Journal of Atmospheric and Solar-Terrestrial Physics 123 (2015) 113–123

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Features of nocturnal low level jet (NLLJ) observed over a tropical Indian station using high resolution Doppler wind lidar

R.D. Ruchith, P. Ernest Raj *,[1]

Indian Institute of Tropical Meteorology, Pune 411008, India

ARTICLE INFO

Article history:
Received 1 November 2014
Received in revised form
31 December 2014
Accepted 3 January 2015
Available online 6 January 2015

Keywords:
Nocturnal low level jet
Doppler wind lidar
Jet core height
Jet speed

ABSTRACT

High resolution Doppler wind lidar measurements made during the period 01 April 2012 to 31 March 2014 over Pune (18°32′N, 73°51′E, 559 m Above Mean Sea Level), India have been used to study Nocturnal Low Level Jet (NLLJ) occurrence and its characteristics. Vertical profiles of horizontal wind in the altitude range from 100 m to 3000 m (at every 50 m interval) and averaged over 5 min have been used to study time–height variations during local nighttime. On several occasions during nighttime the wind profiles showed a narrow region of strong wind speed below 1000 m altitude from surface, suggesting the presence of the low level jet. Analysis of the data indicates that NLLJ occurs more frequently (~66%) during pre-monsoon season (March–May) and on only 14% of the nocturnal period during SW monsoon season (June-September). Mean jet core heights during pre-monsoon, monsoon, post-monsoon (October–November), and winter (December–February) seasons are found to be 687 m, 691 m, 593 m, and 586 m respectively. Seasonal mean jet core speeds during pre-monsoon and monsoon are higher than 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 mean flow over the tropical Indian region. Most frequently occurring jet core height is in the height range 600–700 m with almost 65% of the cases having jet core heights < 700 m and maximum frequency of occurrence of jet speed is in the range 9–11 ms^{-1}. Large east–west temperature gradients, inertial oscillations, stability in the lower atmosphere seem to be some of the factors that play significant role in the formation and sustenance of NLLJ over the location during different seasons.

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 Vickeres (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. Blackadar (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) quantified the inertial oscillation hypothesis. Using this model, Andreas et al. (2000) explained the properties of LLJ

* Corresponding author.
E-mail address: ernestrajp@gmail.com (P. Ernest Raj).
[1] B-8 Mont Vert-2, Pashan-Sus Road, Pune 411021, India.

http://dx.doi.org/10.1016/j.jastp.2015.01.001
1364-6826/

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 Winant 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. (1996) 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. Baas 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. The importance of thermal wind processes in the formation of NLLJ is also discussed in this paper. 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. Recently, Ruchith et al. (2014a) from Doppler wind lidar measurements during Indian monsoon season pointed out that the NLLJ evolves into the daytime MLLJ by moving from lower altitudes to above 1500 m and Ruchith et al. (2014b) discussed the role of surface and boundary layer processes in such temporal evolution. 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. This paper investigates the characteristic features of NLLJ occurring over Pune (18°32′N, 73°51′E, 559 m Above Mean Sea Level), India 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.

2. Data and methodology

Some morphological features of NLLJ observed using a Doppler wind lidar operated at Pune, India are presented here and explained on the basis of surface/lower atmospheric processes. Pune is a typical continental tropical Indian station located about 200 km inland to the east of the Arabian Sea coast and on the lee side of the Western Ghats (mountain ranges). This station is under the influence of westerly/south westerly winds during the southwest monsoon months (June–September) and during the other months, especially in winter (December–February) surface level winds are predominantly easterly/south easterly. South westerly winds blowing from the marine region (Arabian Sea) during monsoon season have a strong westerly component over the Indian continental region and they bring in moisture laden air masses/clouds which results in rainfall over land. Hot summer conditions with stronger surface winds prevail during pre-monsoon season (March–May) over the region. The post-monsoon season (October–November) is of shorter duration when there is a transition from wet/humid monsoon conditions to dry, relatively colder and calm winter conditions. Thus surface temperatures, atmospheric conditions including winds at the surface as well as in the troposphere vary systematically from one season to the other and hence reflect on the seasonal variability of most of the lower atmospheric phenomena through physical and dynamical processes.

Altitude profiles of horizontal and vertical winds were obtained using a Doppler wind lidar (model WindCube-200, Leosphere, France). Such wind lidars have been used in recent times for studying the LLJ-boundary layer interaction (Banta et al., 2003; Wang et al., 2006). WindCube-200 put into operation at Pune is capable of retrieving the 3D components of the wind (east–west, north–south, vertical) in the lower troposphere (from 100 m to around 6000 m above surface level) at every 50 m height interval. The measurement hypothesis of this lidar is that, it uses aerosols as 'tracers', basically assuming that the movement of aerosols is along with the wind. The moving aerosols induce a Doppler shift of frequency which is used to compute the radial velocity of wind. The lidar operates in near-IR wavelength (1.54 μm), and its pulse energy is 100 μJ, scanning cone angle is $\sim 15°$, giving speed and direction accuracy of 0.5 ms^{-1} and 1.5° respectively. A prism in the transmitter optics deflects the laser beam into the atmosphere at an angle of 15° from the vertical. The prism holds still while the lidar sends a stream of pulses (typically 36,000) in a given direction, recording the backscatter in a number of range gates (fixed time delays) triggered by the end of each pulse. Having sent the set number of pulses, the prism rotates to the next azimuth angle to be scanned, each separated by 90°. A full rotation of 360° takes about 50 s and measurements are made in the four cardinal directions starting from North. During the rotation and before the next stream of pulses can be sent, the recorded data are processed. The system is first aligned in the geographical north–south direction. At each direction step (i.e., north, east, south, west), the WindCube-200 combines the four most recent radial speeds recorded at each height to compute the three wind components (u-zonal, v-meridional, w-vertical wind velocities). The zonal and meridional wind components are then used to compute online the horizontal wind speed and direction at all heights. Some more details of the WindCube-200 system and an intercomparison of wind profiles obtained simultaneously with co-located wind lidar and GPS radiosonde are provided recently by Ruchith et al. (2014c). This study showed rms deviation of 1.0–1.6 ms^{-1} in wind speed and 20°–45° in wind direction. The bias and spread in both wind speed and direction have been computed and discussed in the above paper. The inter-comparison of wind profiles obtained by the two independent techniques is very good under conditions of low to moderate wind speeds but showed slight deviation when wind speeds are large mainly due the drift of the radiosonde balloon away from the lidar location. Several earlier studies also showed that winds in the lower atmosphere derived from similar

Doppler wind lidars have good agreement with the wind data obtained simultaneously from other standard wind measuring techniques (e.g., Friedrich et al., 2012; Matthew et al., 2012).

High resolution wind measurements made over Pune during the two year period from 1 April 2012 to 31 March 2014 have been used in this study. Horizontal wind (speed and direction) profiles averaged (online) over 5-min intervals in the altitude range from 100 m to 3000 m (59 altitudes at 50 m height interval), above surface during local nighttime, have been used for the current analysis. 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 this study. The nocturnal period considered for the analysis is between 2200 and 0600 h 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 considered here for analysis and discussion.

