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- Doppler wind lidar measurements over tropical Indian location

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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

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Abstract Doppler wind lidar measurements of horizontal winds at an Indian tropical station, Mahbubnagar (16.73°N, 77.98°E, 445 m above mean sea level), were used to investigate the time evolution of the monsoon low-level jet (MLLJ) during the southwest monsoon season. Vertical profiles of zonal wind in the altitude range of 100 to 3000 m above surface (at every 50 m height interval and 5 min time averaged) obtained during the period 25 July to 23 August 2011 are considered for the analysis. The zonal winds in the altitude up to 3000 m above ground are predominantly westerly throughout the period and on almost all the days there is a westerly wind speed maximum around 500 m above ground during nighttime. Soon after local sunrise, the core of this wind speed maximum (jet) gets lifted up and by afternoon, the westerly wind maximum is shifted to a higher altitude of 2000 m–2500 m without much change in its magnitude. Analysis of the high-resolution lidar data strongly indicates that the same nocturnal LLJ seems to be moving up and evolving into a daytime westerly MLLJ reported in several previous studies. Wind speed and direction derived from the wind lidar agree reasonably well with simultaneously observed GPS upper air sounding wind measurements. Further analysis shows that the time-height evolution of the jet core is closely associated with daytime convection and boundary layer growth. The presence of clouds over the region seems to inhibit this type of time evolution.

1. Introduction

The term "low-level jet" (LLJ) is commonly used in meteorological literature to describe a wide variety of wind features found over nearly every continent on Earth [*Bonner*, 1968; *Uccellini and Johnson*, 1979]. At nighttime under clear-sky conditions and weak synoptic winds, a wind maximum close to the ground can exist, often referred to as nocturnal LLJ. Some authors [*Li and Chen*, 1998] used the term to describe any low-level wind maximum, while others [*Bonner*, 1968] took care to define appropriate wind shear criteria and threshold values of the wind maximum before applying the term low-level jet. *Andreas et al.* [2000] following *Stull* [1988] defined nocturnal LLJ as a maximum in the vertical profile of the wind speed that is at least 2 m/s faster than wind speeds above and below it within the lowest 1500 m of the atmosphere. Because of the widespread LLJ occurrence and its diversity in physical characteristics, the term LLJ is subjected to wide interpretation. Further, the LLJ has significant impact on the development of severe weather [*Frisch et al.*, 1992; *Zhong et al.*, 1996] as it serves as a major moisture transport mechanism and initiates shear instabilities for storm development. *Stull* [1988] summarized various conditions that favor the formation of the LLJ.

The nocturnal LLJ is highly ageostrophic with maximum wind speeds attained shortly after midnight. Observational studies [*Kaimal and Izumi*, 1965; *Parish et al.*, 1988] suggested that this LLJ occurs primarily as a result of inertial oscillations resulting from the sudden decrease in the frictional force during evening [*Blackadar*, 1957]. The role of diabatic heating and cooling of the sloping terrain has also been linked to the evolution of the Great Plains LLJ [*Holton*, 1967]. Another example of LLJ is the so-called barrier jet [*Schwerdtfeger*, 1979; *Parish*, 1982, 1983; *Li and Chen*, 1998], which is a mountain-parallel wind maximum resulting from the geostrophic adjustment as stable air is advected against an elongated topographic ridge. The LLJ also occurs as a result of the secondary circulation associated with an upper tropospheric jet core as suggested by *Uccellini and Johnson* [1979] and *Brill et al.* [1985]. Thermal wind processes associated with land-sea heating contrasts have been identified as fundamental to the structure of these LLJs. Topography also can play a role in providing local enhancements near the coastal zone. *Winant et al.* [1988], *Samelson* [1992], and *Burk and Thompson* [1996], among others, discussed the local terrain influences on the jet. The nocturnal LLJ has an important role in the generation of shear, which is often an important source of turbulence and turbulent fluxes in the nighttime boundary layer [*Mahrt et al*., 1979; *Lenschow et al*., 1988; *Smedman et al*., 1993, 1995, 1997; *Tjernström and Smedman*, 1993; *Mahrt*, 1999; *Mahrt and Vickers*, 2002; *Banta et al*., 2002, 2003]. Sodars and wind profilers have been used for LLJ structure investigation [*Karipot et al*., 2009]. Doppler wind lidars have recently emerged as excellent observational tools in studying LLJ-boundary layer interactions [*Banta et al*., 2003; *Wang et al*., 2006]. Thus, earlier studies indicate that the nocturnal LLJ occurring around 500–700 m above surface seems to be closely associated with boundary layer processes and influenced by local terrain.

A strong cross-equatorial low-level jet stream with a core around 850 hPa (around 1500 m above mean sea level) exists over the Indian Ocean and South Asia during the boreal summer monsoon season (June–September). This appears in the zonal wind profiles as a strong westerly wind maximum over the Indian land region, and the jet core is mainly found at altitudes 1000 m to 2000 m, unlike the above-mentioned nocturnal jet, which lies closer to the ground at nighttime (most frequently between 500 m and 700 m). Analyzing the wind data of 5 years collected by the radiosonde/radio-wind network over India, *Joseph and Raman* [1966] pointed out the existence of this westerly LLJ stream over peninsular India with strong vertical and horizontal wind shears. This LLJ is seen in the region more frequently during the monsoon month of July with a core at about 1.5 km above mean sea level and core wind speeds on the order of 20–30 m/s. This is one of the synoptic components of Indian summer monsoon, with a cross-equatorial current from the southern Indian Ocean to the central Arabian Sea [*Krishnamurti et al*., 1976] and provides a large moisture supply over land regions, fuelling convection [*Sikka and Gadgil*, 1980]. This monsoon LLJ (MLLJ) shows a large spatial and temporal variability on an intraseasonal scale [*Goswami et al*., 1998], which is directly connected to the active and break periods of Indian summer monsoon. *Joseph and Sijikumar* [2004] analyzed the intraseasonal variability of the MLLJ and reported that during active monsoon condition, the core of LLJ passes through peninsular India around the latitude 15°N and in break monsoon conditions, the LLJ passes through the latitude belt 0–10°N. Using lower atmospheric wind profiler (LAWP) data over Gadanki, India, *Kalapureddy et al*. [2007] showed that the MLLJ core lies at a height of 1.8 ± 0.6 km with a mean jet intensity of about 20 m/s. Using measurements from a UHF radar/wind profiler (404 MHz) over Pune (18.38°N, 73.58°E), India, *Joshi et al*. [2006] found that the jet core height varies between 1.6 and 3 km. It is to be noted that the height coverage of the LAWP during clear-air conditions is mostly limited to 2–2.5 km. Also, most of the above cited studies used relatively low-vertical-resolution data sets for studying the MLLJ. Recently *Raman et al*. [2011] explored the spatial and vertical characteristics of MLLJ using frequent ascents of GPS sonde and found that it shows diurnal and intraseasonal variability.

