CHAPTER VI

Features of Nocturnal Low Level Jet (NLLJ) from high-resolution Doppler wind lidar measurements

6.1 Introduction

Low level jet (LLJ) is an important lower atmospheric phenomenon which is observed frequently in horizontal wind profiles in various regions of the world. Many in literature (e.g., Li and Chen, 1998) describe a LLJ as any low level wind maximum while some (Bonner, 1968) define it on the basis of shear and threshold wind maximum values. It is now recognized that this LLJ plays a crucial role in moisture transport and associated storm development (Frisch et al., 1992). At nighttime under clear-sky conditions and weak synoptic winds, a wind maximum close to the ground (few hundred meters above the surface) exists, which is often referred to as nocturnal low level jet (NLLJ). It disappears as day time progresses because of the enhanced vertical mixing, generated by surface warming. LLJ has an important role in generation of shear which often acts as a source of generation of turbulence in the nighttime boundary layer (Mahrt et al., 1979; Lenschow et al., 1988; Smedman et al., 1993; Mahrt, 1999; Mahrt and Vickers, 2002; Banta et al., 2002; 2003). According to Andreas et al. (2000) NLLJ can be broadly defined as a maximum in the wind speed profile that is at least 2 ms$^{-1}$ faster than wind speeds above and below the maxima. Further, this wind speed maximum should be below 1500 m altitude.

Several theories have been proposed to explain the mechanism behind the NLLJ formation. Blackader (1957) proposed that low level jet occurs as a result of inertial oscillation. After sunset, stable stratification begins to develop, turbulence dies out in the layer and the upper part of daytime mixed layer becomes decoupled from the surface in the layer where frictional force will be negligible. Coriolis force will induce an oscillation in wind vector around the geostrophic wind producing a supergeostrophic wind during the night hours. Using a two layer bulk model, Thorpe and Guymer (1977)
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quantified the inertial oscillation hypothesis. Using this model, Andreas et al. (2000) explained the properties of LLJ forming over the Antarctic Weddel Sea. Some other studies mentioned that the presence and properties of LLJ mainly depend on the geographic location and terrain characteristics. Holton (1967) showed that differential heating and cooling of the terrain is important in the formation of LLJ. Barrier jet, which forms as a result of geostrophic adjustment when stable air is advected against an elongated topographic ridge (Parish, 1983), is another example of LLJ. Yet another interesting example of LLJ is that observed over the coastal regions, which usually forms due to large land-sea temperature gradients (Zemba and Friehe, 1987). Beardsley et al. (1987) reported that the series of coastal points and capes along the California coast lead to significant acceleration of the flows in the lower atmosphere. Influence of local terrain on wind profile was discussed by Wintant et al. (1988). Katabatic flows can also cause LLJ (King and Turner, 1997). Some of the LLJ formations are the result of secondary circulation associated with an upper tropospheric jet as suggested by Uccellini and Johnson (1979) and Brill et al. (1985).

Many studies were focused on the climatological characteristics of NLLJ. Bonner (1968) showed that boundary layer jets are more frequent over the Great Plains, USA. A detailed study of NLLJ over north-central Oklahoma was provided by Whiteman et al. (1997). Song et al. (2005) used an extensive data set over Kansas, USA and found that the jet frequency is 63% of the nocturnal period. By using a combination of wind profilers and model, Zhong et al. (2006) have described the warm season NLLJ features over the mid Atlantic states in USA. NLLJ features over Ottawa, Southeastern Canada were studied by Mathieu et al. (2005). Karipot et al. (2009) investigated the characteristic features of NLLJ and its influence on the CO$_2$ fluxes over North Florida area. Bass et al. (2008) studied the climatological features of NLLJ over Cabauw, the Netherlands and showed that moderate geostrophic forcing and high radiative cooling are the favorable condition for the NLLJ occurrence.

Studies of NLLJ characteristics over the Indian monsoon region are few. By using Sodar data and ARW model results, Prabha et al. (2011) described the NLLJ formation on the leeward side of Western Ghats in the southern peninsular India. They pointed out that NLLJ exists during the pre-monsoon time (March – May) and is typically
located around a height range of 600 - 800 m. By using Sodar observations over Pune, India, Murthy et al. (2013) have analyzed the characteristic features of NLLJ during the monsoon months (June - September) and have mentioned that the existence of NLLJ over this region is due to its interaction with the Monsoon Low Level Jet (MLLJ) which is typically located at around 1500 – 2500 m. However, a detailed analysis of NLLJ like its occurrence frequency, seasonal features and relationship with meteorological conditions over the tropical Indian region is not available. The characteristic features of NLLJ occurring over Pune (18°32’N, 73°51’E, 559 m Above Mean Sea Level), India have been investigated in this chapter using high resolution Doppler wind lidar measurements. Attempt is also made here to discuss certain meteorological factors that possibly influence the NLLJ formation and sustenance during nighttime and its seasonal variability.