To define the term 'Low Level Jet', an objective criterion has been adopted by the authors. 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 m height range. This criterion is different from that used by 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. 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.

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 $0.75° \times 0.75°$ 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 $1° \times 1°$ 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:

$$TI = \sigma_V / V_{mean}$$

where σ_V represents the standard deviation of the horizontal wind speed, and V_{mean} designates the mean horizontal wind speed.

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. Further, monthly and seasonal frequency distributions of these parameters are also obtained from the above data. Thus the results on features of NLLJ occurring over the tropical Indian station are presented and discussed in the following Section.

3. Results and discussion

Vertical profiles of horizontal wind speed obtained at 5 min interval from the Doppler wind lidar during nighttime (2200 to 0600 h Local Time) in the altitude range from 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. Fig. 1a–c shows 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 upto 2100 m altitude (Fig. 1a). The NLLJ core region is narrow and lies centered around 550 m above surface right from local midnight hours (0000 h) with wind speeds $> 10\ ms^{-1}$. Wind speeds increase in the post-midnight hours, with core speeds reaching as high as 12–13 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. 1c) significant wind data is available up to only 1600 m during nighttime. The NLLJ core is at very low level (~500 m 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 (2200–0600 h LT) on 28 September 2012 are shown plotted in Fig. 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. Thus 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 such 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.

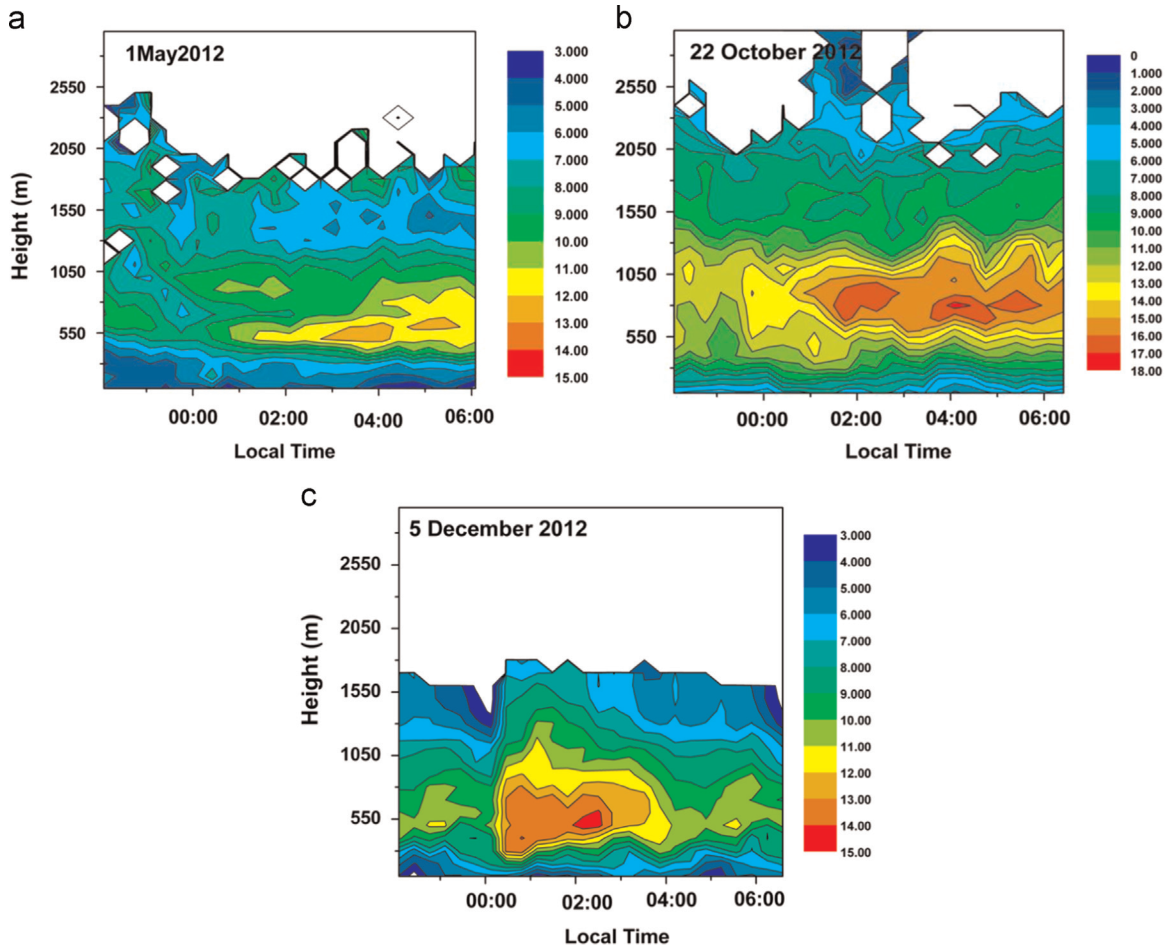

Fig. 1. (a) Time–height variation of lidar-derived horizontal winds during nighttime on a typical pre-monsoon day (01 May 2012). (b) Time–height variation of lidar-derived horizontal winds during nighttime on a typical post-monsoon day (22 October 2012). (c) Time–height variation of lidar-derived horizontal winds during nighttime on a typical winter day (05 December 2012).

3.1. *Seasonal variation of jet CORE height and jet speed*

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 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 ms^{-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. 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 Fig. 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 1) is that during post-monsoon months it is highly variable (C.V. ~70%). The main reason could be that this short two-month period is a transition phase for 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%). Monthly averages of jet core height, jet speed and wind direction have also been evaluated from the 2-year data and shown in Table 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 in these parameters could be due to small-scale local factors. Jet core height as well as jet core width do not show any systematic temporal variation within a particular night. However, analysis shows that jet core width also exhibits seasonal variation, with relatively narrow jet core during winter and pre-monsoon seasons and broader jet core during monsoon season.

