Intriguing Aspects of the Monsoon Low-Level Jet over Peninsular India Revealed by High-Resolution GPS Radiosonde Observations

M. ROJA RAMAN
Department of Physics, Sri Venkateswara University, Tirupati, India

M. VENKAT RATNAM AND M. RAJEEVAN
National Atmospheric Research Laboratory, Gadanki, Tirupati, India

V. V. M. JAGANNADHA RAO
SRRS Government Polytechnic, Sircilla, India

S. VIJAYA BHASKARA RAO
Department of Physics, Sri Venkateswara University, Tirupati, India

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ABSTRACT

The strong cross-equatorial flow in the lower troposphere, widely known as the monsoon low-level jet (MLLJ), plays an important role in the Indian summer monsoon (ISM) rainfall during June–September. Using high-resolution GPS radiosonde observations over Gadanki (13.5°N, 79.2°E), some new aspects of MLLJ have been reported. In the present study it is found that, on average, the MLLJ exists at 710 hPa over southeastern peninsular India, rather than at 850 hPa as reported by earlier studies. It is observed that the ECMWF Re-Analysis (ERA)-Interim data provide better results on the spatial, temporal, and vertical variation of MLLJ. Further, the characteristics of the MLLJ during the active and break spells of ISM are also investigated; higher MLLJ core height and intensity are found during active phases of the Indian monsoon. This study emphasizes the use of high-resolution measurements for studying monsoon dynamics in detail.

1. Introduction

Monsoon dynamics play an important role in determining the amount of precipitation/rainfall across the country during the southwestern monsoon. Among many dynamical parameters, the strong cross-equatorial flow in the lower troposphere widely known as the monsoon low-level jet (MLLJ) plays an important role on the Indian summer monsoon (ISM) rainfall, which occurs during June–September. The strong cross-equatorial flow, which is the manifestation of large thermal gradients between the Asian landmass and surrounding oceans, turns to westerlies because of the Coriolis force over the Arabian Sea forming the MLLJ (Hoskins and Rodwell 1995), and its dynamics have been studied in detail by Rodwell and Hoskins (1995). The strength of MLLJ is modulated between the active and break phases of the ISM. The position and strength of MLLJ decides the barotropic instability required for the genesis of low pressure systems including monsoon depressions over the Bay of Bengal. Further, the variations in the strength of MLLJ determine moisture transport over the Indian landmass. Better understanding of the variations of the MLLJ may lead to better forecasts of the genesis of monsoon synoptic systems.

The existence of low-level jets (LLJs) has been observed in several parts of the world; among these, the most documented one is the Great Plains LLJ in the central United States (Wu and Raman 1997). But most of these jets are southerly in direction and nocturnal in nature. For the first time, Joseph and Raman (1966) established the existence of the MLLJ over peninsular India during the southwestern monsoon with strong vertical
and horizontal wind shear. According to their definition, the MLLJ can be identified as follows: (i) wind speed maxima should be below 6 km and (ii) wind speed should increase below and then decrease above the wind speed maxima. By considering the Indian Daily Weather Reports (IDWR) data of few stations over southern peninsular India, they reported that the MLLJ core lies at 850 hPa, which is approximately at a height of 1.5 km MSL, with speeds of the order of 20–30 m s⁻¹. By considering the same dataset for same stations, Sam and Vittal Murty (2002) described the changes in MLLJ characteristics during the active and break phases of the monsoon.

Findlater (1969a,b) reported that the MLLJ originates as easterlies in the southern Indian Ocean. These easterlies, after crossing the equator as narrow current of air close to the East African coast, turn into a westerly current over the Arabian Sea and enter the Indian region as strong southwesterly winds. Further, using monthly mean winds, Findlater (1971) showed that the LLJ splits into two branches over the Arabian Sea, but this splitting of jet is still debated.