6.2 Data and Methodology

Altitude profiles of horizontal and vertical winds obtained using the Doppler wind lidar described in Chapter II are used for the analysis. High resolution wind measurements made over Pune during the two year period from 1 April 2012 to 31 March 2014 have been used here. Horizontal wind (speed and direction) profiles averaged (online) over 5-min intervals in the altitude range 100 m to 3000 m (59 altitudes at 50 m height interval), above surface during local nighttime, have been considered. During nighttime, as the concentration of light scatterers (usually aerosols) is relatively less, data with significant signal-to-noise ratio on a continuous basis is available below 3000 m only. Moreover as the feature being studied (nocturnal low level jet) occurs invariably below 1500 m, data in the altitude range 100 m to 3000 m seems adequate for the study. The nocturnal period considered for the analysis is between 2200 and 0600 hours IST (UTC+05.30). Thus the lidar data comprising of over 62,500 vertical profiles each of wind speed and direction obtained on about 687 nights during the above two year period have been included for the analysis.

To define the term ‘Low Level Jet’, an objective criterion has been adopted. Any peak/maximum in the horizontal wind speed vertical profile below 1200 m is taken as a LLJ if the wind speed both above and below the height of this wind maximum is lesser
by 1 ms\(^{-1}\) in the nearest 200 meter height range. This criterion is different from that used by Karipot et al. (2009) and Andreas et al. (2000) and also different from Bonner (1968) and Whiteman et al. (1997), who used wind shear criteria in addition to wind speed criteria. The main reason for the choice of the criteria adopted here is that it ensures non-elimination many low level jets. For the purpose of retrieving NLLJ characteristics, hourly averaged profiles of horizontal wind are computed from the 5 min interval online recorded data. Firstly LLJ during nighttime satisfying the above criteria are identified in all the hourly averaged profiles in the 2-year data. It is observed that LLJ are present overall in ~ 42% of the nocturnal period, mainly because of the very low frequency of occurrence of NLLJ during monsoon season. From these nocturnal profiles showing the presence of NLLJ, its characteristics such as jet speed (wind speed at the peak, ms\(^{-1}\)), jet core height (height above surface level at which this peak occurs, m) and wind direction (degrees) in horizontal wind at the peak are picked up for further study. Monthly and seasonal mean jet core height, jet speed and direction for the 2 year period from 1 April 2012 to 31 March 2014 are computed and presented. Further, monthly and seasonal frequency distributions of these parameters are also obtained from the above data and discussed here.

To explain the physical mechanism behind the LLJ formation, the gridded data sets of ERA (ECMWF Re-Analysis) and MERRA (Modern Era Retrospective-Analysis for Research and Applications) for the above 2 year period, have been used in the study. Multi-level air temperature data were taken from ERA-interim data set at 0.75° X 0.75° resolution (http://apps.ecmwf.int/datasets/). ERA-interim provides data four times daily (at 0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC). Surface temperature and total cloud fraction data were taken from the MERRA-reanalysis, NASA site (http://gmao.gsfc.nasa.gov/research/merra/intro.php), which gives hourly data at 1° X 1° resolution. In order to study the relationship of turbulence in the surface layers with NLLJ, Turbulence Intensity (TI) parameter is calculated from the 5-min average wind lidar data by using the following formulae

\[
TI = \frac{\sigma_V}{V_{mean}}
\]
Where $\sigma_V$ represents the standard deviation of the horizontal wind speed, and $V_{\text{mean}}$ designates the mean horizontal wind speed. Some features of NLLJ occurring over the tropical Indian station are presented and discussed in the following Section.