3.2. *Percentage frequency of occurrence*

All the retrieved hourly values of jet core height and jet core

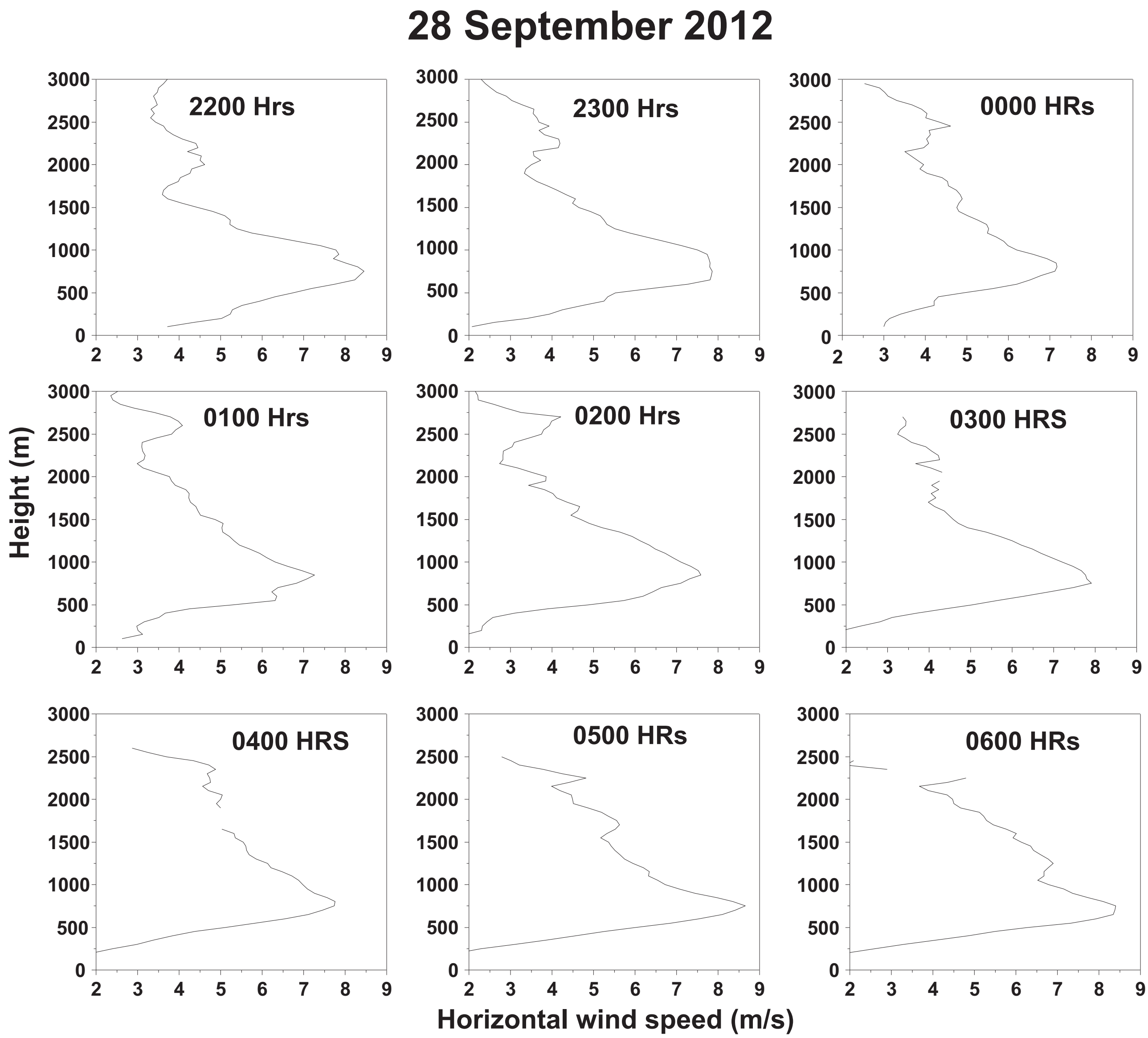

Fig. 2. Hourly averaged lidar-derived horizontal wind profiles during nighttime on 28 September 2012.

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

Season	Jet core height (m)		Jet speed (ms^{-1})		Jet direction (deg)	
	Mean	Std. deviation	Mean	Std. deviation	Mean	Std. deviation
Pre-monsoon	687.0	190.4	9.6	2.2	283	88
Monsoon	690.8	197.2	9.9	3.3	248	70
Post-monsoon	593.4	202.7	7.9	3.0	144	100
Winter	585.6	221.4	7.3	2.7	168	94

speed during nighttime in the two year observation period (01 April 2012–31 March 2014) are taken and percentage frequency of occurrence of these parameters (frequency distribution) in different class intervals is evaluated. Fig. 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 height 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 $\leq 5\%$. Another interesting observation is that 65% of the cases have NLLJ heights below 700 m altitude. Similarly, Fig. 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}.

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. Fig. 5a shows the frequency distribution of jet core height in these three class intervals during monsoon, post-monsoon, winter and pre-monsoon seasons. It is observed that frequency of occurrence of jet core heights is maximum (57–59%) 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