Using Lower Atmospheric Wind Profiler (LAWP) data over Gadanki, Kalapureddy et al. (2007) showed that the MLLJ core lies at a height of 1.8 ± 0.6 km and found the mean jet intensity to be 20 m s⁻¹. Using a similar instrument over Pune (18.3°N, 73.5°E), Joshi et al. (2006) found that the jet core height varies between 1.6 and 3 km. But it is to be noted that the height coverage of LAW during clear-air conditions is mostly limited to 2–2.5 km. Using National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis data, Joseph and Sijikumar (2004) studied the vertical structure of the MLLJ and showed that the MLLJ core lies at 850 hPa uniformly at all locations. However, very recently Roja Raman et al. (2009) observed that these model-derived winds available at standard pressure levels significantly underestimate values when compared to the ground-based observations over the Indian region.

It is worth mentioning that most of the above cited studies used relatively low-vertical-resolution datasets for studying the MLLJ. The present study reports the advantage of high-resolution datasets in observing MLLJ characteristics explicitly. Four years (2006–09) of high-resolution GPS radiosonde observations from Gadanki revealed several important aspects of MLLJ. First, the existence of the MLLJ over Gadanki is confirmed using GPS radiosonde observations, and then the spatial and vertical characteristics of MLLJ are examined using the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA)-Interim and NCEP–NCAR reanalysis datasets. Special attention is paid to the spatial and temporal variation of the MLLJ peak height and peak speed. This study also provides information about the behavior of the MLLJ during active and break phases of ISM. Finally the credibility of various datasets for studying such features is discussed.

2. Data

a. High-resolution GPS radiosonde observations

High-vertical-resolution GPS radiosonde (Vaisala RS-80/92/Meisei) balloons being launched almost regularly over Gadanki (13.5°N, 79.2°E) at 1200 UTC (UTC = LT + 5 h 30 min) since April 2006 have been used. These balloons will effectively cross the jet heights and the observations are made with a vertical resolution of 10 m. However, the data have been equally gridded to 100 m while performing quality checks to minimize the fluctuations that may occur from random motion of the balloon. The complete details of this system and database are available from Nath et al. (2009). As Gadanki is situated at a height of 370 m above mean sea level, data from 400 m to 7 km have been considered for the present study, corresponding to pressure levels of approximately 950 to approximately 430 hPa. The MLLJ peak intensity and core height/pressure have been picked up daily and the values are averaged for representing monthly and inter- and intraseasonal variations.

b. NCEP–NCAR and ECMWF-Interim reanalysis data

NCEP–NCAR reanalysis standard-level postprocessed daily zonal wind data available with 2.5° × 2.5° latitude–longitude grids during monsoons from 1989 to 2009 were also utilized to study the spatial distribution and also to compare the MLLJ features in and around Gadanki. The details of NCEP–NCAR reanalysis data are given in Kalnay et al. (1996). For comparison with GPS radiosonde observations over Gadanki, a grid box covering 12.5°–15°N, 77.5°–80°E has been considered.

In addition, the ERA-Interim reanalysis datasets (Simmons et al. 2007) are also used for the present study. These are third-generation reanalysis data from ECMWF available from January 1989 onward. Interim reanalysis data use mostly the datasets of observations acquired for the 40-yr ECMWF Re-Analysis (ERA-40), supplemented by data for later years from ECMWF operational archive. It provides data at 1.5° × 1.5° latitude–longitude grids with more pressure levels than the ERA-40 and 15-yr ECMWF Re-Analysis (ERA-15) datasets. More details of model development can be obtained from Simmons et al. (2007). For the present study, data from 1989 to 2009 during ISM months [June–September (JJAS)] have been considered.
There are about 17 pressure levels from 1000 to 450 hPa with a vertical resolution of 25 hPa from 1000 to 750 hPa and resolution of 50 hPa from 750 to 450 hPa. For comparison with GPS radiosonde observations over Gadanki, a grid box of 13.5°N, 79.5°E have been considered.

