

A study on the structure of Monsoon Low Level Jet and its variation over small temporal Scales

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**Dr. Ch Kanaka Rao
Lecturer in Electronics
Principal Investigator
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Declaration

I, Dr. Ch Kanaka Rao, Lecturer, Department of Electronics, Sri Y.N. College (A), Narasapur, West Godavari District declare that this Research work entitled “A study on the Structure of Monsoon Low Level Jet and its variation over small temporal Scales “has been written by me under the scheme of U.G.C Minor Research Project in Physics during the period 2017-19, which has not been previously formed the basis for the award of any Degree, Diploma, Associate-ship or Fellowship.

Principal Investigator

Principal

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... *Kanaka Rao*

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Preface

Indian monsoon season is the principal rainy season for the country and the monsoonal rainfall is most important for our agriculture and economy. The monsoon low-level jet (MLLJ) is an integral component of the monsoon system and has been regarded as the indicator for monsoon vigor. Also, knowledge on the low-level jet (LLJ), which occurs at a lower altitude, is very crucial for aviation applications, as it generates strong shear and clear-air turbulence in its lower flanks. So, it is important to understand the spatial and temporal variations in these jets, their linkages with monsoonal rainfall in different regions of India and the underlying processes responsible for these variations.

A variety of data sets, comprising of reanalysis, multisatellite precipitation, Sodar and wind profiler data, for monsoon 2016 are employed to understand the characteristics of LLJ and MLLJ. Spatial patterns of both MLLJ and LLJ look similar with both of them showing their maximum strengths in the western Arabian Sea and also branching into two channels over Indian longitudes. However, the axis of MLLJ and LLJ are found to be slightly different in the Arabian Sea. Also, the LLJ strength is found to be much weaker than that of MLLJ over the Indian landmass, due to surface frictional drag. Occurrence statistics of MLLJ and LLJ also reveals that their maximum occurrence is over the ocean, where they occur for more than 90% of time during the study period. Occurrence statistics of MLLJ and LLJ show strong diurnal variation with maximum occurrence during mid-night-early morning and minimum during afternoon over peninsular India. Detailed scientific analysis of high-resolution horizontal winds obtained by Sodar and Wind profiler revealed that the diurnal variation of winds is quite complex within the ABL and the time of peak wind speed varies with altitude. The largest amplitudes of diurnal cycle are found at the height of MLLJ and it has been shown that the interaction of ABL and synoptic flow is responsible for the observed largest amplitude of diurnal variation.

It is one of very few studies that dealt on MLLJ and LLJ variations during active and break spells for southeast peninsular India over which the mean axis of the MLLJ exists. The active and break spells for southeast peninsular India are identified using 18 years of GSMaP

rainfall measurements. Occurrence statistics of MLLJ during active and break spells clearly shows that it occurs predominantly during break spell over the study region (~70% of total duration) with wider width spreading between 1.5 km and 3.5 km. The occurrence of MLLJ is not only limited during the active spell, but also its height of occurrence and width is also different from that of in break spell. It has been clearly shown that the MLLJ exhibits large variation between active and break spells over southern peninsular India. The branch of MLLJ passing over the peninsular India weakens considerably during the active monsoon, allowing propagation of precipitating systems. During the break spell, presence of strong winds and low-level shears are found to be detrimental for the longevity (and also for propagation) of storms.