6.3 Results and Discussion

6.3.1 Time-height variation of horizontal wind during nighttime

Vertical profiles of horizontal wind speed obtained at 5 min interval from the Doppler wind lidar during nighttime (2200 to 0600 hours Local Time) in the altitude range 100 m to 3000 m, are taken and time-height contour plots are prepared to visualize the occurrence and vertical structure of the nocturnal low level jet. Figures 6.1a, 6.1b, and 6.1c show the time-height variation of horizontal winds during typical pre-monsoon (01 May 2012), post-monsoon (22 October 2012) and winter (05 December 2012) conditions. It can be seen that in all the three cases, there exists a well defined narrow region of strong wind speeds between 100 m and 1000 m altitude. On 01 May significant wind information is available only up to 2100 m altitude (Fig. 6.1a).

![Figure 6.1a](image)

**Figure 6.1a:** Time-height variation of lidar-derived horizontal winds during nighttime on a typical pre-monsoon day (01 May 2012)

The NLLJ core region is narrow and lies centered around 550 m above surface right from local midnight hours (0000 hrs) with wind speeds $> 10$ ms$^{-1}$. Wind speeds
increase in the post-midnight hours, with occasional core speeds in the range of 12 ms\(^{-1}\). On 22 October the jet core is relatively broader and also lies centered at slightly upper height (around 700 – 800 m). The post-midnight jet speeds on this day exceed 16 ms\(^{-1}\). Further it can be seen that wind information is available up to 2500 m throughout the nighttime. Winter nights over the Pune region are generally characterized by clear skies and stable lower atmospheric conditions. Also the atmosphere in the layers close to surface consists of less aerosol (dust) concentrations. This is the reason that on 05 December 2012 (Fig. 6.1c) significant wind data is available up to only 1600 m during nighttime. The NLLJ core is at very low level (~ 500m above surface). Jet core is strong in the hours immediately after midnight with jet speeds exceeding 13 ms\(^{-1}\).

To show the typical vertical structure of horizontal wind obtained with the above wind lidar, hourly averaged wind profiles during nighttime (2200 hrs to 0600 hrs LT) on 28 September 2012 are shown plotted in Figure 6.2 in the height range 100 m and 3000 m. Though the maximum nocturnal wind speeds in the hourly averaged profiles on this day do not seem to exceed 9 ms\(^{-1}\), the instantaneous or 5-min interval profiles show higher magnitude at times. All the vertical profiles here show a distinct peak/maximum between 500 m and 1000 m above surface level which is being referred to as the nocturnal low level jet in the study. Also this low level wind maximum is present throughout the nighttime on this day, as is the case on most of the days whenever NLLJ was present in the two year period. The NLLJ on this day is relatively narrower in width with higher jet speeds occurring in the post-midnight hours.

Thus LLJ during nighttime satisfying the above mentioned criteria are identified in all the available hourly averaged profiles during the 2-year period. It is observed that over this station, NLLJ occurs more frequently during pre-monsoon season (~66% of the nocturnal period) and moderately during winter (52%) and post-monsoon (49%) seasons. On the other hand, jets are present on only 14% of the nocturnal periods during the wet monsoon season. Studying the characteristics of NLLJ over North Florida area in USA using sodar measurements, Karipot *et al.* (2009) observed that jets are present overall in 62% of the nocturnal period, more frequently (70%) during colder months of November-February and lesser (~ 47%) in warmer months of June-August.
Figure 6.1b: Time-height variation of lidar-derived horizontal winds during nighttime on a typical post-monsoon day (22 October 2012)

Figure 6.1c: Time-height variation of lidar-derived horizontal winds during nighttime on a typical winter day (05 December 2012)
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Figure 6.2: Hourly averaged lidar-derived horizontal wind profiles during nighttime on 28 September 2012

6.3.2 Seasonal and monthly mean jet core height and jet speed

From those nocturnal wind profiles showing the presence of the jet, the NLLJ characteristics namely, the jet core height and jet speed are retrieved to study the seasonal mean variations and frequency of occurrence. Also the wind direction at the jet core height level is noted down in each case. As most of the lower atmospheric phenomena in the Indian monsoon region show a significant seasonal variation, seasonal means of jet core height, jet speed and wind direction at the jet core level are obtained for the four seasons along with the standard deviations, which are shown in Table 6.1. Mean jet core height values are higher during pre-monsoon (687 m) and monsoon months (691 m) than those during post-monsoon (593 m) and winter (586 m) months by almost 100 m. Thus NLLJ seems to be at its lowest height during winter over the Pune station. However, the variability in jet core height is relatively higher during winter months (Coefficient of Variability ~ 38%) and is least in pre-monsoon months (C.V. ~ 28%). Mean jet core speeds are stronger by 2 - 3 m s⁻¹ during pre-monsoon and monsoon months compared to
those during winter. Horizontal wind direction at the jet core level is predominantly westerly/north westerly in pre-monsoon, westerly/south westerly in monsoon and broadly south easterly during post-monsoon and winter.

