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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

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ABSTRACT

Monsoon Low Level Jet (MLLJ) is one of the important components of Indian summer monsoon. Using high-resolution measurements of boundary layer wind profiles from a Doppler wind lidar at Mahbubnagar (16.73°N, 77.98°E and 445 m above mean sea level), India, the temporal evolution of the MLLJ has been investigated. Both jet core height and jet speed show clear diurnal variation during the monsoon season. Jet core starts descending down in the evening hours and remains at a height between 600 m and 900 m (above surface level) during nighttime. Soon after local sunrise, jet core starts ascending and reaches heights above 1800 m by afternoon hours. Jet core speed starts strengthening in the nighttime and attains maximum intensity in the early morning hours and then the core speeds decrease around the time when the jet core is at its maximum height. Simultaneous diurnal variations of surface temperature, sensible heat flux, latent heat flux and Richardson number show that daytime heating and turbulence in surface layers enhance mixing in the daytime boundary layer which helps in lifting of the jet core. Shear produced turbulence and momentum fluxes also play a significant role in the diurnal variation of MLLJ. Factors influencing the evolution of the convective boundary layer and factors responsible for formation of nocturnal boundary layer are closely associated with the diurnal variation of MLLJ occurring over the low-latitude south Indian peninsular region during monsoon season. The results emphasize the importance of continuous and high spatial-temporal resolution wind profile measurements in the monsoon boundary layer from a Doppler wind lidar.

1. Introduction

Indian summer monsoon is a part of the Asian monsoon system which exhibits a wide spectrum of variability during the summer monsoon season (June–September). It contributes to 80% of the total annual rainfall in India. Since India is an agriculture-based country which depends on rainfall, the variability in monsoon activity will affect the entire country in its water needs. Frequent or long persisting break conditions during the monsoon season can lead to drought situation. Long breaks during critical growth periods of agricultural crops lead to substantially reduced yield (Gadgil and Joseph, 2003) and so understanding the monsoon intra-seasonal variability is very important. There are many components of the monsoon system which have significant influence on monsoon variability. One of them is the strong cross equatorial wind flow in the lower troposphere, which is known as Monsoon Low Level Jet (MLLJ). It is arising mainly because of thermal gradient between the Asian landmass and surrounding oceans. Initially it is southerly in direction over south Indian Ocean, but as it crosses the equator, because of Coriolis force, it turns south-westerly as it reaches the Indian subcontinent (Hoskins and Rodwell, 1995). The dynamics involved in the sustaining mechanism of this MLLJ is described in detail by Rodwell and Hoskins (1995). It is now recognized that MLLJ is interlinked with the active and break phases of Indian summer monsoon (Goswami et al., 1998) as its strength and position controls the moisture transport over Indian land mass.

The term 'Low Level Jet (LLJ)' is generally used to describe a narrow region of strong winds in the lower atmosphere close to the surface. Its existence and characteristics have been observed and reported from many parts of the world. Most of these are nighttime phenomena. At nighttime under clear-sky conditions and with weak synoptic winds, a wind maximum close to the ground (below 1 km from surface) can exist, often referred to as nocturnal LLJ, the well documented one for example, being the

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Great Plains LLJ (Holton, 1967). Sodars and wind profilers have hitherto been used for investigation of LLJ structure (Karipot et al., 2009). Recently Murthy et al. (2013) reported from sodar-derived winds, the presence of a nocturnal jet over Pune (18.38°N, 73.58°E), India in the 200–500 m layer above ground level during local nighttime hours (2000–0600 h) in south-west monsoon season. Because of its presence at altitudes close to surface and having greater wind speed than in the air above and below, 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.

But the LLJ occurring over the low latitude peninsular Indian region in the daytime boundary layer during south-west monsoon season (June–September) appears to be different from the above mentioned nocturnal LLJ, since this is a strong, predominantly westerly flow with a core region existing at heights above 1 km from surface. Joseph and Raman (1966) pointed out the occurrence of this westerly low-level jet stream over peninsular India, with strong vertical and horizontal wind shears, by analyzing 5-yr radiosonde wind profile data. The features that define MLLJ, according to them, are a wind speed maxima below 6 km, wind speeds lesser in magnitude below and above this wind speed maxima. Further, they reported that this MLLJ exists around 850 mb (around 1.5 km height above mean sea level) with a core speed of 20–30 ms^{-1}. Findlater (1969a, 1969b) mentioned that this MLLJ originates as easterly in southern hemisphere. These easterlies after crossing the equator turn into a westerly current over the Arabian Sea and flow over the Indian subcontinent as strong south-westerly winds. From monthly mean wind data, Findlater (1971) showed that the LLJ splits into two branches over the Arabian Sea, one branch passing southeastward toward Sri Lanka and the other eastward through peninsular India. By using NCEP-NCAR reanalysis daily wind data, Joseph and Sijikumar (2004) studied the intra-seasonal variability of the MLLJ and found that during active monsoon time the core of the MLLJ passes through 10–20°N latitude belt and in break conditions it bypasses Indian subcontinent. They have not found any evidence of the above splitting of MLLJ over Arabian Sea.