1. Introduction:

Indian summer monsoon, a gigantic wind system that travels over vast oceans and brings moisture onto the Indian land mass, is primarily responsible for 80% of annual rainfall over most part of the country. During the second half of May to first half of June, the prevailing low-level northeasterlies change direction to southwesterlies and sets up the monsoon. The monsoon low level jet (MLLJ) and the tropical easterly jet (TEJ) (Jet stream – a strong current of wind) are the two important integral components of monsoon circulation and often used as indicators for monsoon vigor. The TEJ, a narrow current of strong wind with a magnitude as strong as 60 ms^{-1} , is observed in the height region of 200-100 hPa over southern peninsular India. Though a few studies exist linking the TEJ to monsoon depressions that bring copious amount of rain to the core monsoon zone (Rao et al. 2004 and references therein), the MLLJ is regarded as the better indicator of monsoon vigor. The MLLJ, a strong cross-equatorial jet, prevails at around 850 hPa during the summer monsoon period (June through September) over the monsoon region with its core running through the southern peninsular India along $10\text{-}15^\circ \text{ N}$ latitude band. The MLLJ has its origin in the south Indian Ocean north of the Mascarene high as an easterly current, crosses the equator in a narrow longitudinal belt close to the east African coast as a southerly current with speeds at times even as high as 40 m s^{-1} , turns into a westerly current over the Arabian Sea and passes through India to the western Pacific Ocean. Since the MLLJ acts as a main conduit for the moisture transport from oceans, the intraseasonal oscillations (ISO) in MLLJ are often related to ISO's in rainfall over the monsoon region (Joseph and Sijikumar 2004). It is now known that large values of horizontal wind shear on 850 hPa and vertical wind shear between 850 hPa and 200 hPa help in intensifying monsoon depressions (Dash et al. 2004 and references therein). Earlier studies elucidated the variations in MLLJ both in space and time (including

future projections) to a great extent. For instance, the existence of two branches in MLLJ, disappearance of peninsular branch during the break spell, weakening of MLLJ in last five decades, northward migration of LLJ in the climate change scenario, etc. (Joseph and Sijikumar 2004; Joseph and Simon 2005; Sandeep and Ajaymohan 2015; Mohan and Rao 2016). Also, the diurnal variation of winds, including MLLJ, obtained from continuous wind profiler measurements is found to be significant at Gadanki (Sandeep et al. 2014; Mohan and Rao 2016 and references therein).

In addition to the monsoon low-level jet (LLJ), the existence of another low-level jet is often reported in the literature (Banta et al. 2002; Baas et al. 2009). LLJs are frequently observed phenomena in the nocturnal boundary layer (NBL) in many parts of the world. These LLJs attained attention of researchers in recent years for obvious reasons. The need to understand the structure and its variation is continuously increasing given their role in aviation, wind energy applications, the transport of pollutants, and other atmospheric constituents like ozone and carbon dioxide (Karipot et al. 2006). Furthermore, the strong shear below the jet can influence the turbulent exchange between the surface and the atmosphere (Banta et al. 2006) and this clear-air turbulence is a potential hazard to aircraft passenger safety. Meteorologists use the location of some of the jet streams as an aid in weather forecasting. The characteristics and the source of LLJ have been studied by several researchers (Banta et al. 2002, Baas et al. 2009; Cuxart et al. 2011; Kallistratova et al. 2011; Arfeuille et al. 2015 and references therein). The LLJs are observed in the altitude range of 200-500 m above the surface with a small vertical extent (tens to hundreds of meters), but with large horizontal extent. The sources of these LLJs over land are linked to inertial oscillations and mesoscale circulations, triggered by heterogeneous terrain or land-sea contrast (Van De Wiel et al. 2010; Kallistratova et al. 2011). The numerical models

generally do not have such resolutions to resolve the NLLJ and its effects and therefore these circulations are underestimated or overlooked. Therefore, high resolution measurements, both height and time, are required to resolve such small-scale features.

1.1. Objectives:

As outlined above the MLLJ and LLJ are two distinct jets as evidenced by their distinct characteristics. For instance, the LLJ is a mesoscale phenomenon formed and intensified in a stably stratified boundary layer, whereas the MLLJ is a synoptic cross-equatorial flow with several strong linkages with Indian summer monsoon. The height at which these two jets appear are different, LLJ is seen in the height region of 200-500 m and MLLJ on 850 hPa level. The magnitude of these two jets is also different. However, several gap areas exist in our understanding of these jets.