In addition to this, data from regular radiosonde measurements (using tracking radar) at a nearby India Meteorological Department (IMD) station at Chennai (13.0°N, 80.1°E) have also been considered from 2006 to 2009 during ISM months (JJAS) to compare the observed features. Further, the daily gridded rainfall data (Rajeevan and Bhate 2009) available in 0.5° × 0.5° latitude–longitude grids since 1951 provided by IMD are also considered.

3. Results and discussion

a. Vertical distribution of the MLLJ over Gadanki

In general, the MLLJ is defined in terms of the zonal wind and has a strong link with ISM rainfall (Sam and Vittal Murty 2002). To get better picture of monsoon circulation, one needs very high-resolution measurements. When compared to regular radar-tracked radiosonde observations, GPS satellite-tracked radiosonde observations provide the meteorological parameters with very high vertical resolution (Roja Raman et al. 2009). In the present study, such high-resolution GPS radiosonde observations available from Gadanki are used. A typical height–time section of the zonal wind observed with the Gadanki GPS radiosonde during the monsoon of the year 2008 is shown in Fig. 1a. This figure reveals two striking features: the intensity of zonal wind is highly variable from June to September and sometimes have very low intensities at all heights up to 410 hPa. This is associated with the intraseasonal variability (ISV) of the ISM. On day-to-day scale the height of zonal wind maxima is also found to be variable between 2 and 4 km with an average height of about 3 km, which is equivalent to a pressure level of 710 hPa over Gadanki. This result is somewhat surprising as earlier reports mentioned that zonal wind maxima will persist at 850 hPa.

Before going into further details, first it is tested how these features will be represented in the reanalysis datasets that are widely used to study the MLLJ. Figure 1b shows the time–height variation of zonal wind observed by the ERA-Interim reanalysis dataset over the Gadanki grid (13.5°N, 79.5°E) during the same period observed at 1200 UTC. Even though the closest available grid box is slightly away from the observational site, these data also reveal features similar to those observed by Gadanki GPS radiosonde, except with smaller magnitudes (by ~2–3 m s⁻¹) than that of Gadanki GPS radiosonde. Interestingly, the ERA dataset over Gadanki also shows the wind maxima most of the times at a pressure level lower (higher height) than 850 hPa. On an average the zonal wind maxima are found around 728 hPa, which is equivalent to a height of approximately 2.8 km.

The height–time section of the zonal wind observed by the NCEP–NCAR data over the grid box averaged from 12.5° to 15°N and 77.5° to 80°E at 1200 UTC is shown in Fig. 1c. More or less similar features are noticed as observed by GPS radiosonde and ERA-Interim, but the magnitudes are much lower (by 5 m s⁻¹) than with the GPS radiosonde. Also, the wind maxima are observed around 850-hPa level, unlike those observed by other two datasets.

The magnitude of zonal wind maxima is also compared among the three datasets and is shown in Fig. 1d. At the beginning of the monsoon, the wind maxima are...
very low (2 m s\(^{-1}\)) and gradually increase with the progression of the monsoon over the observation site and reach as high as 18 m s\(^{-1}\) over Gadanki. This peak intensity continues for a few days, decreases rapidly, and again continues for a few days. This variation in peak intensity is closely linked to the active and break phases of the monsoon (Jagannadha Rao et al. 2007). As revealed from Figs. 1a–c, in general Gadanki GPS radiosonde data show higher magnitudes of zonal wind by about 2–4 m s\(^{-1}\) than the ERA-Interim data and by about 6–8 m s\(^{-1}\) than the NCEP–NCAR data. However, the day-to-day changes are almost similar in all the datasets, including sharp changes from low to high values. Also, as pointed by Annamalai et al. (1999), ECMWF (ERA-15 and ERA-40) datasets show near-real features of MLLJ characteristics. These features are seen almost in all the years among different datasets over Gadanki with large interannual variation.

b. Diurnal variation of the MLLJ over Gadanki

Note that results presented above are taken at 1200 UTC. Before going into further detail, it is worthwhile to see how much diurnal variation exists in the MLLJ intensity and height. Although the diurnal variation of the MLLJ is least explored, by considering the diurnal cycle measured with UHF radar over Gadanki Kalapureddy et al. (2007) showed that the MLLJ exhibits strong diurnal variability in intensity and height of the jet core, with its core peaking up to 3 km during 0900–2200 LT. In the present study, the GPS radiosonde measurements and other reanalysis datasets over Gadanki have been considered to study the diurnal variation of MLLJ. For studying diurnal variation, GPS radiosonde data launched 4 times a day for three continuous days each month have been considered.