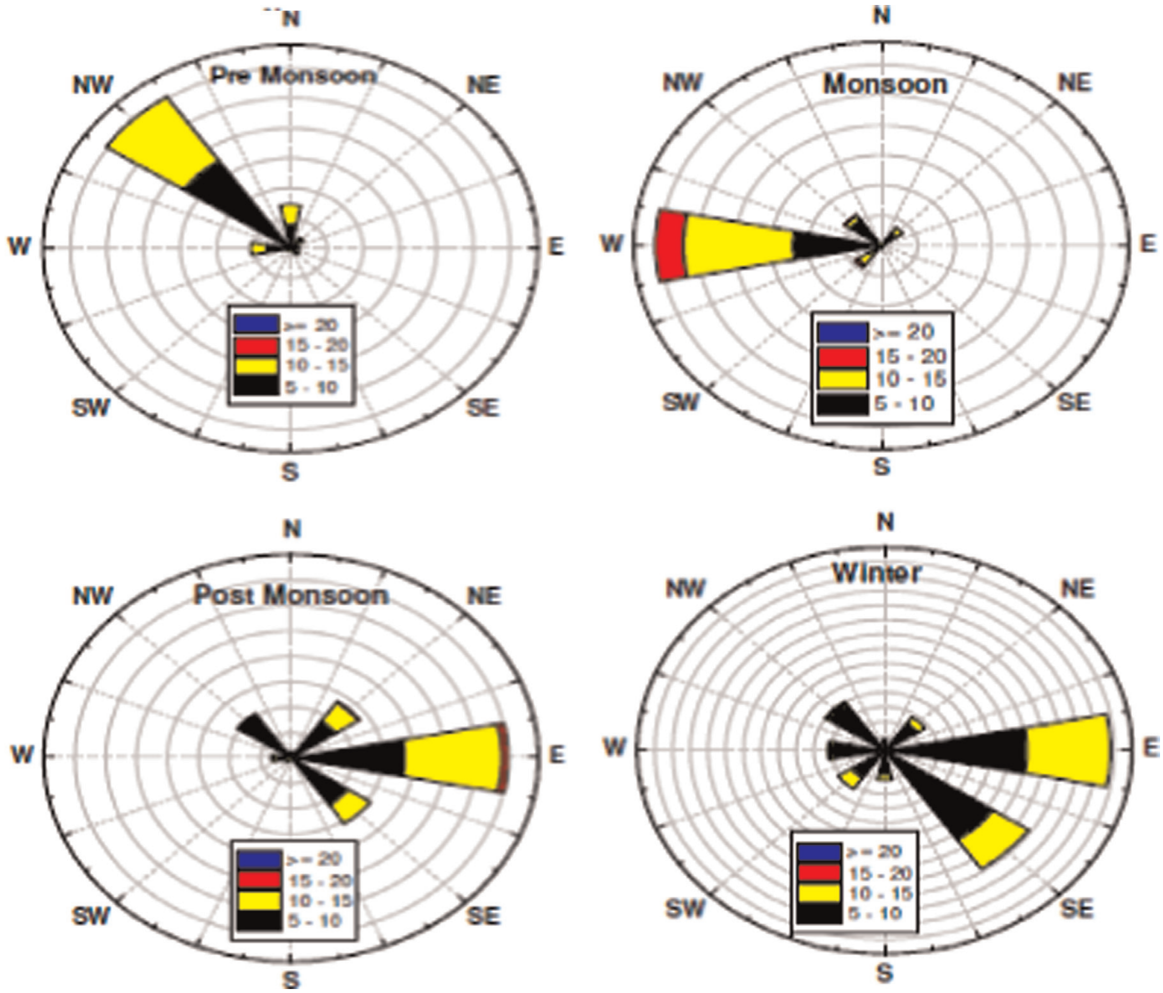

Fig. 3. Horizontal wind speed and direction at jet core height for four major seasons during the period 01 April 2012–31 March 2014.

Table 2
Monthly mean jet core height, jet speed and wind direction at the NLLJ peak.

Month	Jet core height (m)		Jet speed (ms^{-1})		Jet direction (deg)	
	Mean	Std. deviation	Mean	Std. deviation	Mean	Std. deviation
January	578.1	207.0	6.9	2.6	169	86.6
February	618.3	248.0	7.1	2.6	198	107.5
March	622.9	200.8	8.4	2.6	217	118.7
April	696.1	198.9	9.4	2.1	286	88.3
May	697.5	177.8	10.2	2.0	300	66.9
June	725.9	175.1	10.5	3.0	260	36.7
July	671.7	188.2	10.9	4.0	253	49.4
August	735.5	172.0	12.6	2.9	270	10.9
September	639.2	220.5	8.3	2.9	225	101.7
October	627.4	214.7	8.3	3.1	151	105.6
November	566.3	190.2	7.5	2.9	140	96.3
December	563.3	210.1	7.8	2.8	138	76.2

occurrence of nearly 13%. During post-monsoon and winter seasons 51–58% of the cases have jet core heights < 600 m and less than 10% of the cases have jet core heights > 900 m. Fig. 5b shows the frequency distribution of NLLJ speed during the four seasons. Jet speeds are classified into three broad ranges, 5–10 ms^{-1}, 10–15 ms^{-1} and > 15 ms^{-1}. During monsoon and pre-monsoon seasons, jet speeds in the range 10–15 ms^{-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 ms^{-1} only during monsoon season. Jet speeds in the range 5–10 ms^{-1} have the highest frequency of occurrence during all the four seasons (48–76%).

3.3. *Possible mechanisms for formation of NLLJ*

Several forcing mechanisms have been proposed for the formation of NLLJ over the Great Plains (Wu and Sethu, 1998) and Rocky Mountains (Zaitao Pan and Arritt, 2003) including inertial oscillation, baroclinicity over sloping terrain, thermal gradient because of the sloping terrain and the horizontal synoptic pressure gradient. Uccellini (1980) mentioned that terrain effects can increase the magnitude of the low level jet. One of the important 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 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 2012–31 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. Fig. 6 shows the monthly averaged horizontal temperature gradient at the four different timings. It is seen that at 1800 UTC (2330 h LT) and 0000 UTC (0530 h LT), which fall in the local nighttime, the temperature

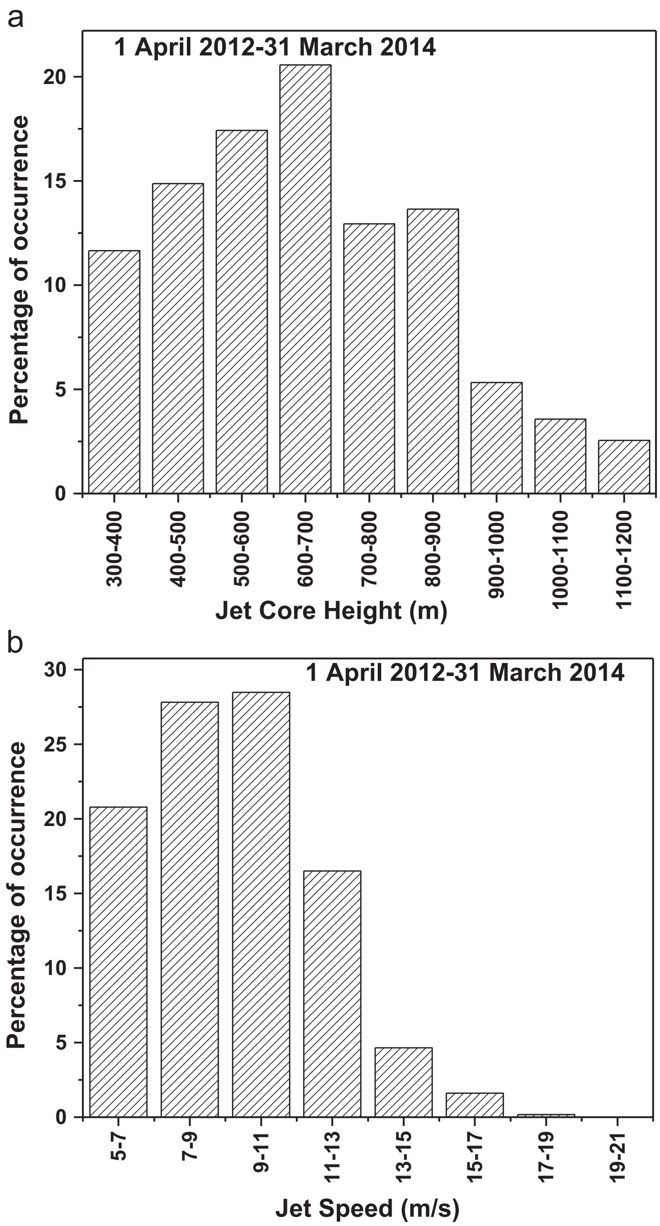

Fig. 4. (a) Percentage frequency of occurrence of jet core height in 100 m class intervals from 100 m to 1200 m altitude above surface during the 2-year observational period. (b) Percentage frequency of occurrence of jet speed in 2 ms^{-1} class intervals during the 2-year observational period.

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 (Fig. 3, Tables 1 and 2) also confirms that during pre-monsoon months predominantly northwesterly winds prevail over the station.

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 (e.g., 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. Analysis of two year wind lidar data discussed above (Fig. 4a) showed that percentage frequency of occurrence of jet core height is significant in the altitude range 300–900 m with highest occurrence frequency being in the range 600–700 m. Also jet core height occurrence is found to be relatively higher (> 10%) in the 300–700 m altitude region. Therefore hodograph analysis has been attempted for the wind data at 300 m, 500 m and 700 m altitudes. Hourly averaged meridional and zonal winds from Doppler wind lidar observations at these three heights on 1 May 2012, 22 October 2012 and 5 December 2012, typically representative of pre-monsoon, post-monsoon and winter seasons are considered here. 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. Fig. 7a 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 Fig. 7b. 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 (Fig. 7c) 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 h. 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 for this analysis. 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 Fig. 8. All the cases show the predominant diurnal periodicity (24 h) and also a hint of semi-diurnal oscillation (12 h). Further, most of the amplitude spectra show broad or multiple peaks in the periodicity range 30–50 h. In the pre-monsoon case (1–7 May 2012), no significant peak was seen around 38 h (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 h 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 h.