- It is not clear how often the LLJ occurs during the summer monsoon season?
- Even if it occurs, will it occur in isolation or as a coupled system with MLLJ?
- What is the vertical structure of these jets?
- Is it possible to identify the LLJ in the presence of strong MLLJ?
- How do LLJ and MLLJ vary in a day during the monsoon season?
- Do they show different characteristics in active and break cycles of the monsoon?

2. Data and Study region:

2.1. Data and instrumentation:

A variety of data sets for the monsoon period of 2016 are used for the present study. The ERA5-derived wind velocities (zonal (u) and meridional (v) velocities and horizontal wind speed and direction) are employed to understand the climatological wind variations in the monsoon season at two different altitudes (850 hP and 925 hPa, representing the heights of MLLJ and LLJ). The synoptic wind variations during the active and break spells of the monsoon are also examined with the same data set. The ERA5 reanalysis data are available with 1 hr temporal resolution and $0.1^\circ \times 0.1^\circ$ spatial resolution (Kubota et al 2020). To discern active and break spells, 18 years (2001-2018) of Global Satellite Mapping of Precipitation (GSMaP) gauge-adjusted precipitation rate (standard version 6) dataset with $0.1^\circ \times 0.1^\circ$ and 1 hr spatial and temporal resolutions is used (Chen et al. 2008).

To address the above scientific issues, continuous measurements of winds covering the entire boundary layer are highly essential. Such measurements are now available at National Atmospheric Research Laboratory (NARL), Gadanki (13.5° N, 79.2° E), where a Doppler SOUNd Detection And Ranging (SODAR) (Anandan et al. 2008) and a Ultra High Frequency (UHF) wind profiler (Srinivasulu et al. 2012) are being operated continuously since the beginning of the monsoon season-2015. This unique dataset provides answers to the above questions and improves our understanding on the monsoon jets, in general, and LLJ and MLLJ, in particular.

The low-level winds (below 500 m) are obtained with an indigenously developed phased array Doppler Sodar, operating at an acoustic frequency of 1.8 kHz. This sodar pumps acoustic energy

with a peak power of 100 W using 52 antenna array elements (distributed in 8x8 format) and measures the returned energy to estimate the signal-to-noise ratio (SNR), turbulence (in terms of spectral width of the spectra σ) and Doppler velocity with a temporal resolution of 30 s and vertical resolution of 30 m. 3-D winds are obtained by using Doppler velocities in 3 non-coplanar directions, obtained from 2 tilting beams (towards East and North with an off-zenith angle of 16°) and a zenith beam. The accuracies of the sodar-derived wind speed and directions are 0.1 m s^{-1} and 3° , respectively (Anandan et al. 2008). Important technical specifications of the sodar are given in Table 1 and its image is shown in Figure 1.

Indigenously developed (at NARL) UHF wind profiler measurements are employed in the present study to understand and study small-scale variations (including diurnal) of MLLJ. The fully active phased array UHF profiler (arranged in a 16×16 matrix) operates at 1.280 MHz with a peak output power of 1.2 kW. It utilizes butler beam formation network to obtain radial velocities in off-zenith directions. The radar operates in 4 modes continuously switching between the modes. Among 4 modes, two modes are designed to obtain high-resolution winds (high mode with $4 \mu\text{s}$ coded pulse with $1 \mu\text{s}$ baud and low mode with $1 \mu\text{s}$ uncoded pulse) with temporal and heights resolutions of 3 min and 150 m, respectively. Remaining two modes are for studying precipitation and are not employed in the present study. Both wind modes operate in 5 beam mode with 4 off-vertical beams pointing towards East, West, North and South at 15° and a vertical beam. The antenna array of UHF profiler with the clutter fence is depicted in Figure 1 and its important specifications are summarized in Table 1 (Srinivasulu et al. 2012).