<table>
<thead>
<tr>
<th>Season</th>
<th>Jet Core Height (m)</th>
<th>Jet Speed (ms⁻¹)</th>
<th>Jet Direction (degrees)</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>Pre-monsoon</td>
<td>687.0</td>
<td>190.4</td>
<td>9.6</td>
</tr>
<tr>
<td>Monsoon</td>
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<tr>
<td>Post-monsoon</td>
<td>593.4</td>
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<td>7.9</td>
</tr>
<tr>
<td>Winter</td>
<td>585.6</td>
<td>221.4</td>
<td>7.3</td>
</tr>
</tbody>
</table>

**Table 6.1:** Seasonal mean and standard deviation of jet core height, jet speed and wind direction in the NLLJ core for two year period 1 April 2012 to 31 March 2014

Wind rose patterns of horizontal winds at jet core level only during days of occurrence of NLLJ in the 2-year period for the four seasons are shown in Figure 6.3. It shows that the horizontal wind directions in the jet core are consistent with the seasonal variations in the large-scale wind pattern in lower atmosphere in the Indian tropical region. It is also seen that there are few occasions during the monsoon season when the hourly average jet core speeds during nighttime are as high as 15 – 20 ms⁻¹. Another observation from wind direction at jet core height (Table 6.1) is that during post-monsoon months it is highly variable (C.V. ~70%) because this season is a transitional period of conditions in the large-scale wind field from highly dynamic SW monsoon conditions to
a more stable and calmer winter conditions. Wind direction during the SW monsoon season inside the NLLJ core is consistently south westerly showing least variability (C.V. ~28%).

Figure 6.3: Horizontal wind speed and direction at jet core height for four major seasons during the period 01 April 2012 – 31 March 2014

Monthly averages of jet core height, jet speed and wind direction have also been evaluated from the 2-year data and shown in Table 6.2. Thus on a monthly mean scale, lowest jet core height (563 m) is observed during the winter month of December and maximum jet core height (736 m) is observed during August. Similarly monthly mean jet core speed is least (6.9 ms\(^{-1}\)) during the month of January and maximum speed (12.6 ms\(^{-1}\)) is observed during the month of August. Both jet core height and jet speed on a monthly mean scale show a smooth annual oscillation consistent with the broad scale seasonality of atmospheric thermal and wind field variations associated with the tropical continental environment. But the day to day variations and temporal variations within a night could be due to small-scale local factors.
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<table>
<thead>
<tr>
<th>Month</th>
<th>Jet Core Height (m)</th>
<th>Jet Speed (m/s)</th>
<th>Jet Direction (degrees)</th>
</tr>
</thead>
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<td></td>
<td>Mean</td>
<td>Std. deviation</td>
<td>Mean</td>
</tr>
<tr>
<td>January</td>
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<td>207.0</td>
<td>6.9</td>
</tr>
<tr>
<td>February</td>
<td>618.3</td>
<td>248.0</td>
<td>7.1</td>
</tr>
<tr>
<td>March</td>
<td>622.9</td>
<td>200.8</td>
<td>8.4</td>
</tr>
<tr>
<td>April</td>
<td>696.1</td>
<td>198.9</td>
<td>9.4</td>
</tr>
<tr>
<td>May</td>
<td>697.5</td>
<td>177.8</td>
<td>10.2</td>
</tr>
<tr>
<td>June</td>
<td>725.9</td>
<td>175.1</td>
<td>10.5</td>
</tr>
<tr>
<td>July</td>
<td>671.7</td>
<td>188.2</td>
<td>10.9</td>
</tr>
<tr>
<td>August</td>
<td>735.5</td>
<td>172.0</td>
<td>12.6</td>
</tr>
<tr>
<td>September</td>
<td>639.2</td>
<td>220.5</td>
<td>8.3</td>
</tr>
<tr>
<td>October</td>
<td>627.4</td>
<td>214.7</td>
<td>8.3</td>
</tr>
<tr>
<td>November</td>
<td>566.3</td>
<td>190.2</td>
<td>7.5</td>
</tr>
<tr>
<td>December</td>
<td>563.3</td>
<td>210.1</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Table 6.2: Monthly mean jet core height, jet speed and wind direction at the NLLJ peak