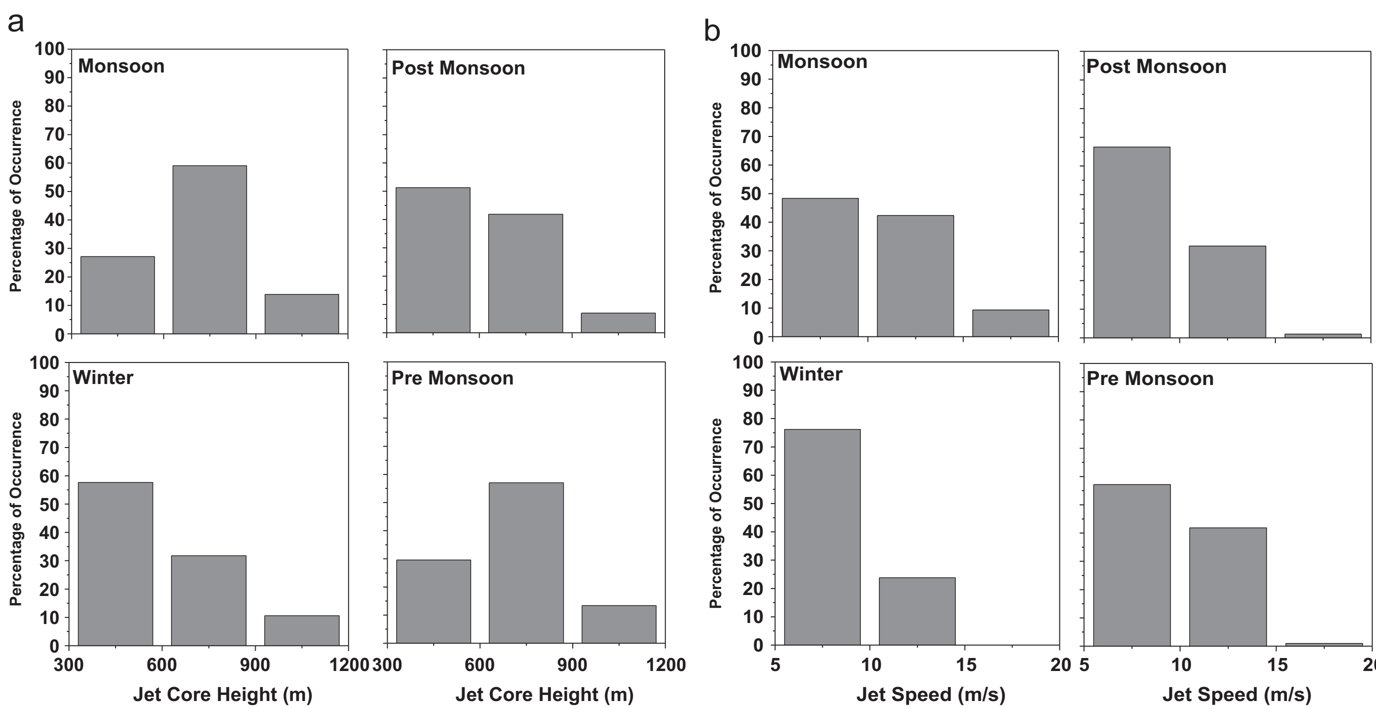

Fig. 5. (a) Season-wise percentage frequency of occurrence of jet core height. (b) Season-wise percentage frequency of occurrence of jet speed.

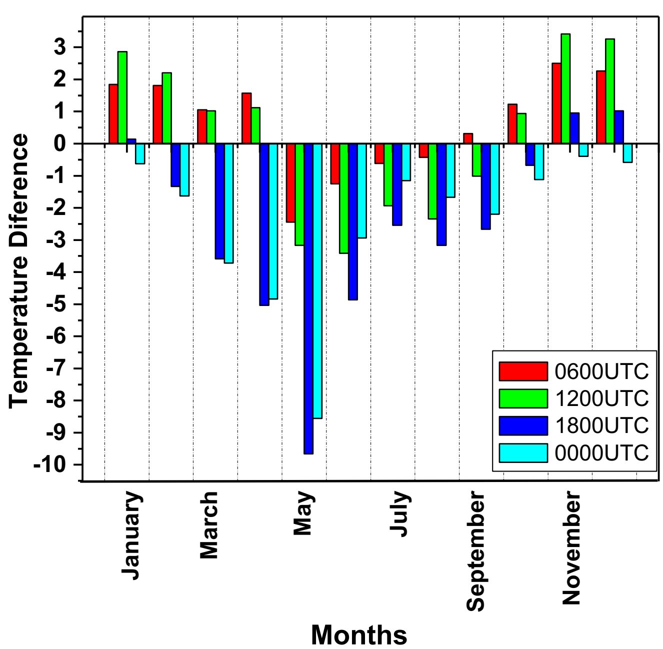

Fig. 6. Monthly mean zonal temperature gradient at 925 hPa level for four timings (0000 UTC, 0600 UTC, 1200 UTC, 1800 UTC).

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 2012–31 March 2014). The data is once again grouped into the above mentioned 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 Fig. 9 (left panel). It is observed that during pre-monsoon and monsoon seasons 85–95% of the time nighttime surface temperatures are in the range 294–299 K. Whereas, during post-monsoon and winter seasons 45–62% of nighttime temperatures are in the lower range of 288–293 K. Further, more than 20% of the time surface temperatures during winter are below 288 K 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 Fig. 9 (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 mostly 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 plotted in Fig. 10. Here the data is taken from late evening hours (from 2000 h LT) to see the transition in turbulence characteristics from daytime to nighttime conditions. 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.