A typical example showing the diurnal variation of MLLJ observed with GPS radiosonde during 21–23 July 2009 is shown in Fig. 2a. The intensity (core height) of MLLJ is found at a maximum (minimum) during night local time and at a minimum (maximum) during day local time. Interestingly, the ERA-Interim dataset for the same period shown in Fig. 2b also depicts more or less similar variations, with only small changes in the magnitudes. However, the NCEP–NCAR data, despite showing diurnal variation (Fig. 2c) in the intensity of MLLJ, could not reproduce any change in the height of jet core. Since the diurnal features observed with GPS radiosonde and ERA-Interim match well, the
ERA-Interim data have been considered to accurately reflect the mean diurnal variation in MLLJ features over the Gadanki grid.

Figure 2d shows the mean diurnal variation of MLLJ observed using the ERA-Interim zonal wind data available at four intervals per day during peak monsoon months (July and August) averaged during 2006–09. From Fig. 2d, in general zonal wind maximum height (intensity) is noticed at 867 hPa (12.2 m s\(^{-1}\)) at 0000 UTC; this increases (decreases) gradually and reaches 765 hPa (9.84 m s\(^{-1}\)) at 0600 UTC and 732 hPa (9.84 m s\(^{-1}\)) at 1200 UTC and then gradually decreases (increases). Thus, the MLLJ reveals strong diurnal variation in wind maxima height of about 100 hPa and slight variation in the intensity of about 2 m s\(^{-1}\) over Gadanki. Hence, Gadanki GPS radiosonde observations taken at 1200 UTC are expected to show the MLLJ always at higher heights as the MLLJ is shifted toward greater height (lower pressure) during daytime. Since large diurnal variation exists in the MLLJ, it is suggested to consider the time of observation in future studies related to zonal wind maxima. Since the GPS radiosonde observations are available at 1200 UTC, hereafter the zonal wind maxima features only at 1200 UTC will be dealt with in all the datasets unless otherwise specified.

c. **Spatial distribution of the MLLJ**

As mentioned earlier, the reanalysis datasets have been used to study the spatial distribution of MLLJ. Taniguchi and Koike (2006) reported that the presence of low-level westerly wind exceeding 8 m s\(^{-1}\) at 850 hPa will strongly represent the monsoon activity over Arabian Sea as well as over the Indian region. The mean spatial variation of zonal wind at 850 and 700 hPa using ERA-Interim and NCEP–NCAR reanalysis data averaged from 2006 to 2009 during peak monsoon months (July and August) is shown in Fig. 3. The contours of westerly
wind exceeding 8 m s\(^{-1}\) are only shown in Fig. 3. From Figs. 3a and 3b, it is evident that the core of zonal wind maxima lies at 850 hPa over Arabian Sea and extends horizontally and vertically with decreasing intensity. The intensity decreases with height; the center of the core at each level is seen around 13°N and 60°E and the 8 m s\(^{-1}\) contour is extended up to 700 hPa over Indian region. Although the intensity of zonal wind at 700 hPa is lower than at 850 hPa over Arabian Sea, note that it is seen slightly higher at 700 hPa over southeastern peninsular India. NCEP–NCAR data also show (Figs. 3c,d) similar features, with the core at 850 hPa with its center around 13°N and 60°E, but at 700 hPa the 8 m s\(^{-1}\) contour is not extended to southeastern peninsular India and Sri Lanka, unlike in the ERA-Interim dataset. It is interesting to see that MLLJ core features are reproduced well spatially in both datasets at 850 hPa but not at 700 hPa, particularly in southeastern peninsular India.