Figure 1: Indigenously developed Doppler Sodar and UHF wind profiler at NARL, Gadanki

Table 1: Important specifications and parameters of Sodar and UHF wind profiler used in the present study

| Parameter | SODAR | UHF Wind profiler |
|------------------|----------|--|
| Frequency | 1.8 kHz | 1.3575 GHz |
| Beam width | 5° | 3° |
| Pulse width | 180 ms | 4 μ s coded with 1 μ s baud length |
| FFT points | 4096 | 128 |
| Range resolution | 30 m | 150 m |
| Beams | Z, N & E | Z, E, W, N & S |
| IPP | 9 sec | 80 μ s |
| Peak power | 100W | 1 kW |

2.2. Study region

NARL (Gadanki) is located in a complex hilly terrain 370 m above the mean sea level (a.s.l) in southern peninsular India (Figure 2), ~90 km away from the east coast of India. The height of hills surrounding Gadanki (within 10 km) varies from 300 to 700 m a.s.l. The ecology comprises an uneven mix of dense forest, waste land and agriculture (mostly sugarcane and mango fields) surrounding rural population centres. This semi-arid region receives most of its annual rainfall (790 mm) in two monsoon seasons, the south-west monsoon (June through September) (53 % of

the annual rainfall) and the northeast monsoon (October through December) (33 % of the annual rainfall). Remaining occurs in premonsoon (March through May), predominantly in the form of convective rain. The rainfall during the southwest monsoon occurs predominantly during the evening to midnight period. About 66 % of total rainfall is convective in nature, while the remaining rain is widespread stratiform in character (Rao et al. 2008; Sandeep et al. 2014; Saikranthi et al. 2014)

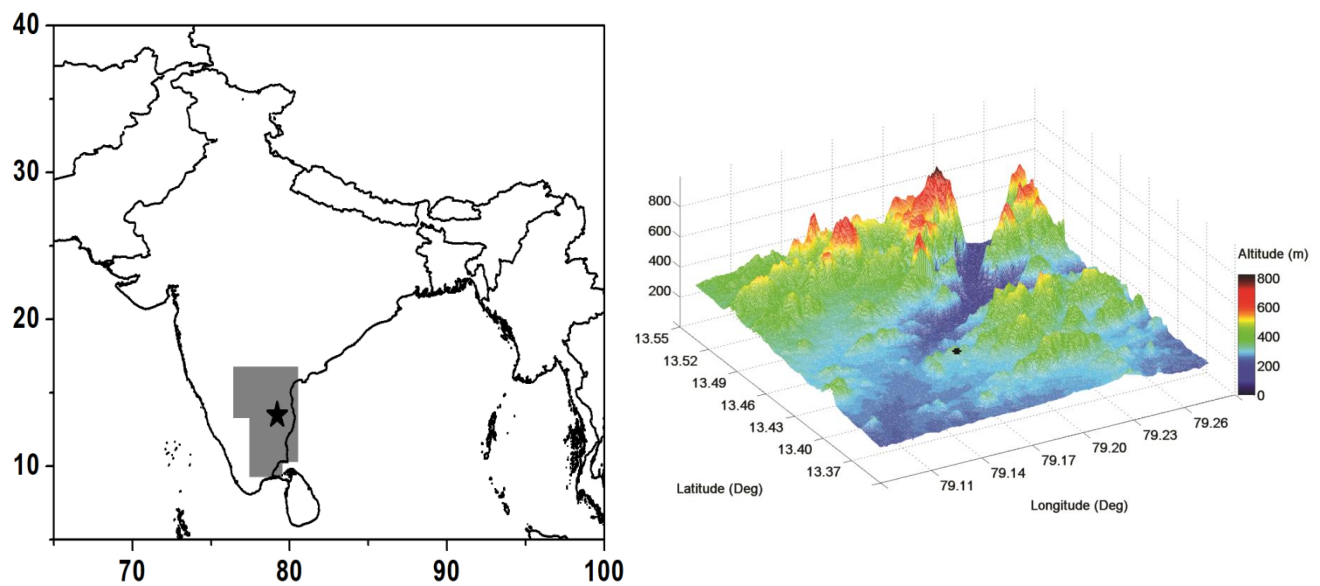


Figure 2: Location of Gadanki, indicated by a star (left panel) and the complex topography surrounding the study region (right panel). Details of gray shading are given in Section 4.