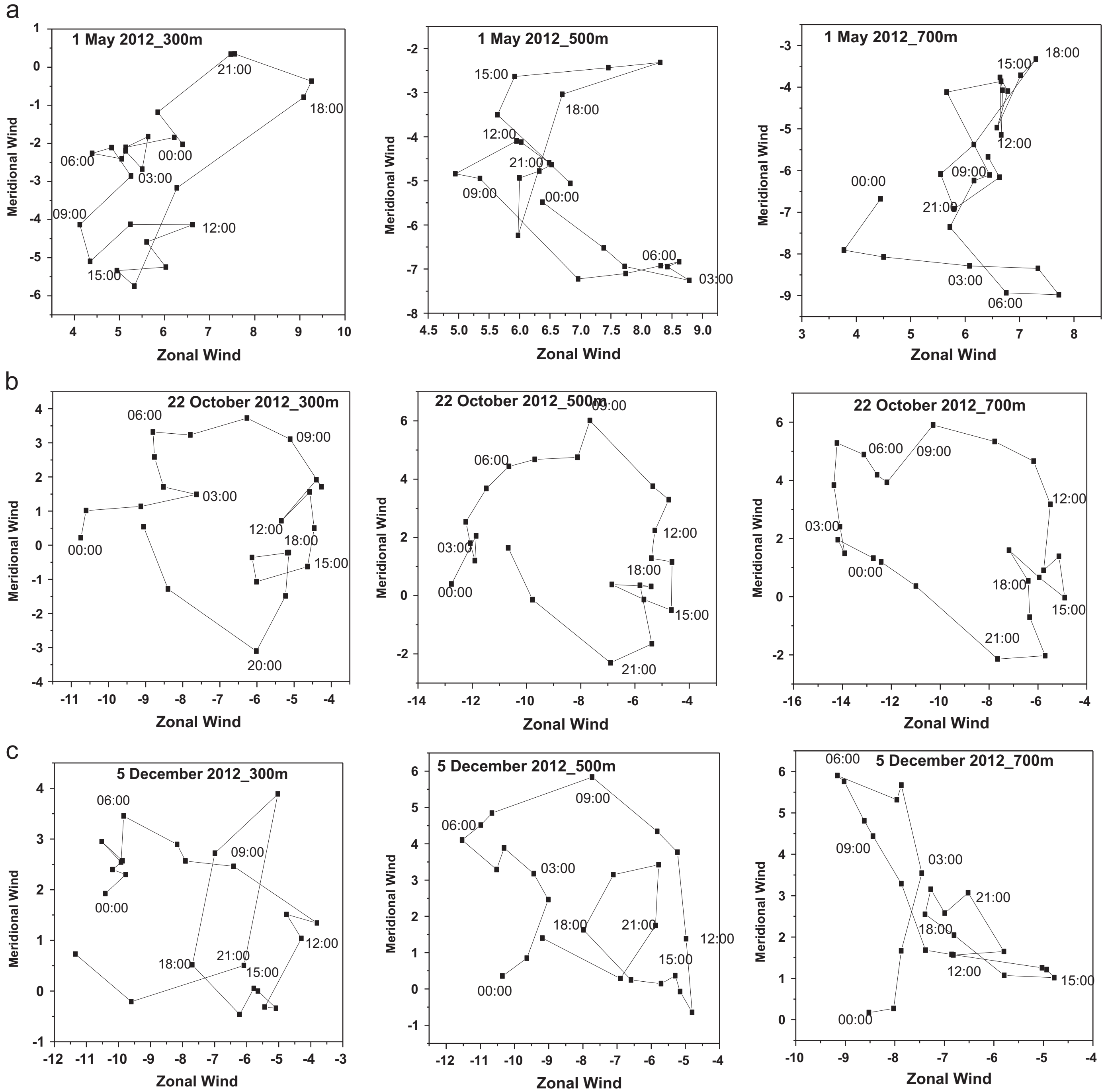

Fig. 7. (a) Hourly variation of meridional wind with zonal wind at three heights (300 m, 500 m, 700 m) during a typical pre-monsoon day (01 May 2012). (b) Hourly variation of meridional wind with zonal wind at three heights (300 m, 500 m, 700 m) during a typical post-monsoon day (22 October 2012). (c) 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).

4. Conclusion

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 (height above surface at which this peak occurs) and wind direction of horizontal wind at the peak, over a tropical Indian station (Pune) obtained from high resolution Doppler wind lidar during two year period (01 April 2012–31 March 2014) have been presented and discussed in the paper. 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. Further, seasonal average jet core speeds are higher during monsoon (9.9 ms^{-1}) and pre-monsoon (9.6 ms^{-1}) compared to those in post-monsoon (7.9 ms^{-1}) and winter (7.3 ms^{-1}). This may be due to the strong large-scale southwesterly monsoon flow, where one would expect jet speeds to be higher during monsoon season. On

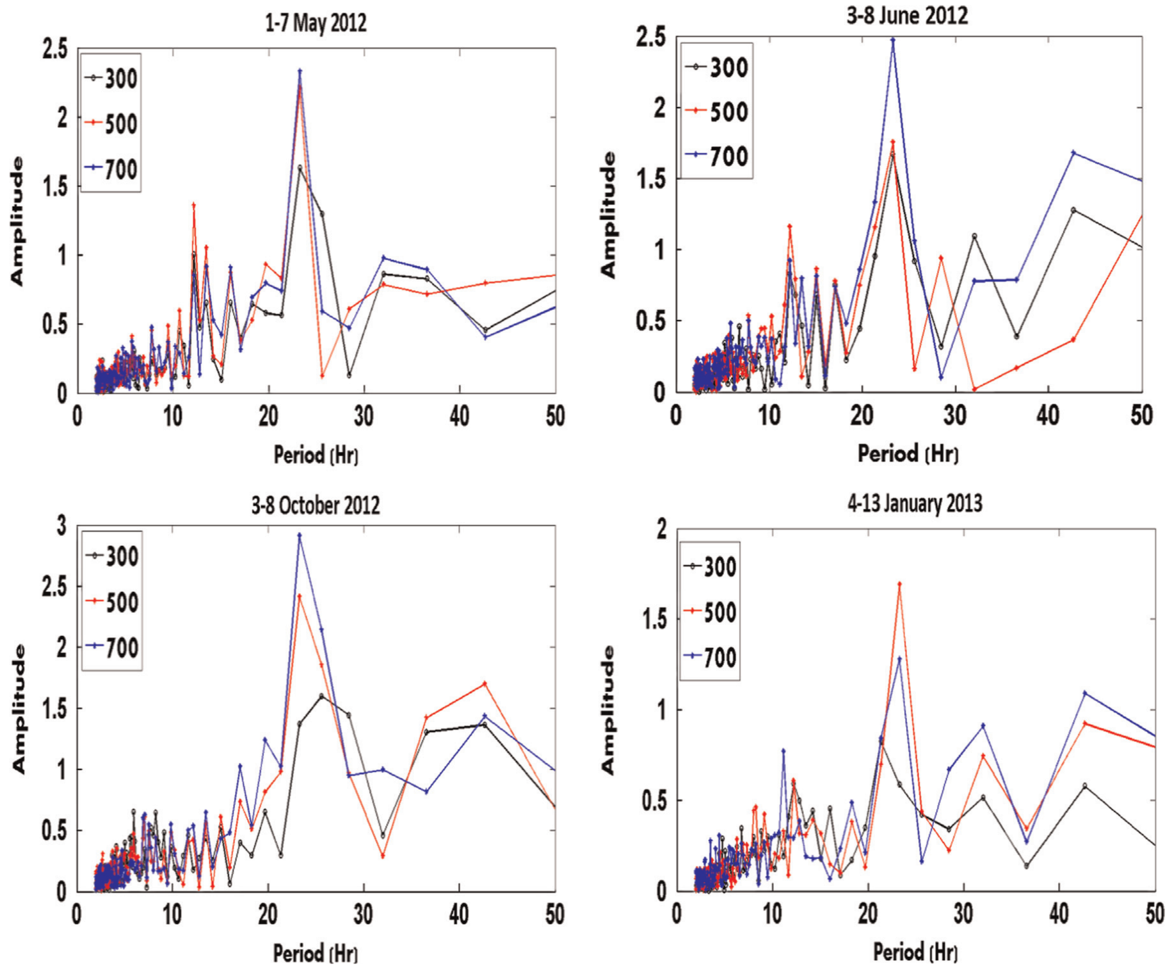

Fig. 8. Amplitude spectra of horizontal wind at three heights (300 m, 500 m, 700 m) during the periods 01–07 May 2012, 03–08 June 2012, 03–08 October 2012, and 04–13 January 2013.