Remote sensing of horizontal and vertical winds using the Doppler lidar technique was introduced as early as the mid-1960s [*Forman et al*., 1965] and since then, methods have vastly improved [*Rothermel et al*., 1998; *Aitken et al*., 2012]. The Doppler lidar technique basically utilizes aerosols in the atmosphere as natural tracers for measuring atmospheric motions. Presently both continuous wave and pulsed Doppler lidars are being used for wind measurements [*Mann et al*., 2010]. An advanced version of a pulsed Doppler wind lidar (Model WindCube-200) was originally installed at Indian Institute of Tropical Meteorology (IITM), Pune (18°32′N, 73° 51′E, 559 m above mean sea level), India, for studying the fine resolution wind structure in both time and space. This wind lidar was operated at another tropical India station, Mahbubnagar (16.73°N, 77.98°E, 445 m above mean sea level), on campaign mode during June–October 2011. The current study reports some results obtained from the wind lidar measurements made over this station. Details of the site and instruments used are briefly provided in the following section.

2. System Description and Data Analysis

A new generation Doppler wind lidar called "WindCube-200" developed by LEOSPHERE, France, in cooperation with the French Aerospace Agency (Office National d'Etudes et de Recherche Aérospatiales) is being operated to obtain high-resolution wind structure in both time and space in the tropical monsoon region. It has the capability to give the 3-D components of the wind in the troposphere from 100 m to about 12,000 m depending on the availability of sufficient number of scatterers. The measurement hypothesis of this lidar is that it uses aerosols as "tracers", basically assuming that the movement of aerosols is along with

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the wind. The moving aerosols induce a Doppler shift of frequency, which is used to compute the radial velocity of wind. The WindCube-200 operates in the near-IR wavelength (1.54 μm) region, and its pulse energy is 100 μJ, scanning cone angle ~15°, and speed and direction accuracy 0.5 m/s and 1.5°, respectively. The prism, which deflects the laser beam from the vertical, 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. The typical beam accumulation time along a given direction is 11,796 ms (i.e., 11.8 s) for 36,000 numbers of averaging pulses/shots with height coverage limited to 6000 m. Having sent the number of pulses, the prism rotates to the next azimuth angle, each separated by 90° to steer the beam from one direction to the other. 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. At each direction step, the WindCube combines the four most recent radial speeds at each height to compute the three wind components (*u*-zonal, *v*-meridional, and *w*-vertical wind velocities). In the WindCube-200, the system set threshold for carrier-to-noise ratio (CNR), which is equivalent to signal-to-noise ratio, is −30 dB. The CNR threshold generally depends on the configured accumulation time and in the current WindCube-200; the accumulation time is set to 36,000 shots/line of sight. However, for better data quality, care has been taken in the current study to use only data whose CNR is better than −25 dB for further analysis and discussion. Also, in this lidar system, the effect of the instrument range function on CNR measurement is removed above 100 m altitude. Some more details of the WindCube principle and its performance are provided by *Courtney et al.* [2008], *Mann et al.* [2010], and *Aitken et al.* [2012].

Wind profiles obtained from the wind lidar were compared to those obtained from GPS (Global Positioning System) upper air sounding balloon ascents at the same location and found to be in agreement to reasonable extent. The GPS system used for the current observations is a Vaisala make DigiCORA Sounding System MW31, which includes a Vaisala Radiosonde RS92, a Ground Check Set, and a GPS antenna. The Sounding Processing Subsystem makes extensive use of the Software Defined Radio technology for receiving radiosonde signals. This system has the capability to measure meteorological parameters (pressure, temperature, humidity, wind speed, and wind direction) with height resolution as high as 3 m. The Radiosonde RS92-SGP has a silicon pressure sensor, a heated twin humidity sensor, and a small, fast temperature sensor. This radiosonde type features a GPS receiver for wind finding. The instrument is uplifted using an 875 g rubber balloon with hydrogen gas filled in at an ascent rate of about 5 m/s. The operating telemetry range with the Vaisala RS92-SGP radiosonde is up to 200 km. Altitude profiles of zonal (E-W) wind speed obtained from this GPS sounding system are used here for comparisons with those simultaneously measured with the WindCube-200.

Lidar-derived wind measurements were made at Mahbubnagar, in southern part of India, during an intensive ground observational campaign (CAIPEEX-IGOC-2011) conducted from June to October 2011. The primary aim of this campaign was to investigate cloud-aerosol interactions by making ground-based as well as aircraft observations. However, the wind measurements made during this campaign were used here to investigate the MLLJ. Mahbubnagar is a tropical semiurban station situated to the southeast in the semiarid region of peninsular India on the eastern edge of the Deccan Plateau, as shown in the map (Figure 1). The observational location is on the southern slopes of the low lying mountain ranges (whose maximum height is 600 m above mean sea level) oriented in the northwest-southeast direction. Several of these mountain ranges create parallel valleys, which join to an area with average elevation of 100 m above mean sea level. The land use category around the location is cropland. The actual observational location is in level terrain (average elevation is 440 m above mean sea level); however, there are few low lying hills in the north and in the south sector. Southwesterly winds blowing from the marine region (Arabian Sea) during monsoon season have a strong westerly component over the Indian continental region. These westerlies bring moisture laden air masses, which give monsoon rainfall over land. The wind lidar was operated at this station on continuous mode. The vertical profile of wind parameters (*u*, *v*, and *w*) from the wind lidar starts at 100 m aboveground level and at 50 m height interval from there on. It provides time-averaged vertical profiles of wind speed and direction as well as those of zonal (east-west), meridional (north-south), and vertical winds at every 5 min. In the current study, such continuous 5 min averaged vertical profiles of zonal wind from 100 m to 3000 m altitude obtained during the period 25 July to 23 August have been used to investigate the time-height variations in zonal wind, the features of nocturnal/monsoon LLJ, and also to examine the evolution of the nocturnal jet observed over this tropical monsoon region.