6.3.3 Frequency distribution of jet core height and jet speed

All the retrieved hourly values of jet core height and jet core speed during nighttime in the two year observation period (01 April 2012 to 31 March 2014) are taken and percentage frequency of occurrence of these parameters (frequency distribution) in different class intervals is evaluated. Figure 6.4a shows the frequency distribution of jet core height in 100 m class interval from 300 m to 1200 m above surface level. A normal distribution is seen but slightly skewed towards lower height side. Maximum frequency of occurrence of jet core height (~ 21 %) is in the range 600 – 700 m over Pune region.
Nearly 12% of the time, jet core heights are as low as 300 – 400 m above surface. Frequency of occurrence falls off rapidly on the higher jet core height side. Above 900 m the frequency of occurrence is \(< 5\%\). Another interesting observation is that 65% of the cases have NLLJ heights below 700 m altitude. Similarly, Figure 6.4b shows the frequency distribution of jet speed in class intervals of 2 ms\(^{-1}\) starting from 5 ms\(^{-1}\). Maximum frequency of occurrence of jet speed (~ 28%) is in the speed range 9 – 11 ms\(^{-1}\). But jet speeds in the range 7 – 9 ms\(^{-1}\) also have nearly the same percentage frequency of occurrence. About 8% of the cases show jet speeds in excess of 13 ms\(^{-1}\).

**Figure 6.4a**: Percentage frequency of occurrence of a) jet core height in 100 m class intervals from 100 m to 1200 m altitude above surface b) jet speed in 2 ms\(^{-1}\) class intervals, during the 2-year observational period
Both jet core height and jet speed data obtained from hourly averaged wind profiles is categorized into the four major seasons and frequency distributions are obtained separately. Jet core heights are divided into three broad class intervals, namely < 600 m, 600 – 900 m and > 900 m. Figure 6.5a shows the frequency distribution of jet core height in these three class intervals during monsoon, post-monsoon, winter and pre-monsoon seasons.

Figure 6.5: Season-wise percentage frequency of occurrence of a) jet core height

b) Jet speed
It is observed that frequency of occurrence of jet core heights is maximum (57% to 59%) in the mid height band (600 – 900 m) during monsoon and pre-monsoon seasons. Also during these two seasons, jet core heights > 900 m have percentage frequency of occurrence of nearly 13%. During post-monsoon and winter seasons 51% to 58% of the cases have jet core heights < 600 m and less than 10% of the cases have jet core heights > 900 m. Figure 6.5b shows the frequency distribution of NLLJ speed during the four seasons. Jet speeds are classified into three broad ranges, 5-10 m$^{-1}$, 10-15 m$^{-1}$ and >15 m$^{-1}$. During monsoon and pre-monsoon seasons, jet speeds in the range 10-15 m$^{-1}$ have higher percentage frequency of occurrence (~ 42%) compared to that in other two seasons. About 9% of the cases have jet speeds in excess of 15 m$^{-1}$ only during monsoon season. Jet speeds in the range 5-10 m$^{-1}$ have high frequency of occurrence during all the four seasons (48% - 76%). Similarly, Table 6.3 shows the monthly frequency distribution of jet core height and jet speed in the same class intervals considered for the above seasonal analysis.

6.3.4 Temporal-seasonal variations in jet core width

During each NLLJ occurring day the jet core width (m) has been estimated using an objective criterion. As in the case of jet core height, the jet core width also does not show any systematic temporal variation within a particular night. However, analysis shows that jet core width exhibits significant seasonal variation. Figure 6.6a shows the seasonal mean nighttime (2000 – 0600 hrs LT) temporal variation of jet core width. It is observed that throughout the nighttime, NLLJ was narrow in width during winter and pre-monsoon seasons. Jet core is relatively broad during monsoon season and also shows high temporal fluctuation. Monthly mean jet core widths along with the standard deviations computed from the two year observations (01 April 2012 to 31 March 2014) is given in Table 6.4. On a seasonal mean scale jet core widths are 377 m, 536 m, 426 m and 349 m during pre-monsoon, monsoon, post-monsoon and winter seasons, respectively. Thus NLLJ during winter days are relatively narrowest in width. Frequency of occurrence of jet core widths during the four seasons in 300 m class intervals is shown in Figure 6.6b. It is observed that jet widths < 300 m are most frequent during winter. During other three seasons the most frequently occurring jet core
widths are in the range 300 – 600 m. Widths > 600 occur significantly during the monsoon season.