In view of its importance, many observational studies of MLLJ have been undertaken in India using wind profilers and GPS radiosonde. 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 ms^{-1}. Using measurements from a UHF radar/wind profiler (404 MHz) over Pune, India, Joshi et al. (2006) found that the jet core height varies between 1.6 and 3 km. Most of the above cited studies used relatively low vertical resolution datasets for investigating the MLLJ. Recently Raman et al. (2011) explored the spatial characteristics of MLLJ using frequent ascents of GPS sonde and found that it exhibits diurnal and intra-seasonal variability. But still the diurnal variability in core height and intensity of MLLJ remains unexplored fully. In the current study, authors try to give some insight into the features of the MLLJ and attempt to explain the atmospheric factors that influence the diurnal variability/evolution of the jet core height and jet core speed. Through analysis of simultaneously measured surface meteorological parameters, possible interlinking processes and mechanisms of MLLJ and the role of surface and boundary layer processes on the temporal evolution of MLLJ are explored and presented below.

2. System description and data analysis

A Doppler wind lidar (WindCube-200) developed by LEOSPHERE, France in cooperation with the French Aerospace Agency (Office National d′Etudes et de Recherche Aérospatiales) is being used to obtain high resolution wind structure both in time and space in the tropical Indian monsoon region. With this system one can measure simultaneously all the three components of atmospheric winds (east-west, north-south, vertical) in the lower troposphere (100–6000 m) at 50 m height interval and at about 60–80 s time interval. The measurement hypothesis of this lidar is that, it uses aerosols as 'tracers' along the line of sight, basically assuming that the movement of aerosols is along with the mean wind. The moving aerosols in the atmosphere induce a change in frequency of the backscattered light. This Doppler shift of frequency and the sign of the shift will depend ultimately on the aerosols which move either towards or away from the instrument. The frequency difference between the emitted and backscattered light is measured which is directly proportional to radial wind speed.

WindCube-200 operates in near-IR wavelength (1.54 μm), and its pulse energy is 100 μJ, scanning cone angle is ~15°, and speed and direction accuracy are 0.5 ms^{-1} and 1.5° respectively. It has a 15° prism to deflect the beam from the vertical. The prism holds still while the lidar sends a stream of pulses (typically 36000) 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 60–80 s. During the rotation and before the next stream of pulses can be sent, the recorded data are processed. At each direction step (north, east, south, west), the WindCube combines the four most recent radial speeds at each height to compute the three wind components (u-zonal, v-meridional, w-vertical wind velocities).

Lidar-derived wind measurements have been made at Mahbubnagar (16.73°N, 77.98°E, 445 m above mean sea level), India as part of an intensive ground observational campaign (CAIPEEX-IGOC-2011) conducted during the period June–October 2011. The primary aim of this campaign was to investigate cloud-aerosol interactions by making ground-based as well as aircraft observations. Altitude profiles (100–3000 m) of lidar-derived zonal wind averaged over every 5 min have mainly been used in this study to discuss the features of LLJ. Mahbubnagar is a tropical semi-urban station which is situated to the south east in the semi-arid region of peninsular India on the eastern edge of the Deccan Plateau. 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. The station is approximately 100 km south west of Hyderabad, a large urban city and falls in the rain shadow region. Clouds in this region are strongly influenced by the underlying boundary layer, where dynamics is controlled by surface generated eddies.

As part of the above ground-based observations, a 20-m micrometeorological tower has been installed at the site, nearly 1 km away from the wind lidar location in the open field devoid of trees and other obstructions. The main aim involves measurement of all components of surface energy balance and turbulence parameters in the surface layer, such that complete energy balance could be evaluated. Slow sensors for measuring air temperature, wind speed and relative humidity have been fitted on the tower at 5 levels, namely 1 m, 2 m, 4 m, 12 m, and 18 m. Eddy covariance system (comprising fast response sonic anemometer, CO_2 analyzer and water vapor sensor) for measuring the turbulent fluctuations in wind, temperature, water vapor and CO_2 were installed on the tower at 8 m and 16 m heights. To calculate sensible heat flux and latent heat flux, 1-s interval data obtained from the tower measurements have been used in the current study. Due to limitation in availability of continuous data during the periods 13–22 July 2011 and 1–7 August 2011, for the calculation of