3. Variation of MLLJ and LLJ:

3.1. Synoptic variation:

The two conspicuous and important features of the Indian monsoon circulation are the presence of MLLJ and Tropical Easterly Jet (TEJ), both are seen prominently over the southern peninsular India, between 12° and 15° N. Earlier studies have shown that MLLJ occurs at 850 hPa, which shows large spatial variability but is tightly coupled with the vigor of monsoon (Joseph and

Sijikumar 2004; Goswami 2005; Rao et al. 2009; Mohan and Rao 2016). On the other hand, the LLJ occurs at much lower heights and is coupled with ABL dynamics.

To understand the spatial variability of MLLJ and LLJ, seasonal mean winds (June-September) obtained from ERA5 are examined at 850 hPa and 925 hPa, respectively (Figure 3). The top panel of Figure 3 shows that the core of the LLJ splits over the Arabian Sea with one branch (say first branch) passing over the southern peninsular India centered around 16°N and the other toward southeast and veers cyclonically (second branch) before merging with the first branch in the Bay of Bengal (near the coast of Malay peninsula). The splitting of LLJ in the Arabian Sea is reported earlier by many investigators, and it was attributed to barotropic instability (Findlater, 1971). The branch over southern peninsular India is very important as it brings moist-laden air on to the Indian landmass and forms the primary moisture source during monsoon season. It is also responsible for copious rainfall along the west coast, one of the wettest regions of the world, due to the uplifting of moist air that it brings by Western Ghats. The MLLJ is strongest over the Arabian Sea and along the second branch, wherein mean wind speeds exceed 15 m s^{-1} . The strength of first branch (or branch over the land) is weaker (with wind speeds of $\sim 10\text{-}12 \text{ m s}^{-1}$) because of friction. Wind speeds often exceed 20 m s^{-1} in spells even by the first branch, i.e., over southern peninsular India. After merging in the Bay of Bengal the MLLJ veers cyclonically and move northwestward. The MLLJ and cyclonic circulation is very important for the formation of low-pressure systems/depressions, popularly known as monsoon low-pressure systems, in the head Bay of Bengal, which propagate onto the land and produce copious rainfall in the core monsoon zone (or monsoon trough region). This occurs in spells of few days, called active spells, and the occurrence and duration of these spells are tightly coupled with MLLJ.

The LLJ on 925 hPa level also show strong winds over the Arabian Sea and cyclonic circulation nearly parallel to the southern coast India and in the monsoon trough region, like MLLJ. However, few differences are strikingly apparent between MLLJ and LLJ, besides the height difference of their occurrence. 1. The axis of core LLJ is more tilted towards the northwest India in comparison to that of southern peninsular India by MLLJ. 2. As a result, the northwest India receives more lower tropospheric moisture from the Arabian Sea and such moistening of northwest India is very important for the deep convective systems, predominantly occurring in that region. The cold down-slope winds from the mountain range caps this moist air and thereby increases the convective available potential energy (CAPE) enormously and leads to deep convective storms, often crossing the tropopause (Houze et al. 2015). Though northwest India is a dry region, most of the rain convective in nature in this region (Saikranthi et al. 2014). 3) Considerable weakening of wind speeds over the southern peninsular India with mean wind speeds ranging $6-8 \text{ m s}^{-1}$. Since the LLJ occurs at a much lower height than MLLJ, the surface frictional drag is more severe over the land (particularly by the Western Ghats).

As seen above, both these jets are modified or modulated by surface processes through ABL dynamics. Since all the parameters in the ABL exhibit large diurnal variation, it is prudent to understand the vertical structure and diurnal variability of MLLJ/LLJ with high resolution measurements. Fortunately, NARL lies in the core axis of these jets and equips Sodar and Wind profiler, both provides high-resolution winds and turbulence information, both parameters crucial to understand the diurnal variation of these jets. The next section focuses on these aspects.