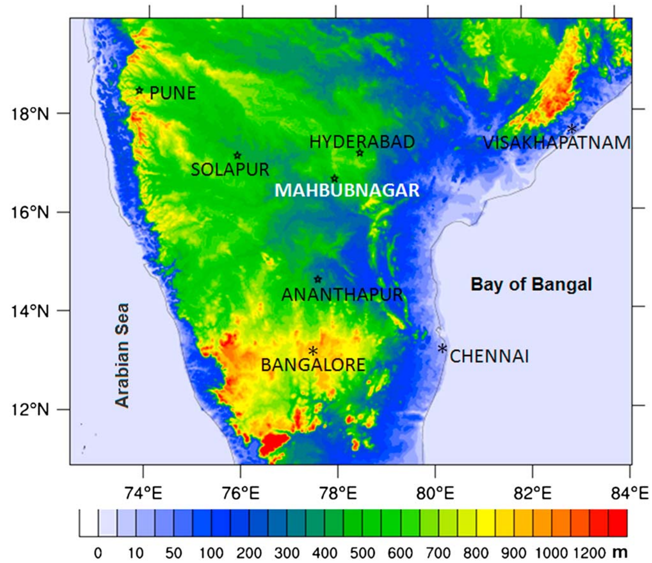

Figure 1. Topographic map of south peninsular India showing the location of wind lidar measurements (Mahbubnagar) with respect to other urban cities.

3. Results and Discussion

Large-scale horizontal winds in the surface levels are westerly/southwesterly over the Indian subcontinent region during the southwest monsoon season from June to September. Thus, the zonal wind component is strong, and westerlies prevail predominantly up to an altitude of about 3000 m above the surface, especially in the southern Indian peninsula, where the observations have been taken. In the entire analysis made and presented in the current study, vertical profiles of zonal wind speed (*u* component) alone are used. Typical time-height variations of zonal wind during four diurnal cycles from 15 to 19 August 2011 are shown in Figure 2. It is observed that on all the days, there are westerly wind speed maxima during late night hours (around 22:00 to 04:00 h local time) in the height region 400–500 m aboveground level. By the following local midnoon time, the westerly wind maximum is shifted to a higher altitude and lay centered around 1500–2000 m altitude during afternoon hours. The upward sloping wind speed contours in the figure during all the diurnal cycles seems to indicate that the same nocturnal LLJ core is moving up and evolving into daytime westerly MLLJ that was reported by previous studies [*Goswami et al*., 1998; *Joseph and Sijikumar*, 2004; *Kalapureddy et al*., 2007]. It is to be noted that during the period of study, the zonal winds in the region up to 3000 m above ground are predominantly westerly (positive wind speed values). Such type of temporal evolution is seen in the entire data during the July–August period. However, whenever there is the presence of low-level cloud cover over the location (visual observation), this type of smooth evolution of nocturnal LLJ is absent as noticed on 19 August in Figure 2. To see the time evolution of the LLJ more closely, time-height contours of zonal wind on one typical day, i.e., on 11 August 2011, are shown in Figure 3. One can see that from premidnight hours to about 07:00 h local time (LT) of 11 August, the nocturnal LLJ lies stratified between 400 and 700 m above ground. The jet speeds during this period are in the range of 13–16 m/s. The height of the wind speed maximum starts shifting up soon after sunrise and by late afternoon lays centered around 2500 m altitude. This upward movement of the jet core was steady and smooth and on this particular day was at a rate of about 130 m/h. The peak wind speed in the core of the jet is of nearly same magnitude, more or less, throughout the entire diurnal evolution. Another point to note is that on this day, zonal winds were again entirely westerly throughout the altitude range of 100–3000 m.

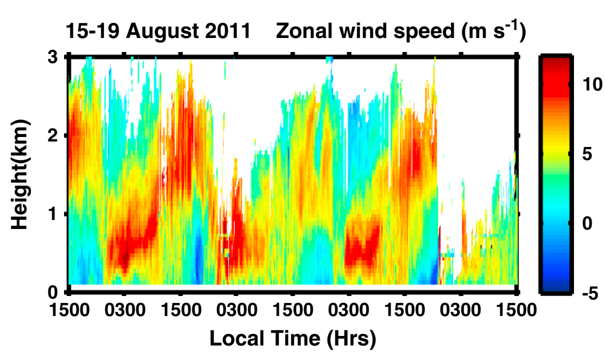

Figure 2. Time-height variations of zonal wind in the altitude range of 100–3000 m during the period 15–19 August 2011 at Mahbubnagar.