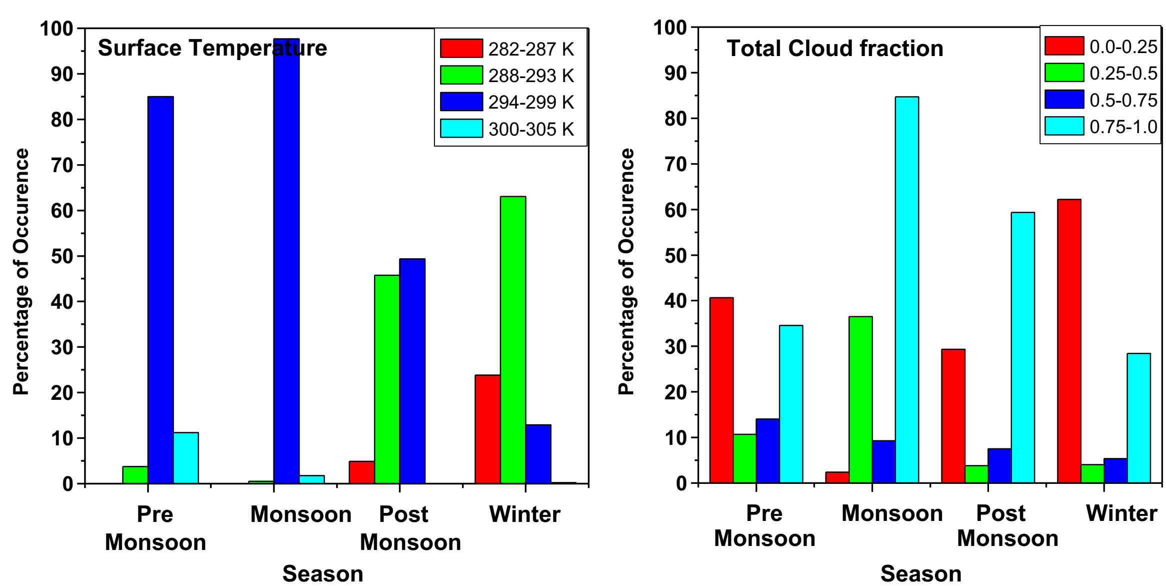

Fig. 9. Percentage frequency of occurrence of surface temperature (left panel) and total cloud fraction (right panel) separately for four seasons for Pune location during the 2-year period obtained from MERRA-reanalysis data set.

some occasions during the monsoon season, 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 large-scale seasonal 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}.

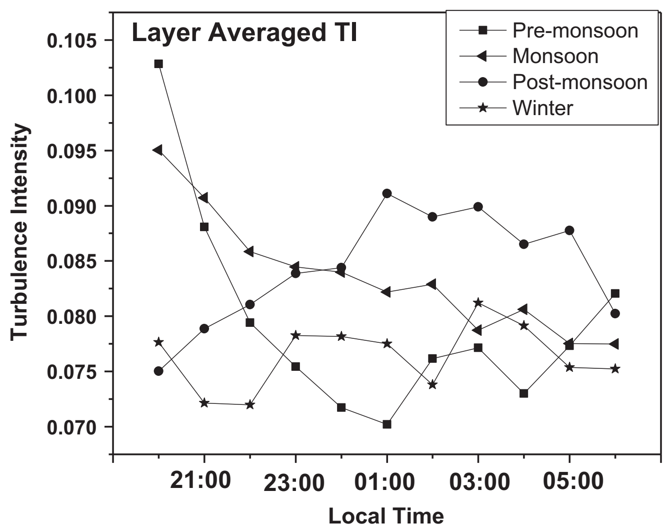

Fig. 10. Seasonal mean temporal variation of turbulence intensity during local nighttime hours.

Observed large west–east (zonal) temperature gradient at 925 hPa level may explain 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.

Acknowledgments

Authors are grateful to Director, IITM for his encouragement and support. Thanks are due to M.C.R. Kalapureddy and K.K. Dani for help in data retrieval and analysis and also to B.S. Murthy and Anandakumar Karipot for very useful discussions while preparing the manuscript. One of the authors (RDR) would like to gratefully acknowledge CSIR, Government of India for providing research fellowship to undertake the work.