Table 6.3: Monthly frequency distribution of jet core height (in three height ranges) and jet speed (in three speed ranges)
Figure 6.6a: Seasonal mean temporal (2000 hrs to 0600 hrs LT) variation of jet core width.

Figure 6.6b: Season-wise percentage frequency of occurrence of jet core width in 300 m class intervals
Table 6.4: Monthly mean and standard deviation of jet core width for two year period 1 April 2012 to 31 March 2014

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean</th>
<th>SD</th>
<th>Month</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>337.3</td>
<td>280.0</td>
<td>July</td>
<td>576.1</td>
<td>257.9</td>
</tr>
<tr>
<td>February</td>
<td>334.2</td>
<td>263.7</td>
<td>August</td>
<td>750.0</td>
<td>261.0</td>
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<tr>
<td>March</td>
<td>343.6</td>
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<td>September</td>
<td>503.0</td>
<td>349.1</td>
</tr>
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<td>April</td>
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<td>214.4</td>
<td>October</td>
<td>463.4</td>
<td>329.0</td>
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<tr>
<td>May</td>
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<td>292.0</td>
<td>November</td>
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<td>302.0</td>
</tr>
<tr>
<td>June</td>
<td>510.1</td>
<td>325.0</td>
<td>December</td>
<td>362.7</td>
<td>256.4</td>
</tr>
</tbody>
</table>

6.3.5 Role of horizontal temperature gradient, inertial oscillations and stable lower atmospheric conditions on NLLJ formation

One of the main mechanisms for formation of NLLJ over continental region could be the one related to horizontal temperature gradient between the valley and slopes. This can be explained well by the thermal wind relation (Holton, 1967), where the horizontal temperature gradient is related to the meridional wind component. For this purpose, the gridded ERA-interim multilevel air temperature data for the period 01 April 2012 to 31 March 2014 is considered here. Two grid points 74°E (slope) and 79°E (valley) in the east-west (zonal) direction around the Pune latitude were selected. Temperatures at 925 hPa level at four timings, 0000 UTC, 0600 UTC, 1200 UTC, 1800 UTC at the two points are taken and the east-west temperature gradient (T_{74} – T_{79}) on a daily basis is computed.
Figure 7.7 shows the monthly averaged horizontal temperature gradient at the four different timings. It is seen that at 1800 UTC (2330 hrs LT) and 0000 UTC (0530 hrs LT), which fall in the local nighttime, the temperature gradient is almost always negative in all the months, implying that temperatures are higher at the eastern point (i.e., a west-east gradient). Also this negative gradient starts increasing in magnitude from March onwards and reaches a maximum (~ 10°C) by the pre-monsoon month of May. Thus the west-east temperature gradients during pre-monsoon season are higher in magnitude compared to those during other three seasons. Such a large temperature gradient can explain the existence of NLLJ during the pre-monsoon season over the Pune location.

From thermal wind relation, temperature gradient in the zonal direction will increase the meridional component shear. This increase in meridional shear adds a northerly component to the mean flow, which leads to the formation of nocturnal LLJ which will be northwesterly in direction during pre-monsoon. Direction analysis of the NLLJ core (Figure 6.3, Table 6.1 and Table 6.2) also confirms that during pre-monsoon months predominantly northwesterly winds prevail over the station.

![Figure 6.7: Monthly mean zonal temperature gradient at 925 hPa level for four timings (0000 UTC, 0600 UTC, 1200 UTC, 1800 UTC)](image-url)
Another mechanism that is thought to be leading to the formation of NLLJ is inertial oscillation. This has been reported to be the main mechanism for the jet formation in many part of the world like Great Plains of USA (eg., Blackadar, 1957). In order to examine whether this mechanism has any role in the formation of NLLJ over the Indian tropical region, wind hodograph analysis was carried out for data on few typical days. Hourly averaged meridional and zonal winds from Doppler wind lidar observations at three heights (300 m, 500 m, and 700 m) on 1 May 2012, 22 October 2012 and 5 December 2012, typically representative of pre-monsoon, post-monsoon and winter seasons, are considered here.