The discrepancy in the wind maxima height at each grid point is further investigated. The spatial variation of mean (July–August) height and pressure at zonal wind maxima averaged from 1989 to 2009 using ERA-Interim reanalysis and NCEP–NCAR reanalysis datasets are shown in Figs. 4a and 4b, respectively. During the peak monsoon months of July and August in each year from 1989 to 2009, the pressures levels (height) of wind maxima at each grid point are picked up and the mean spatial variation in the wind maxima pressure level is shown in these figures. In the ERA-Interim dataset, it is clearly noticed that on average over southeastern peninsular India, the zonal wind maxima pressure level is observed at low (higher) pressure levels (heights). In particular, over Gadanki (location shown with a star) it is 750 hPa that agrees well with the mean pressure level observed by the Gadanki GPS radiosonde. Interestingly, NCEP–NCAR data also showed a slight increase in MLLJ height at 825 hPa (Fig. 4b).

The longitudinal variation of the height of wind maxima at 13.5°N (ERA-Interim) and 12.5°–15°N (NCEP–NCAR) averaged from 2006 to 2009 during peak monsoon months (July–August) shown in Fig. 4c reveals the presence of wind maxima at much lower pressure levels (higher heights) in the longitudinal band of 78.5°–82.5°E, unlike reported earlier as its existence at 850 hPa uniformly throughout all the longitudes over the Indian region. The latitudinal variation of the height of wind maxima at 79.5°E (ERA-Interim) and 80°E (NCEP–NCAR) averaged for 4 yr shown in Fig. 4d depicts that higher heights extend to a latitude band of 10.5°–13.5°N. Interestingly, long-term (1989–2009) mean longitudinal and latitudinal variation of height of wind maxima (ERA-Interim) also show exactly similar trends to that of 4-yr mean variation. Again, ERA-Interim datasets show near-realistic features of the MLLJ with the 4-yr (July–August) mean height (pressure) of wind maxima along with standard error observed with GPS radiosonde measurements over Gadanki also superimposed for comparison.
During the monsoon, zonal wind shows gradual increase in the westerlies from the surface and attains its maximum above 1 km, then decreasing gradually. As mentioned earlier, this phenomenon of changes in the magnitude of zonal wind with height was first defined as the LLJ by Reiter (1961); Joseph and Raman (1966) later identified the existence of the MLLJ over southern peninsular India. But all the earlier studies mentioned that the peak intensity of MLLJ is more than 15–20 m s\(^{-1}\) and the peak will be always at the 850-hPa pressure level. It is to be noted that all these studies of the MLLJ were made based on limited low-vertical-resolution datasets at different regions and may not be valid at all locations. Moreover, there may be interannual and decadal changes in MLLJ characteristics. In fact, such features are observed (not shown) in long-term radiosonde data collected from Chennai, but this is outside the scope of the present study.

The mean profiles of the low-level zonal wind averaged from 2006 to 2009 in the peak monsoon months of July and August are shown in Fig. 5. The very fine structure of low-level wind observed with the Gadanki GPS radiosonde shows the advantage of having the high-vertical-resolution data. The peak jet speed on average is observed to be 8.7 m s\(^{-1}\) with a standard deviation (error) of 6.1 m s\(^{-1}\) (0.4 m s\(^{-1}\)). However, the jet height is observed at 2.8 km, which is in contradiction to the peak height first reported by Joseph and Raman (1966). This observation also overrides the general thinking of MLLJ existence at 1.5 km above mean sea level, which roughly corresponds to the pressure level of 850 hPa. To justify the observed peculiarity in the peak height, the average zonal wind for the same period has been considered from the nearby IMD radiosonde station Chennai, which is at a radial distance of 120 km southward from Gadanki. The mean profile of the MLLJ observed using IMD radiosonde data shows a peak intensity of approximately 8 m s\(^{-1}\) with a broad peak height starting from 1.5 to 3 km. In general, although this height range is in good agreement with the radiosonde observation from Gadanki, the existence of the broad peak is mainly due to low vertical resolution. In addition, in case of the IMD radiosonde, the available number of data points decreases significantly with height when compared to constant number of data points in the case of the Gadanki GPS radiosonde, which is clear from Fig. 5a. These two radiosonde profiles were also compared with the mean profiles obtained using NCEP–NCAR and ERA-Interim reanalysis over the Gadanki grid box and superimposed in Fig. 5a.
the ERA-Interim profile agrees well with the Gadanki GPS radiosonde observations in terms of both wind speed and wind maxima height. However, the NCEP–NCAR profile shows the wind maxima at 850 hPa with slightly higher intensity.