To see the height variation of zonal wind speed obtained from wind lidar on 11 August 2011, one typical nighttime average profile (04:00 to 05:45 h LT) and one daytime average profile (17:25 to 17:55 h LT) are computed and shown in Figure 4 (top). The nighttime profile shows a well-defined nocturnal jet centered around 600 m. The peak wind speed at this height was about 16 m/s. Nocturnal LLJs are characterized by a core of strong wind speeds confined to a narrow height range. The late afternoon profile of wind speed shows a broader maximum around

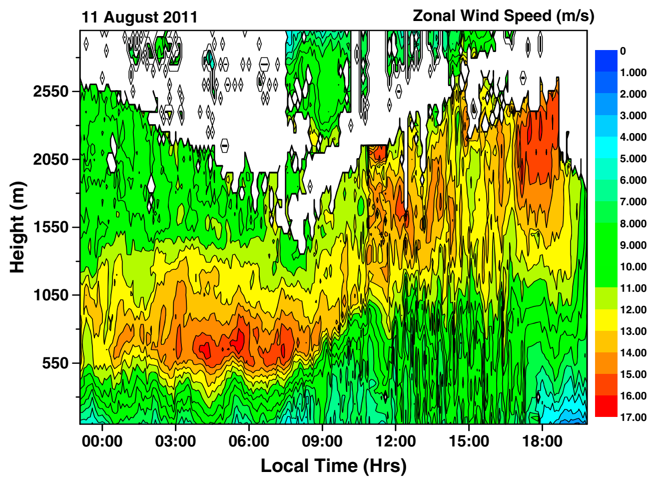

Figure 3. Time-height variations of zonal wind on a typical day (11 August 2011).

2200–2400 m altitude and with a speed of nearly same magnitude. At Mahbubnagar observation site, GPS upper air soundings were launched daily around noontime during the period of the observational campaign. Figure 4 (bottom) shows the zonal wind profiles near simultaneously obtained from wind lidar and radiosonde. It is seen that the wind profile obtained by two independent techniques agree qualitatively, with both profiles showing peak zonal wind speed of 15–16 m/s around 1600 m. Statistical analysis of the comparisons between the two techniques showed that the vertical variations agree within the uncertainties like instrumental errors. Also, conditions like spatial/temporal inhomogeneities and the radiosonde drift during the measurement could also contribute to the differences. The estimated RMS error between the two measurements made over a 4 month period is between 1.0 and 1.4 m/s in the height range of 100–2000 m. Once again, the positive values of zonal winds in all the vertical profiles indicate prevalence of westerlies.

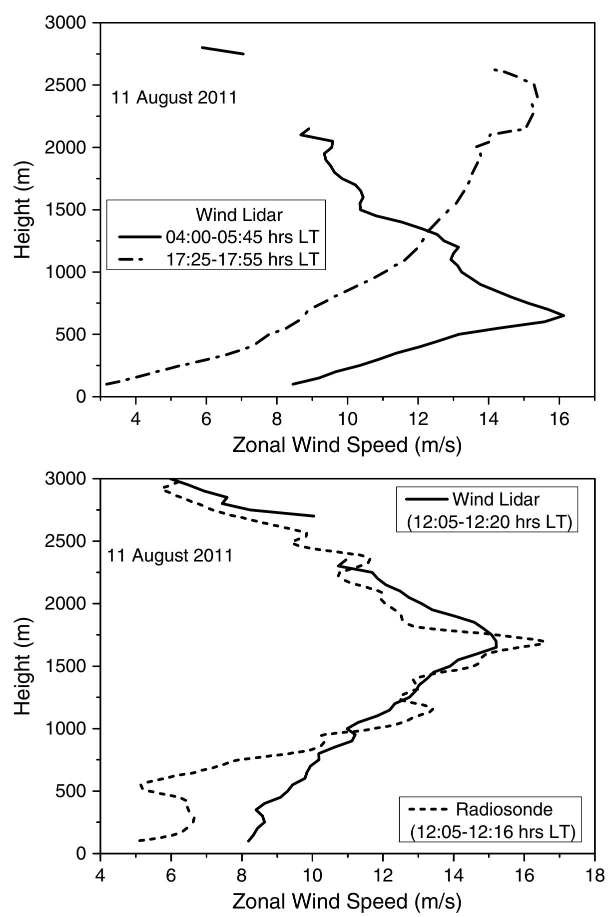

Figure 4. (top) Vertical profiles of zonal wind on 11 August 2011 during typical nighttime and day time conditions and (bottom) comparison of wind lidar and radiosonde measurements during noon time.

In order to examine if the above-mentioned diurnal variation in the height of the jet core exists on all the days, the 5 min average vertical profiles (100–3000 m) during the period 25 July to 23 August 2011 are taken and at each time the height of the jet core (peak in the wind speed) as well as the zonal wind speed at that height are picked up. Figure 5 shows the temporal variation of the height of wind speed maximum (Figure 5, top) and wind speed at that height (Figure 5, bottom) continuously for nearly 1 month duration. This period is generally under active southwest monsoon conditions over the observational region [*Rajeevan et al.*, 2010; *India Meteorological Department*, 2012]. One can notice the systematic diurnal oscillation in the height of the LLJ with lower heights during nighttime. On several days, the height of the LLJ core exceeded 2000 m during daytime. Also, occurrence of nocturnal jet below 500 m on several days is noticed. However, the amplitude of this diurnal oscillation in core height varies from day to day probably due to different local as well as large-scale atmospheric conditions. The amplitude of diurnal oscillation seems to be large when the LLJ core wind speeds are greater than 15 m/s. The wind speeds

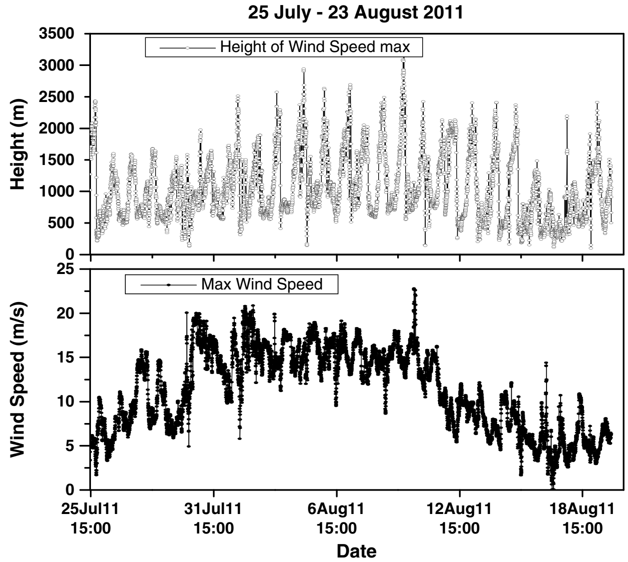

Figure 5. Temporal variation (at 5 min interval) of the height of (top) wind speed maximum and (bottom) wind speed during the period 25 July to 23 August 2011 at Mahbubnagar.