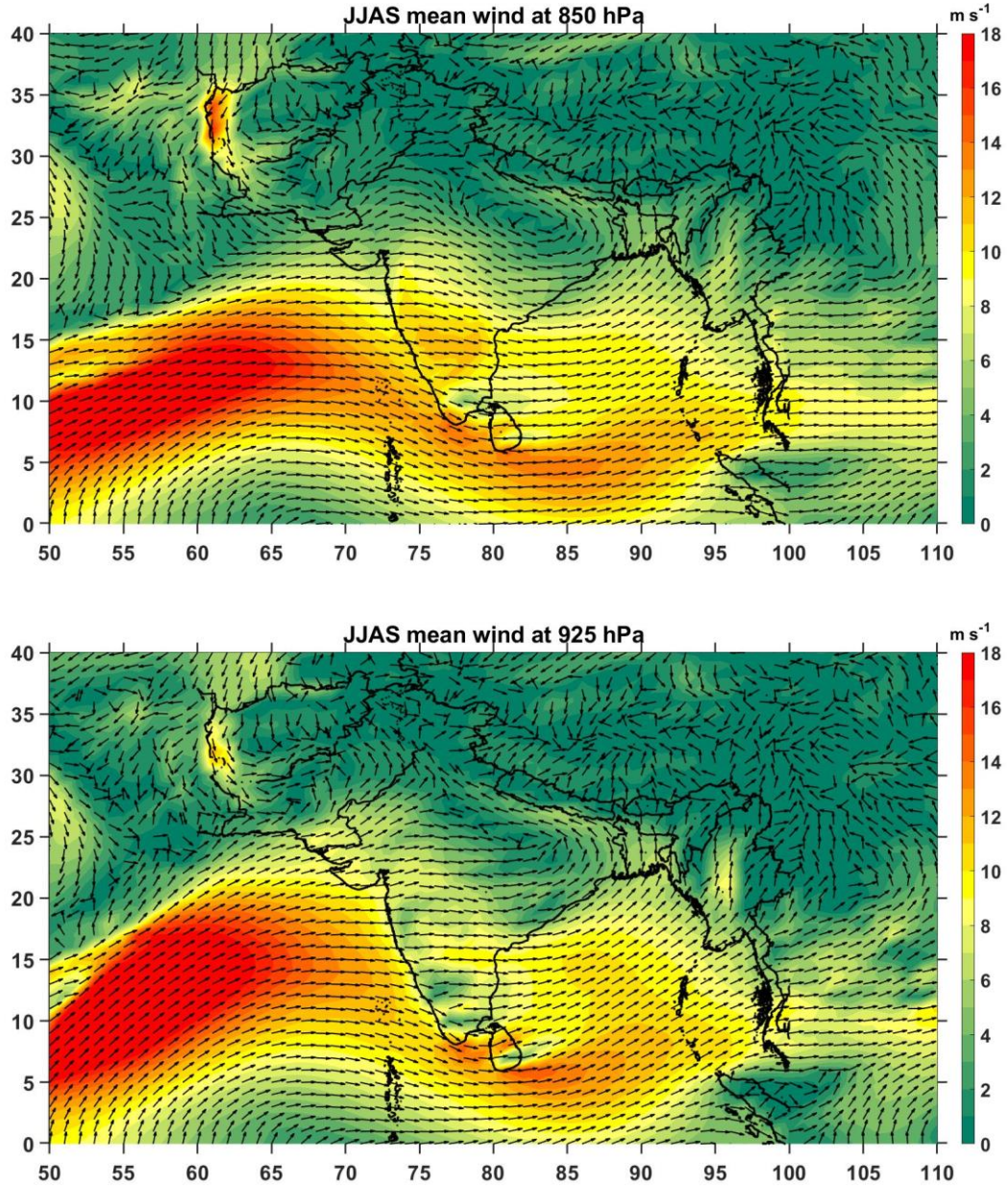


Figure 3: Spatial variation of wind speed at 850 hPa and 925 hPa pressure levels, depicting the climatological variation of MLLJ and LLJ over the study region.