d. Percentage occurrence of MLLJ over Gadanki

On average, the 4-yr mean zonal wind maximum is seen around 8 m s\(^{-1}\). Supporting the report made by Taniguchi and Koike (2006) and based on the results obtained in the present study, zonal winds with wind speed exceeding 8 m s\(^{-1}\) have been considered as the MLLJ, and days with zonal wind maxima exceeding 8 m s\(^{-1}\) have been separated out and the percentage occurrence of MLLJ has been estimated from the available days of the GPS radiosonde observations. Figure 5b shows the percentage occurrence of the presence of MLLJ during the monsoon months of June, July, August, and September of the years 2006–09. The minimum and maximum percentage occurrences of MLLJ are seen during June and July, except in the year 2008 when the minimum and maximum percentage occurrences are noticed in July and June, respectively. This may be due to the early onset of monsoon in the year 2008 and several breaks later in July. Considering all the days of monsoon months in each year from ERA-Interim and NCEP–NCAR reanalysis datasets over Gadanki grid, the percentage occurrence of MLLJ over Gadanki is also superimposed in Fig. 5b. Again, ERA-Interim dataset shows near-realistic values although similar trends are seen in all the three datasets.

It is well known that the ISM exhibits pronounced intraseasonal variability on time scales ranging from a few days to more than a month. Earlier reports reveal that the MLLJ exhibits strong intraseasonal oscillation (ISO) during the monsoon with two main modes: the quasi-biweekly mode with a period of 10–20 days and a longer intraseasonal mode with a 30–60-day period (Krishnamurti and Bhalme 1976; Joseph and Sijikumar 2004). Figure 5c shows the Lomb–Scargle (LS) periodogram analysis of the MLLJ occurrence over Gadanki for the year 2008 using all three datasets. The dominant periodicities are observed to be 45 days (with 99% confidence level). The dominant periodicity also shows large interseasonal variations with peaks of 38–40, 40–42, and 48–50 days in 2006, 2007, and 2009, respectively (not shown). Here it is obvious that a strong MJO is persistent in the MLLJ over Gadanki during the monsoon. These oscillations in the MLLJ are strongly associated with the activity of the monsoon; thus, the behavior of the MLLJ during each phase of monsoon is worth investigating using this high-resolution data.

4. MLLJ features over Gadanki during active and break phases

There have been several studies on the active and break phases of ISM based on the rainfall by considering all-India daily rainfall or central-India rainfall obtained from the IMD (Gadgil and Joseph 2003; Kripalani et al. 2004; Rajeevan et al. 2006, 2010). The daily accumulated rainfall (mm day\(^{-1}\)) in the recent year 2009 over central India, along with the climate normal obtained from IMD gridded rainfall data, is shown in Fig. 6a. Further, the active and break spells of the monsoon during 2006–09 have been identified following Roja Raman et al. (2009). In brief, days with rainfall exceeding the climate mean (1951–2009) rainfall are considered as active, and others are treated as break days; for both cases the condition should persist consistently for 3 days. Based on these criteria, the low-level winds have been separated for each spell and the behavior of the MLLJ over Gadanki during central India active and break phases has been studied. From a typical example of the mean zonal wind observed during active (13–24 July 2009) and break (25 July–10 August 2009) spells shown in Fig. 6b, one can notice that all the three datasets show similar features with high (low) intensity during the active (break) spell, with a slightly higher jet core height (height of wind maximum).