References

Andreas, E.L., Claffey, K.J., Makshtas, A.P., 2000. Low-level atmospheric jets and inversions over Western Weddell Sea. Bound.-Layer Meteorol. 97, 459–486.
Bonner, W.D., 1968. Climatology of the low-level jet. Mon. Weather Rev. 96, 833–850.
Beardsley, R.C., Dorman, C.E., Friehe, C.A., Rosenfield, L.K., Wyant, C.D., 1987. Local atmospheric forcing during the coastal ocean dynamics experiment 1: a description of the marine boundary layer and atmospheric conditions over a northern California upwelling region. J. Geophys. Res. 92, 1467–1488.
Banta, R.M., Newsom, R.K., Lundquist, J.K., Pichugina, Y.L., Coulter, R.L., Mahrt, L.J., 2002. Nocturnal low-level jet characteristics over Kansas during CASES-99. Bound.-Layer Meteorol. 105, 221–252.
Banta, R.M., Pichugina, Y.L., Newsom, R.K., 2003. Relationship between low-level jet properties and turbulence kinetic energy in the nocturnal stable boundary layer. J. Atmos. Sci. 60, 2549–2555.
Baas, P., de Roode, S.R., Lenderink, G., 2008. The scaling behavior of a turbulent kinetic energy closure model for stably stratified conditions. Bound.-Layer Meteorol. 127, 17–36. http://dx.doi.org/10.1007/s10546-007-9253.
Blackadar, A.K., 1957. Boundary layer wind maxima and their significance for the growth of nocturnal inversion. Bull. Am. Meteorol. Soc. 38, 283–290.
Brill, K.F., Uccellini, L.W., Burkhart, R.P., Warner, T.T., Anthes, R.A., 1985. Numerical simulations of a transverse indirect circulation and low level jet in the exit region of an upper-level jet. J. Atmos. Sci. 42, 1306–1320.
Friedrich, K., Lundquist, J.K., Aitken, M., Kalina, E.A., Marshall, R.F., 2012. Stability and turbulence in the atmospheric boundary layer: a comparison of remote sensing and tower observations. Geophys. Res. Lett. 39, L03801. http://dx.doi.org/10.1029/2011GL050413.
Frisch, A.S., Orr, B.W., Martner, B.E., 1992. Doppler radar observations of the development of a boundary-layer nocturnal jet. Mon. Weather Rev. 120, 3–16.
Holton, J.R., 1967. The diurnal boundary layer wind oscillation above sloping terrain. Tellus 19, 199–205.
Karipot, A., Leclerc, M.Y., Zhang, G., Lewin, K.F., Nagy, J., Hendrey, G.R., Starr, G., 2008. Influence of nocturnal low-level jet on turbulence structure and CO2 flux measurements over a forest canopy. J. Geophys. Res. 113, D10102. http://dx.doi.org/10.1029/2007JD009149.
Karipot, A., Leclerc, M.Y., Zhang, G., 2009. Characteristics of nocturnal low-level jets observed in the North Florida area. Mon. Weather Rev. 137, 2605–2621. http://dx.doi.org/10.1175/2009MWR2705.1.
King, J.C., Turner, J., 1997. Antarctic Meteorology and Climatology. Cambridge University Press, Cambridge, p. 409.
Lenschow, D.H., Li, X.S., Zhu, C.J., Stankov, B.B., 1988. The stably stratified boundary layer over the Great Plains. I. Mean and turbulent structure. Bound.-Layer Meteorol. 42, 95–121.
Li, J., Chen, Y.L., 1998. Barrier jets during TAMEX. Mon. Weather Rev. 126, 959–971.
Mahrt, L., Heald, R.C., Lenschow, D.H., Stankov, B.B., Troen, I., 1979. An observational study of the structure of the nocturnal boundary layer. Bound.-Layer Meteorol. 17, 247–264.
Mahrt, L., 1999. Stratified atmospheric boundary layers. Bound.-Layer Meteorol. 90, 375–396.
Mahrt, L., Vickeres, D., 2002. Contrasting vertical structures of nocturnal boundary layers. Bound.-Layer Meteorol. 105, 351–363.
Mathieu, N., Strachan, I.B., Leclerc, M.Y., Karipot, A., Pattey, E., 2005. Role of low-level jets and boundary layer properties on the NBL budget technique. Agric. For. Meteorol. 135, 35–43.
Matthew, L.A., Rhodes, M.E., Lundquist, J.K., 2012. Performance of a wind-profiling lidar in the region of wind turbine rotor disks. J. Atmos. Ocean. Technol. 29, 347–355. http://dx.doi.org/10.1175/JTECH-d-11-00033.1.
Murthy, B.S., Latha, R., Sreeja, P., 2013. Boundary layer jet on the lee side of Western Ghats during southwest monsoon as revealed by high resolution sodar winds. J. Atmos. Sol. Terr. Phys. 105-106, 101–109.
Parish, T.R., 1983. The influence of the Antarctic Peninsula on the wind field over the western Weddell Sea. J. Geophys. Res. 88, 2684–2692.
Prabha, T.V., Goswami, B.N., Murthy, B.S., Kulkarni, J.R., 2011. Nocturnal low-level jet and 'atmospheric streams' over the rain shadow region of Indian Western Ghats. Q. J. R. Meteorol. Soc. 137, 1273–1287.
Ruchith, R.D., Ernest Raj, P., Kalapureddy, M.C.R., Deshpande, S.M., Dani, K.K., 2014a. Time evolution of monsoon low-level jet observed over an Indian tropical station during the peak monsoon period from high-resolution Doppler wind lidar measurements. J. Geophys. Res. 119, 1786–1795. http://dx.doi.org/10.1002/2013JD020752.
Ruchith, R.D., Ernest Raj, P., Kalapureddy, M.C.R., Dharmaraj, T., 2014b. Role of surface and boundary layer processes in the temporal evolution of monsoon low level jet (MLLJ) observed from high resolution Doppler wind lidar measurements. J. Atmos. Sol. Terr. Phys. 121, http://dx.doi.org/10.1016/j.jastp.2014.09.016.
Ruchith, R.D., Kalapureddy, M.C.R., Deshpande, S.M., Dani, K.K., Ernest Raj, P., 2014c. Inter-comparison of wind profiles in the tropical boundary layer remotely sensed from GPS radiosonde and Doppler wind lidar. Int. J. Remote Sens. 35, 3300–3315. http://dx.doi.org/10.1080/01431161.2014.902552.
Smedman, A.S., Tjernstrom, M., Högström, U., 1993. Analysis of the turbulence structure of a marine low-level jet. Bound.-Layer Meteorol. 66, 105–126.
Song, J., Liao, K., Coulter, R.L., Lesht, B.M., 2005. Climatology of the low-level jet at the southern Great Plains atmospheric boundary layer experiment site. J. Appl. Meteorol. 44, 1593–1606.
Thorpe, A.J., Guymer, T.H., 1977. The nocturnal jet. Q. J. R. Meteorol. Soc. 103, 633–653.
Uccellini, L.W., 1980. On the role of upper tropospheric jet streaks and leeside cyclogenesis in the development of low level jet in the Great Plains. Mon. Weather Rev. 108, 1689–1696.
Uccellini, L.W., Johnson, D.R., 1979. The coupling of upper and lower tropospheric jet streams and implications for the development of severe convective storms. Mon. Weather Rev. 107, 682–703.
Wang, Y., Newsom, R.K., Calhoun, R., 2006. Nocturnal low-level-jet-dominated atmospheric boundary layer observed by a Doppler lidar over Oklahoma city during JU2003. J. Appl. Meteorol. Climatol. 46, 2098–2109.
Whiteman, C.D., Bian, X., Zhong, S., 1997. Low-level jet climatology from enhanced rawinsonde observations at a site in the Southern Great Plains. J. Appl. Meteorol. 36, 1363–1376.
Winant, C.D., Dorman, C.E., Friehe, C.A., Beardsley, R.C., 1988. The marine layer off northern California: an example of supercritical channel flow. J. Atmos. Sci. 45, 3588–3605.
Wu, Y., Sethu, Raman, 1998. The summertime Great Plains low level jet and the effect of its origin on moisture transport. Bound.-Layer Meteorol. 88, 445–466.
Zaitao Pan, Moti Segal, Arritt, R.W., 2003. Role of topography in forcing low-level jets in the central United States during the 1993 flood-altered terrain simulations. Mon. Weather Rev. 132, 392–403.
Zemba, J., Friehe, C.A., 1987. The marine boundary layer jet in the coastal ocean dynamics experiment. J. Geophys. Res. 92, 1489–1496.
Zhong, S., Fast, J.D., Bian, X., 1996. A case study of the Great Plains low-level jet using wind profiler network data and a high resolution mesoscale model. Mon. Weather Rev. 124, 785–806.