3.2. Vertical and Diurnal variation of horizontal winds over Gadanki

To understand vertical and diurnal variation of horizontal wind speeds over Gadanki, in southeast peninsular India, two days of continuous high resolution wind and turbulence

measurements (Sodar - 5 min. averaged and wind profiler - 3 minutes averaged) are considered as representative days. Figure 4 shows sodar and wind profiler derived signal-to-noise ratio (SNR in dB) and Doppler width (in m s^{-1}). The SNR indicates the returned signal strength and also gives a clue on the reliability of data, i.e., higher SNR indicates reliable data and low SNR indicates poor quality data. The wind profiler (Sodar) SNR indicates the quality of data is good up to 4 (0.30-0.36) km. The data above these heights are not reliable and are not considered for analysis or discussion in this study. The Doppler spectral width indicates the strength of turbulence, though the measured spectral width also comprises non-turbulent contributions. The non-turbulence contributions (beam, shear and wave broadening) need to be removed to accurately quantify turbulence (Rao et al. 2001). As the present study focuses more on Jet streams, Doppler widths were not corrected, but discussed only to give a glimpse of their variation with height and time.

The examples shown in Figures 4 and 5 resemble the classic growth model of the ABL during fair weather conditions. The solar heating in the morning causes thermals to rise, transporting heat and moisture to higher altitudes. The initial growth of the ABL, which is rather gradual, but once the ABL reaches the previous day's residual layer, it grows rapidly up to the level of the capping inversion. During this period, the drier free tropospheric air descends to replace the rising air parcels. These intense updrafts and downdrafts cause intense turbulent mixing. Figures 4 and 5 clearly show large values of Doppler width extending to the ABL top (~3 km on 3 Aug 2016), indicating the occurrence of intense mixing in the ABL. Following the decay of thermals and vertical mixing in the evening, the ABL collapses.

