the representative days (a) 6th May, (b) 23rd June, (c) 25th July, (d) 8th August and (e) 14th September of 1999.](image-url)
ABL depth varies from 0.6 to 3.5 km at a particular location due to many meteorological factors prevailing over the station. One can see diurnal variation of ABL height. During day time CBL top can be treated as ABL depth. CBL height is one of the fundamental parameters in many meteorological applications. It is also very important for modeling and interpreting the dynamics and chemistry of the ABL. Unfortunately, simple parameterization of CBL height in terms of surface meteorological data is often insufficient, especially in tropical region (Reddy et al 2001). Our knowledge of the tropical ABL is to be updated with more reliable observations. Ground based remote sensing instrument such as LAWP can be used for ABL dynamics. Therefore, the observations using this instrument are useful to delineate the diurnal evolution of the ABL structure. The vertical extent of the ABL can be defined in different ways: the height where the vertical gradient of virtual potential temperature has a maximum; the cross over point of the buoyancy flux profiles (Wyngaard and Lemone, 1980); the region of enhanced radar reflectivity due to the sharp variation of the temperature and humidity (White and Fairall 1991).

The diurnal variation of the height time intensity plot of signal to noise ratio (SNR) is presented in Fig.5.9. The SNR is determined by the reflectivity turbulence seen by the LAWP, which depends on the strength of the mechanical turbulence and the background refractive index gradient (Gage 1990). The convective boundary layer top can be identified on the figure as the level at which sign of SNR change. During southwest monsoon season, the signal is almost captured by the LAWP to identify the ABL height. The diurnal evolution of the ABL is depicted in figure 5.9 from a to e. On a diurnal basis, the boundary layer height starts to grow from around 0800 hours in the morning and dissipate after sun set. The height of the ABL during daytime in May is almost 3 km. But during the southwest monsoon season the ABL height is small compared to that in May. The maximum reflectivity is seen just below LLJ core in the months of June, July and August. During early morning hours the reflectivity maximum is found around 1.5 km and CBL gets deepened as the day progresses. Due to the activity of the CBL, thermals are intensified and they transport surface properties upward and upper air properties to surface. Fig.5.10 shows the time-height plot of the vertical wind from the LAWP.
Fig. 5.10 Diurnal variation of vertical wind (ms$^{-1}$) from LAWP for the representative days (a) 6th May, (b) 23rd June, (c) 25th July, (d) 8th August and (e) 14th September of 1999.

during the above periods. The vertical wind shows sinking motion during most of the daytime, indicating transport of momentum from LLJ to surface. In the entire CBL the vertical wind shows sinking motion during most of the days, indicating transport of momentum from upper level to surface. The intensity of the downward component is high in the lower layers between noon to around 1600 hours. The structure is different from day to day. In most of the cases, the vertical wind in the upper levels show upward movement from the core of the LLJ.
5.8 Variation of LLJ during active and weak phases

The active and weak phases of southwest monsoon is a northward propagating component of Intra Seasonal Oscillation (Yasunari, 1979, 1981; Sikka and Gadgil, 1980; Krishnamurthy and Subramanyam, 1982). The wind strength during active and weak phases has shown significant changes. The diurnal evolution of LLJ is studied using LAWP and NCEP/NCAR reanalysis data set. The time series plot of area averaged (10° N - 20° N & 70° E - 80° E) zonal wind at 850 hPa during monsoon season is given in Fig.5.11 to identify the variation in wind speed and to identify the days of active and weak phases. Zonal wind structure during active days (16th July to 20th July, 5 days) and weak days (12th August to 15th August, 4 days) of the year 1999 are seen in the Fig.5.12a and Fig.5.12b respectively. From the graph we can see that the LLJ wind strength during active monsoon period is more than 22 ms⁻¹ and while during weak phases the maximum value is only about 18 ms⁻¹. Other than this variation, both of these phases have significant diurnal variation. During active phase of southwest monsoon the wind strength maximum found after mid night to early morning hours and this significant high value may be due to the modulation with the nocturnal LLJ. During the daytime the wind core strength is found to decrease and
the depth of the LLJ core is found in a higher level due to the development of the CBL. In the surface layers during active phases the wind strength is almost 5 ms$^{-1}$ but during weak phases in certain occasions the wind strength is less and perhaps the direction is found to be easterly. The core of LLJ during active phases is around 1.8 km in early morning hours and during weak it is about 1.2 km height.
Fig. 5.13 Height – time plot of the zonal wind (ms⁻¹) during active and weak phase of southwest monsoon from NCEP/NCAR reanalysis data set.

Similar features are further studied using NCEP/NCAR reanalysis: 4 times instantaneous observation of daily data set during the same period (Fig. 5.11a and Fig. 5.11b). The figure closely resembles that of the LAWP results, confirming the earlier results. The NCEP data set has a spatial resolution of 2.5° x 2.5° latitude-longitude grid. To capture the signal at the site, we selected an area over a small region (12.5° N - 15° N & 77.5° E - 80° E) to take average wind with height during active and weak phases. From the figure, clear diurnal variation is noticed during both the phases. The wind strength during active days is more than that of the weak phases but the strength of wind is lower in the case of NCEP analysis during both active and weak phases. The reduced magnitude of the LLJ core in the NCEP
analysis can be attributed to the averaging effect. The maximum wind strength during active period is more than 15 ms$^{-1}$ and the maximum wind speed during weak phase is around 9 ms$^{-1}$. The maximum wind strength is found during early morning hours as in the case of LAWP analysis in both active and weak phases.