Similar analysis has been performed for all the years from 2006 to 2009 by considering the peak monsoon months of July and August (62 days each year, total 248 days) and the 4-yr mean zonal wind during active and break phases is shown in Fig. 6c. Note that there are 117 (106) active (break) days out of 248 total days in ERA-Interim and NCEP–NCAR reanalysis datasets. However, as there exist some data gaps in the case of the Gadanki GPS radiosonde, there are 107 (88) active (break) days out of 221 available days. The 4-yr mean profiles (Fig. 6c) also have similar feature as observed in the typical examples shown in Fig. 6b. From the Gadanki GPS radiosonde profile it is clear that the jet peak intensity is about 12 m s\(^{-1}\) (5 m s\(^{-1}\)) and is at 710 hPa (740 hPa) during the active phase (break phase).

ERA-Interim data also show a similar trend, although some discrepancy at lower altitudes, with jet peak intensity of 12 m s\(^{-1}\) (5 m s\(^{-1}\)) at 700 hPa (775 hPa) during the active (break) phase of the monsoon. NCEP–NCAR data also show significant differences in the zonal wind intensity during active and break spells; however, the wind maxima are seen at 850 hPa (925 hPa) during the active (break) phase over Gadanki grid. This large difference in the zonal wind intensity during active and break monsoon phases can be attributed to the movement of the MLLJ core associated with
large-scale monsoon circulation north and south of the study region.

5. Summary and conclusions

This paper presents a diagnostic study of the characteristics of the MLLJ using three different datasets: one observational and the other two reanalysis datasets. The main conclusions drawn from the present study are summarized below:

1) The MLLJ exhibits strong diurnal variation in its intensity and core height with higher height and lower intensity at 1200 UTC over southeastern peninsular India. Since large diurnal variation exists in the MLLJ, it is suggested to consider the time of observation in future studies dealing with MLLJ.
2) Large intraseasonal and interannual variation in MLLJ occurrence is noticed during 4 yr (2006–09). The maximum and minimum percentage occurrences of MLLJ are observed to be in the months of July and June, respectively, except in the year 2008. The dominant periodicity in MLLJ is observed to be 40–50 days, revealing the dominance of MJO, although quasi-biweekly periods also coexist.

3) Unlike reported earlier, the mean core height of MLLJ over Gadanki lies around 3 km, which is equivalent to a pressure level of 710 hPa rather than 850 hPa.

4) While strongly supporting the higher core height of MLLJ reported in the present study over Gadanki, the ERA-Interim reanalysis also reveals that the observed higher core height exists throughout southeastern peninsular India.

5) The structure and dynamics of the MLLJ are highly dependent on the activity of the monsoon. During the active (break) phase of monsoon, the core of MLLJ exists at slightly higher (lower) heights with more (less) intensity.

6) Based on the NCEP–NCAR and ERA-Interim datasets, it is evident that in models (including those used in reanalysis) higher vertical resolution is necessary for realistic representation of the MLLJ.

Thus, the most important conclusion drawn from the present study is that the MLLJ core height does not lie at a fixed height/pressure level homogeneously throughout southern peninsular India; rather, it varies with location depending on the topography surrounding it. The most striking feature noticed from the present study is that the mean core height of the MLLJ lies around 3 km. This is perhaps due to the MLLJ coming from a northwesterly direction; crossing the Eastern Ghats may lift the jet to higher heights. It is suggested that future monsoon modelers/forecasters may need to consider key terrain features while dealing the MLLJ and rainfall. Neither the Western Ghats nor the funnel-shaped hilly terrain of the northeastern portion of southern India is factored into the existing models.

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REFERENCES


Roja Raman, M., V. V. M. Jagannadha Rao, M. Venkat Ratnam, M. Rajeevan, S. V. B. Rao, D. Narayana Rao, and N. Prabhakara