in the jet core were as high as 20 m/s on some days. The occurrence frequency of height of LLJ core and the core speed during the above 1 month period is shown as histograms in Figure 6. The data are separated into typical daytime (10:00–16:00 h LT) and nighttime (23:00–06:00 h LT). It is observed that most frequently occurring height of the maximum wind speed during daytime shows a broad peak between 1200 and 1600 m, whereas during nighttime, the most frequently occurring LLJ core height is narrow around 600 m. The frequency histogram of LLJ core speed shows a bimodal distribution during both daytime and nighttime. Most frequently occurring maximum wind speeds are centered around 7 m/s and 14 m/s during daytime and around 7 m/s and 17 m/s during nighttime. Thus, the

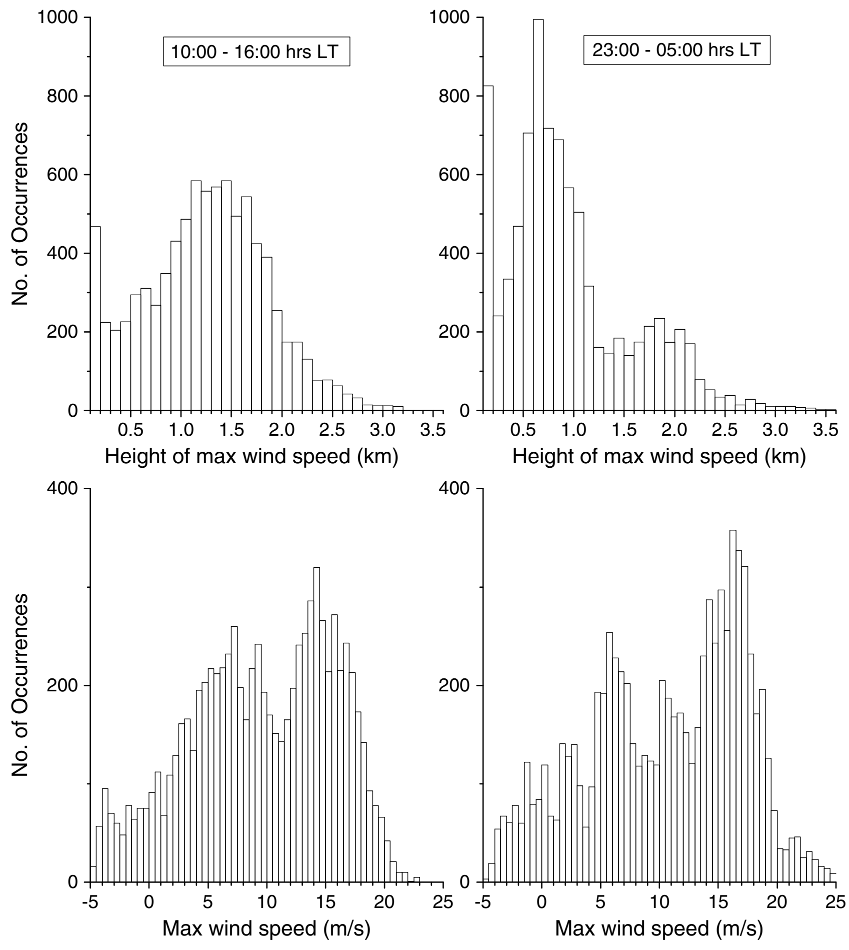

Figure 6. Frequency of the occurrence of (top row) the height of the jet core and (bottom row) maximum wind speed in the jet core during (fist column) daytime and (second column) nighttime for the lidar data collected during the period 25 July to 23 August 2011.

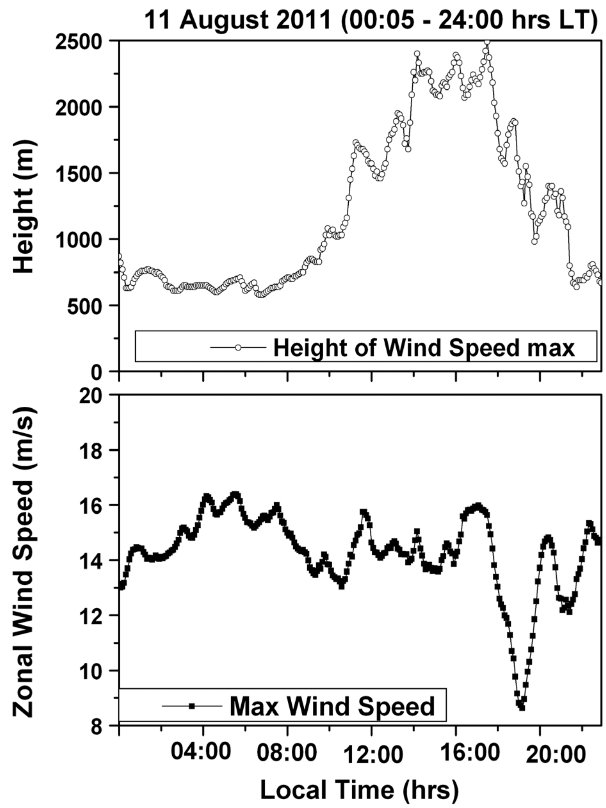

Figure 7. Temporal variation (at 5 min interval) of the (top) height of wind speed maximum and (bottom) wind speed on 11 August 2011.