![Hodograph plots for different heights](image)

**Figure 6.8a:** Hourly variation of meridional wind with zonal wind at three heights (300 m, 500 m, 700 m) during a typical pre-monsoon day (01 May 2012)
Figure 6.8b: Hourly variation of meridional wind with zonal wind at three heights (300 m, 500 m, 700 m) during a typical post-monsoon day (22 October 2012)

Figure 6.8c: Hourly variation of meridional wind with zonal wind at three heights (300 m, 500 m, 700 m) during a typical winter day (05 December 2012)
A clockwise turning of wind vector at the jet height during the night is generally suggested as evidence of the presence of inertial oscillation (Whiteman et al., 1997; Karipot et al., 2008). Not much observational evidence exists in literature for the possible formation of NLLJ through inertial oscillation. Figure 6.8a shows the hodograph analysis for the 1 May 2012 wind data at three height levels separately. Local time labels are indicated at three hour intervals and 00:00 indicates local midnight. Anti-clockwise rotation of the wind vector is observed at the level of 300 m which seems to be very atypical. At other two height levels, there is no clear turning of the wind vector with time. This implies that inertial oscillation may not be a significant factor for the formation of jet during the pre-monsoon season. Hodograph analysis for 22 October 2012 representative of post-monsoon season is shown in Figures 8.8b. It is seen that at all the three height levels, wind shows a clear clockwise rotation with time, which gives a clue that inertial oscillation may be having a role in the jet formation during this season. Similarly the analysis of 5 December 2012 wind data (Figure 8.8c) also shows the clockwise turning in 300 m and 500 m height level winds, suggesting the role of inertial oscillation. However, at 700 m level on this day a systematic rotation of wind vector is absent. Mention is made here that during December the average jet core height is around 560 m over this station.

The inertial period corresponding to the Pune latitude is 37.7 hours. In order to check the presence of inertial periodicity in winds over Pune, spectral analysis of horizontal wind data was carried out for 4 cases. Each case comprises of continuous data (time-series data), at the same three heights as above (i.e., 300 m, 500 m, and 700 m), for a period of 5 days during each season. Hourly averaged horizontal wind data from lidar has been used and the data periods selected are 1-7 May 2012, 3-8 June 2012, 3-8 October 2012 and 4-13 January 2013, which represent the four seasons pre-monsoon, monsoon, post-monsoon and winter respectively. The time-series data is subjected to spectral analysis by FFT method. The amplitude spectra at the three heights for the four cases are shown plotted in Figure 6.9. All the cases show the predominant diurnal periodicity (24 hrs) and also a hint of semi-diurnal oscillation (12 hrs). Further, most of the amplitude spectra show broad or multiple peaks in the periodicity range 30 to 50 hrs.
Figure 6.9: Amplitude spectra of horizontal wind at three heights (300 m, 500 m, 700 m) during the periods 01-07 May 2012, 03-08 June 2012, 03-08 October 2012, and 04-13 January 2013.

Figure 6.10: Percentage frequency of occurrence of surface temperature (left panel) and total cloud fraction (right panel) separately for four seasons for Pune location during the 2-year period obtained from MERRA-reanalysis data set.
In the pre-monsoon case (1-7 May 2012), no significant peak was seen around 38 hours (inertial periodicity) at any of the three height levels. Post-monsoon (3-8 October 2012) and winter (4-13 January 2013) cases show a peak with a periodicity of about 43 hrs in addition to the diurnal oscillation in all the three height levels. This suggests that in winter and post-monsoon seasons inertial oscillation may have a role in NLLJ formation. However, the observed periodicity is broad and slightly longer than the theoretically given value of ~38 hrs.