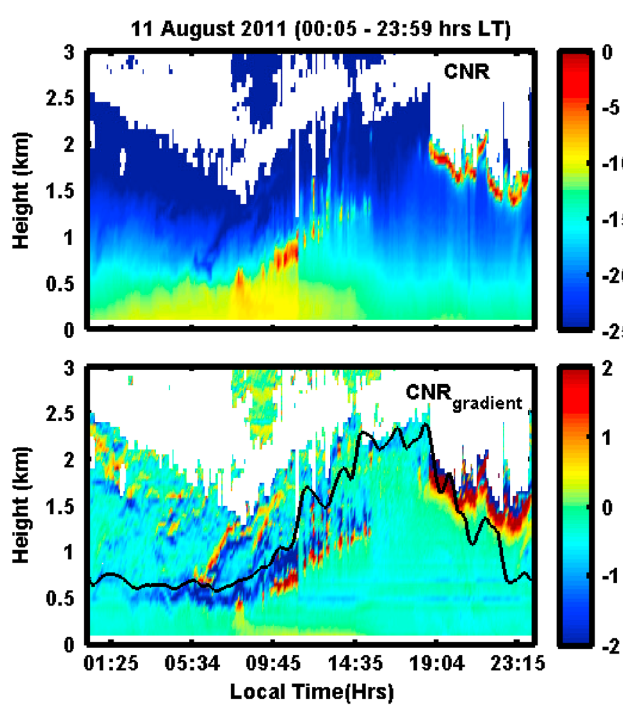

Figure 8. (top) Time-height distribution of carrier-to-noise ratio: CNR and (bottom) CNR gradient along with time variation of height of wind speed maximum on 11 August 2011.

core of the nocturnal LLJ shows higher wind speed during the active phase than during normal conditions of southwest monsoon over this tropical Indian station.

To examine this diurnal variation in more detail, 5 min data of the height of LLJ core and maximum wind speed are shown for 11 August 2011 in Figure 7. It is clearly seen that the nocturnal jet lies between 600 and 700 m during nighttime, with very little variation and soon after local sunrise, starts lifting up. This upward movement of LLJ core height is sometimes smooth and rapid and sometimes oscillatory. It attains a peak height of nearly 2500 m by 2–3 h after local noon and by local sunset time collapses to around 500 m altitude. This type of diurnal variation in core height is noticed on almost all the days. Wind speeds in the core of the jet are between 14 m/s and 16 m/s on this particular day and a sudden drop to lower values (~8 m/s) by sunset time occurs.

At Mahbubnagar, a semiarid location, during the period of study, nearly clear skies were observed in the forenoon hours. By late afternoon, convection becomes strong and low-level clouds start forming resulting in convective (occasionally thunderstorm) rainfall on many days. Thus, daytime convection and ground heating must be aiding the upward movement of the LLJ. To demonstrate this, vertical distribution of CNR (equivalent to signal-to-noise ratio), which is strongly correlated to aerosol backscatter [*Aitken et al.*, 2012], of the WindCube-200 wind lidar on 11 August 2011 is shown in Figure 8 (top). Strong backscattered signal from the surface layers in the daytime implies the presence of aerosols in this region. The CNR gradient is then computed and shown in Figure 8 (bottom). The largest negative gradient in vertical profile of aerosol backscatter from surface denotes the boundary of well-mixed boundary layer below and stable layers aloft [*Endlich et al.*, 1979; *Ernest Raj and Devara*, 1992, 1993; *Ernest Raj et al.*, 2011]. In Figure 8 (bottom), along with the CNR gradient, the height of the LLJ core on 11 August 2011 (as shown in Figure 7) is superposed. It is observed that as the convective boundary layer grows after sunrise, it seems to be pushing the LLJ core upward. In the growing stage, it is seen that

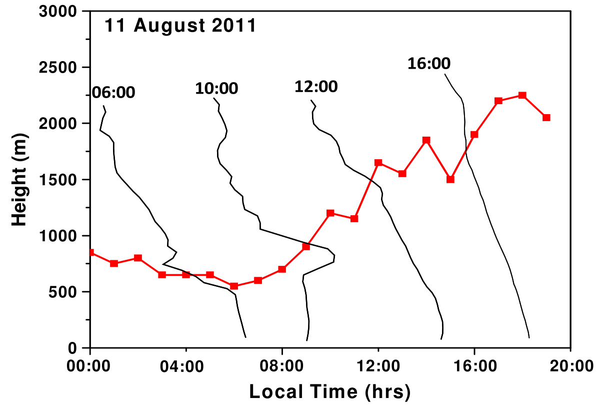

Figure 9. Temporal variation of height of zonal wind speed maximum (red curve) and overlaid vertical profiles of carrier-to-noise ratio (black solid) at four typical hours on 11 August 2011.

the largest negative gradient in CNR is always just below the peak height of westerly jet core. Also, the day time surface heating will influence the surface fluxes, and these fluxes will generate more turbulence at the surface and layers above it and enhance the mixing processes within the boundary layer. Wind shear below the jet core region may also have substantial influence in the lifting of the jet core. Thus, the evolution of the nocturnal LLJ after sunrise appears to be associated with the convection driven growth of the atmospheric boundary layer or the mixed layer, which are in turn influenced by surface level processes during convectively active monsoon period. This type of time evolution was not possible to be discerned from Sodar observations because of their height limitation. Clear-air VHF radars give information mostly above 1000 m and hence do not capture the features of nocturnal LLJ, while UHF radars can give wind information from around 400 m [*Kalapureddy et al.*, 2007]. Figure 9 shows the hourly variation of the height of the LLJ on 11 August 2012. Vertical profiles of aerosol backscatter (in terms of CNR) obtained from the lidar at 06:00, 10:00, 12:00, and 16:00 h LT are superimposed on the time evolution of westerly LLJ. One can notice a strong backscatter (aerosols) just below this wind speed maximum in all the four profiles. Thus, as the nocturnal LLJ starts evolving and moving upward after sunrise, strong convection (upward vertical motions and mixing) seems to carry the aerosols and other atmospheric constituents aloft. As these aerosols reach the heights of 2000–3000 m, they interact with available moisture by acting as cloud condensation nuclei. Thus, the cloud-aerosol interaction may lead to convectively generated clouds, to their vertical growth, and then to precipitation in the late afternoon hours. During the period of observations reported here at Mahbubnagar, there were observations of frequent rain spells in the afternoon/evening hours, which are consistent with the earlier reported observational and model results on diurnal variation in precipitation over interior India [*Basu*, 2007; *Roy and Balling*, 2007; *Baisutti et al.*, 2012]. Thus, boundary layer horizontal winds and associated wind shears and turbulence seem to have close interaction with convective activity, cloud processes, and convective rain over the region.