To examine surface level stability conditions during nighttime over the observational location, hourly surface temperature and total cloud fraction data for the Pune latitude/longitude grid position have been taken from the MERRA-reanalysis data sets for the same 2-year period (01 April 2012 to 31 March 2014). The data is once again grouped into the aforementioned four seasons. Percentage frequency of occurrence of surface temperatures in four 6°K wide temperature intervals (282-287°K, 288-293°K, 294-299°K, and 300-305°K) is evaluated for the four seasons and is shown in Figure 6.10 (left panel). It is observed that during pre-monsoon and monsoon seasons 85% - 95% of the time nighttime surface temperatures are in the range 294-299K. Whereas, during post-monsoon and winter seasons 45% - 62% of nighttime temperatures are in the lower range of 288-293K. Further, more than 20% of the time surface temperatures during winter are below 288K over this location. Similarly, frequency of occurrence of total cloud fraction in four intervals (0.0-0.25, 0.25-0.5, 0.5-0.75, and 0.75-1.0) over the location during the four seasons is shown in Figure 6.10 (right panel). More than 80% of the time, night skies have higher cloud fraction (0.75-1.0) during monsoon months. Cloud fraction is less during winter indicating that nighttime skies are more often clear during winter. Thus these observations indicate that during winter months and also to some extent during post-monsoon months the nighttime sky conditions facilitate more terrestrial long-wave radiation to escape freely from earth’s surface, resulting in cooler surface and atmospheric layers close to surface. So the nocturnal boundary layer (NBL) tends to be more stable during these two seasons. In order to analyze the influence of turbulence in the surface and related atmospheric layers, hourly layer-averaged turbulence intensity (TI) values are estimated from wind lidar observations of horizontal wind. Layer averaging is done between 100 m and 400 m in the vertical. Seasonal mean
temporal variations of TI are evaluated and shown in Figure 6.11. Here the data is taken from late evening hours (from 2000 hrs LT) to see the transition in turbulence characteristics from daytime to nighttime conditions.

![Layer Averaged TI](image)

**Figure 6.11**: Seasonal mean temporal variation of Turbulence Intensity during local nighttime hours

It is seen that during winter season, TI values are very low throughout nighttime and even in the later evening hours. During pre-monsoon TI value is high in the late evening hour which decreases rapidly by mid-night. Monsoon and post-monsoon months show relatively high TI values during nighttime, indicating existence of moderate turbulence in the surface layers. Thus during winter there seems to be less turbulence in the nighttime surface layers. Also because of more surface cooling, turbulence in the NBL ceases and the layer becomes more stable leading to formation of a stable boundary layer (SBL) in nocturnal winter. The SBL is reported to have a major influence in the formation of NLLJ (Blackadar, 1957; Bonner, 1968) as the air flow immediately above the SBL will accelerate to form the NLLJ.

### 6.4 Summary

Nocturnal low level jet (NLLJ) occurrence and its characteristics, such as jet speed (wind speed at the peak in altitude profile of horizontal wind), jet core height
Features of Nocturnal Low Level Jet (NLLJ) from high-resolution Doppler wind lidar measurements

(height above surface at which this peak occurs) and wind direction of horizontal wind at the peak, over Pune obtained from high resolution Doppler wind lidar during two year period (01 April 2012 – 31 March 2014) have been presented and discussed. Time-height variations of horizontal wind during nighttime on several days showed the presence of a narrow region of strong wind speeds (peak) between the surface and 1000 m altitude, which is identified as the low level jet. Observations show that this NLLJ occurs more frequently (66%) during pre-monsoon season and on only 14% of the nocturnal period during SW monsoon season. Mean jet core height values are higher during pre-monsoon (687 m) and monsoon months (691 m) than those during post-monsoon (593 m) and winter (586 m) months. Variability in jet core height is relatively higher during winter months. Jet core speeds, on seasonal mean scale, are stronger by almost 2 - 3 ms\(^{-1}\) during pre-monsoon and monsoon compared to those during winter. There are some occasions during monsoon season when hourly mean jet speeds during nighttime are as high as 15 - 20 ms\(^{-1}\). Horizontal wind directions in the NLLJ during different seasons are consistent with the seasonal large-scale wind patterns (mean flow) over the tropical Indian region. Most frequently occurring jet core height over the Pune station is in the range 600 – 700 m and almost 65% of the cases have jet core heights below 700 m. Similarly, maximum frequency of occurrence of jet speeds is in the range 9 - 11 ms\(^{-1}\). As in the case of jet core height, the jet core width also does not show any systematic temporal variation within a particular night but exhibits a significant seasonal variation. Throughout the nighttime, NLLJ is narrow in width during winter and pre-monsoon seasons. Jet core is relatively broad during monsoon season and also shows high temporal fluctuation. It is observed that jet widths < 300 m are most frequent during winter. Observed large west-east (zonal) temperature gradient at 925 hPa level may be associated with the occurrence of NLLJ during pre-monsoon season over Pune. Wind hodograph analysis shows that during pre-monsoon and to some extent during winter, nocturnal winds show a clockwise rotation with time, suggesting the role of inertial oscillations in NLLJ formation. Stable lower atmospheric conditions, weak turbulence and cloud free skies in nocturnal winters could play significant role in the formation and sustenance of NLLJ during winter season at this location.