4. Summary

High spatial and temporal resolution vertical profiles of zonal wind obtained from Doppler wind lidar in the altitude range of 100 m to 3000 m aboveground level (at every 50 m height interval and 5 min time averaged) at a tropical Indian station during the period 25 July to 23 August are used to investigate the time evolution of the nocturnal monsoon LLJ occurring over this region. During this period of southwest monsoon, the zonal winds in the altitudes up to 3000 m above ground are predominantly westerly. Results show that on almost all the days, there is a nocturnal westerly wind speed maximum (jet) around 400–500 m above ground. Soon after local sunrise, the core of the jet smoothly gets lifted up and by afternoon, the westerly wind maximum is shifted to higher altitudes of around 2000 m–2500 m. The high-resolution lidar observations seem to indicate that the nocturnal LLJ itself is moving to higher altitudes and evolving into daytime westerly monsoon LLJ. By late afternoon, the core of the jet collapses to lower altitudes, sometimes quite abruptly. This type of diurnal oscillation in the height of the wind speed maximum is seen throughout the 1 month monsoon period data. The amplitude of the diurnal oscillation seems to be larger when the wind speeds in the core of the jet are high ($>$15 m/s). The most frequently occurring LLJ height is 600 m during nighttime and between 1200 m and 1600 m during daytime. Wind speeds in the core of the jet were relatively higher in magnitude during nighttime. Height variation of zonal wind derived from the wind lidar compares qualitatively with simultaneously observed GPS upper air sounding (radiosonde) wind measurements. The current observations also indicate that the upward movement of the jet core is closely associated with daytime convection and boundary layer growth. As the core of strong westerly winds moves up after sunrise, the associated wind shear and turbulence mix well the surface level aerosols and other constituents and help to transport them to higher levels. The presence of clouds overhead in the region seems to inhibit this type of time evolution.

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References

Aitken, M. L., M. E. Rhodes, and J. K. Lundquist (2012), Performance of a wind-profiling lidar in the region of wind turbine rotor disks, *J. Atmos. Oceanic Technol.*, *29*, 347–355, doi:10.1175/JTECH-D-11-00033.1.

Andreas, E. L., K. J. Claffey, and A. P. Makshtas (2000), Low-level atmospheric jets and inversions over Western Weddell Sea, *Boundary Layer Meteorol.*, *97*, 459–486.

Baisutti, M., S. E. Yuter, C. D. Burleyson, and A. H. Sobel (2012), Very high resolution rainfall patterns measured by TRMM precipitation radar: Seasonal and diurnal cycles, *Clim. Dyn.*, *39*, 239–258.

Banta, R. M., R. K. Newsom, J. K. Lundquist, Y. L. Pichugina, R. L. Coulter, and L. J. Mahrt (2002), Nocturnal low-level jet characteristics over Kansas during CASES-99, *Boundary Layer Meteorol.*, *105*, 221–252.

Banta, R. M., Y. L. Pichugina, and R. K. Newsom (2003), Relationship between low-level jet properties and turbulence kinetic energy in the nocturnal stable boundary layer, *J. Atmos. Sci.*, *60*, 2549–2555.

Basu, B. K. (2007), Diurnal variation in precipitation over India during the summer monsoon season: Observed and model predicted, *Mon. Weather Rev.*, *135*, 2155–2167.

Blackadar, A. K. (1957), Boundary layer wind maxima and their significance for the growth of nocturnal inversion, *Bull. Am. Meteorol. Soc.*, *38*, 283–290.

Bonner, W. D. (1968), Climatology of the low-level jet, *Mon. Weather Rev.*, *96*, 833–850.

Brill, K. F., L. W. Uccellini, R. P. Burkhart, T. T. Warner, and R. A. Anthes (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.

Burk, S. D., and W. T. Thompson (1996), The summertime low-level jet and marine boundary layer structure along the California coast, *Mon. Weather Rev.*, *124*, 668–686.

Courtney, M., R. Wagner, and P. Lindelöw (2008), Testing and comparison of lidars for profile and turbulence measurements in wind energy, *IOP Conf. Ser. Earth Environ. Sci.*, *1*, 012,021, doi:10.1088/1755-1315/1/1/012021.

Endlich, R. M., F. L. Ludwig, and E. E. Uthe (1979), An automatic method for determining the mixing depth from lidar observations, *Atmos. Environ.*, *13*, 1051–1056.

Ernest Raj, P., and P. C. S. Devara (1992), Laser radar applications to air pollution potential measurements during post-sunset period, *J. Opt.*, *21*, 87–92.

Ernest Raj, P., and P. C. S. Devara (1993), On the stable stratification of the nocturnal lower troposphere inferred from lidar observations over, Pune, *Boundary Layer Meteorol.*, *65*, 197–205.

Ernest Raj, P., M. C. R. Kalapureddy, Y. Jaya Rao, S. M. Sonbawne, K. K. Dani, and P. C. S. Devara (2011), Lidar remote sensing of the mixed layer height over a tropical urban Indian station, *Int. J. Remote Sens.*, *32*, 4819–4833, doi:10.1080/01431161.2010.489263.

Forman, J. R., J. W. George, and R. D. Lewis (1965), Measurement of localized flow velocities in gases with a laser Doppler flowmeter, *Appl. Phys. Lett.*, *7*, 77–78.

Frisch, A. S., B. W. Orr, and B. E. Martner (1992), Doppler radar observations of the development of a boundary-layer nocturnal jet, *Mon. Weather Rev.*, *120*, 3–16.

Goswami, B. N., D. Sengupta, and G. Suresh Kumar (1998), Intraseasonal oscillations and interannual variability of surface winds over the Indian monsoon region, *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, *107*(1), 45–64.

Holton, J. R. (1967), The diurnal boundary layer wind oscillation above sloping terrain, *Tellus*, *19*, 199–205.

IMD (2012), *Monsoon 2011 – A Report*, IMD Met. Monograph 'Synoptic Meteorology', No. 01/2012, edited by A. Tyagi and D. S. Pai, pp. 178, National Climate Centre, IMD, Pune.

Joseph, P. V., and P. L. Raman (1966), Existence of low-level westerly jet-stream over peninsular India during July, *Indian J. Meteorol. Phys.*, *17*, 407–410.

Joseph, P. V., and S. Sijikumar (2004), Intraseasonal variability of the low-level jet stream of the Asian Summer Monsoon, *J. Clim.*, *17*, 1449–1458.

Joshi, R. R., S. M. Deshpande, N. Singh, S. H. Damle, and G. B. Pant (2006), UHF wind profiler observations of monsoon low level jet over Pune, *Indian J. Radio Space Phys.*, *35*, 349–359.

Kaimal, J. C., and Y. Izumi (1965), Vertical velocity fluctuations in a nocturnal low-level jet, *J. Appl. Meteorol.*, *4*, 576–584.

Kalapureddy, M. C. R., D. N. Rao, A. R. Jain, and Y. Ohno (2007), Wind profiler observations of a monsoon low-level jet over a tropical Indian station, *Ann. Geophys.*, *25*, 2125–2137.

Karipot, A., Y. Monique, Y. Leclerc, and G. Zhang (2009), Characteristics of nocturnal low-level jets observed in the north Florida area, *Mon. Weather Rev.*, *137*, 2605–2621.

Krishnamurti, T. N., J. Molinari, and H. L. Pan (1976), Numerical simulation of the Somali jet, *J. Atmos. Sci.*, *33*, 2350–2362.

Lenschow, D. H., X. S. Li, C.-J. Zhu, and B. B. Stankov (1988), The stably stratified boundary layer over the Great Plains. I. Mean and turbulent structure, *Boundary Layer Meteorol.*, *42*, 95–121.

Li, J., and Y. L. Chen (1998), Barrier jets during TAMEX, *Mon. Weather Rev.*, *126*, 959–971.

Mahrt, L. (1999), Stratified atmospheric boundary layers, *Boundary Layer Meteorol.*, *90*, 375–396.

Mahrt, L., and D. Vickers (2002), Contrasting vertical structures of nocturnal boundary layers, *Boundary Layer Meteorol.*, *105*, 351–363.

Mahrt, L., R. C. Heald, D. H. Lenschow, B. B. Stankov, and I. Troen (1979), An observational study of the structure of the nocturnal boundary layer, *Boundary Layer Meteorol.*, *17*, 247–264.

Mann, J., A. Peña, F. Bingöl, R. Wagner, and M. S. Courtney (2010), Lidar scanning of momentum flux in and above the atmospheric surface layer, *J. Atmos. Oceanic Technol.*, *27*, 959–976.

Parish, T. R. (1982), Barrier winds along the Sierra Nevada mountains, *J. Appl. Meteorol.*, *21*, 925–930.

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.

Parish, T. R., A. R. Rodi, and R. D. Clark (1988), A case study of the summertime Great Plains low-level jet, *Mon. Weather Rev.*, *116*, 94–105, doi:10.1175/1520-0493(1988)116<0094:ACSOTS>2.0.CO;2.

Rajeevan, M., S. Gadgil, and J. Bhate (2010), Active and break spells of the Indian summer monsoon, *J. Earth Syst. Sci.*, *119*, 229–247.

Raman, R. M., M. V. Ratnam, M. Rajeevan, V. V. M. J. Rao, and S. V. B. Rao (2011), Intriguing aspects of the monsoon low-level jet over peninsular India revealed by high-resolution GPS radiosonde observations, *J. Atmos. Sci.*, *68*, 1413–1423.

Rothermel, J., L. D. Olivier, R. M. Banta, R. M. Hardesty, J. N. Howell, D. R. Cutten, S. C. Johnson, R. T. Menzies, and D. M. Tratt (1998), Remote sensing of multi-level wind fields with high-energy airborne scanning coherent Doppler lidar, *Opt. Express*, *2*, 40–50.

Roy, S. S., and C. Balling (2007), Diurnal variation in summer season precipitation in India, *Int. J. Climatol.*, *27*, 969–976.

Samelson, R. M. (1992), Supercritical marine-layer flow along a smoothly varying coastline, *J. Atmos. Sci.*, *49*, 1571–1584.

Schwerdtfeger, W. (1979), Meteorological aspects of the drift of ice from the Weddell Sea toward the middle-latitude westerlies, *J. Geophys. Res.*, *84*, 6321–6327.

Sikka, D. R., and S. Gadgil (1980), On the maximum cloud zone and the ITCZ over Indian longitudes during the south-west monsoon, *Mon. Weather Rev.*, *108*, 1840–1853.

Smedman, A. S., M. Tjernstrom, and U. Högström (1993), Analysis of the turbulence structure of a marine low-level jet, *Boundary Layer Meteorol.*, *66*, 105–126.

Smedman, A. S., H. Bergstrom, and U. Hogstrom (1995), Spectra, variances and length scales in a marine stable boundary layer dominated by a low level jet, *Boundary Layer Meteorol.*, *76*, 211–232.

Smedman, A. S., H. Bergström, and B. Grisogono (1997), Evolution of stable internal boundary layers over a cold sea, *J. Geophys. Res.*, *102*, 1091–1099.

Stull, R. B. (1988), *An Introduction to Boundary Layer Meteorology*, 666 pp., Kluwer Academic Publishers, Dordrecht, The Netherlands.

Tjernström, M., and A. S. Smedman (1993), The vertical turbulence structure of the coastal marine atmospheric boundary layer, *J. Geophys. Res.*, *98*, 4809–4826.

Uccellini, L. W., and D. R. Johnson (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., R. K. Newsom, and R. Calhoun (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.

Winant, C. D., C. E. Dorman, C. A. Friehe, and R. C. Beardsley (1988), The marine layer off northern California: An example of supercritical channel flow, *J. Atmos. Sci.*, *45*, 3588–3605.

Zhong, S., J. D. Fast, and X. Bian (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.