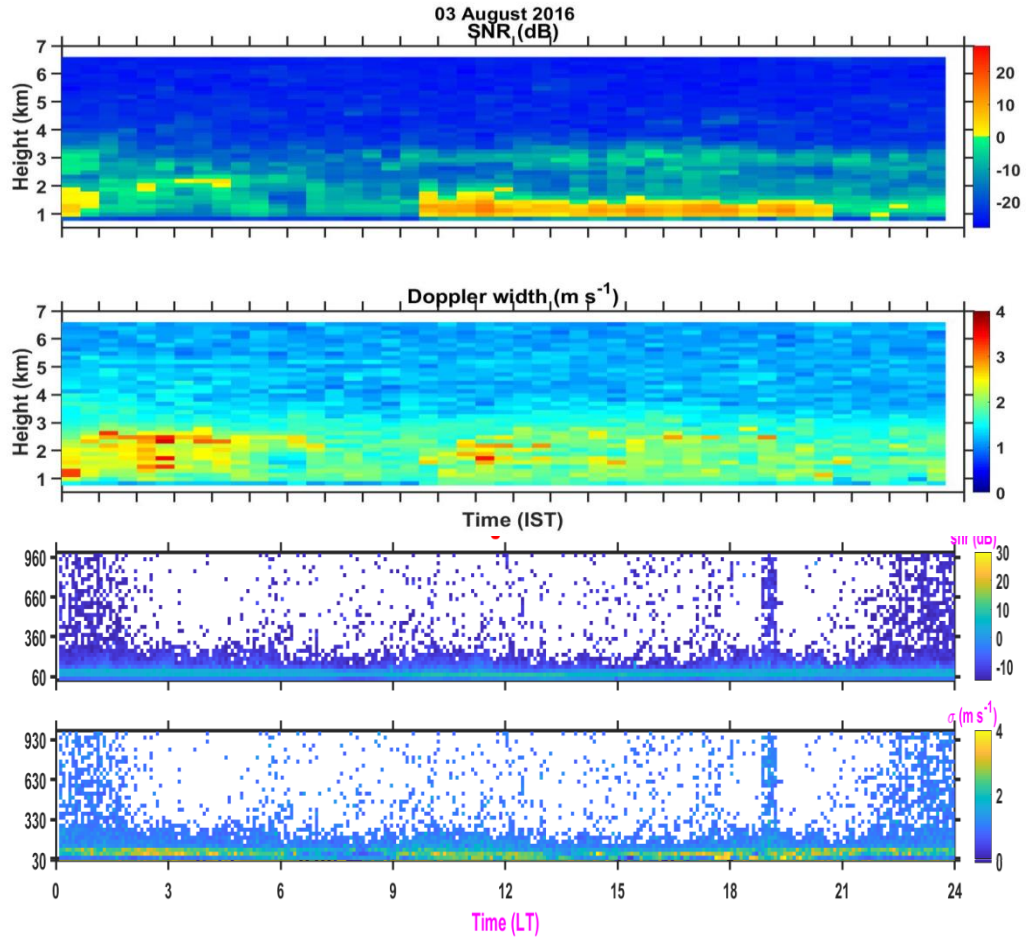


Figure 4: Height-time variation of SNR and Doppler width obtained by wind profiler (top two panels) and sodar (bottom two panels).

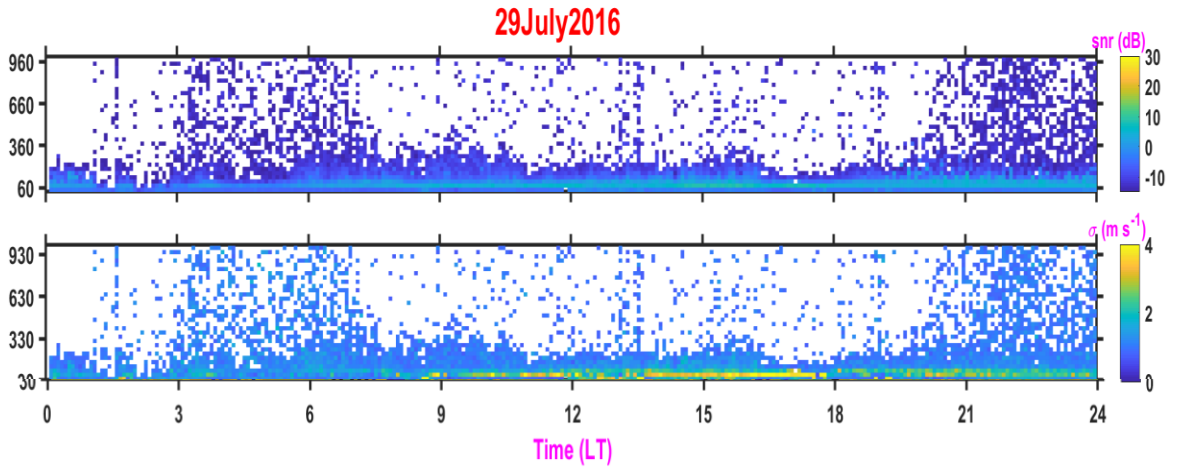


Figure 5: Same as Figure 4, but only for Sodar derived SNR and Doppler width

Figures 6 and 7 show typical diurnal variation of zonal, meridional and vertical wind speeds on selected two days, i.e., 03 August 2016 and 29 July 2016, respectively. Though the time gap between these examples is only 4 days, the wind exhibits large variation in magnitude between them. Both zonal and meridional wind velocities are much higher on 03 August 2016 than on 29 July 2016. Winds also exhibit a distinct diurnal cycle near surface with stronger winds during the day than night in both spells. The strengthening of the surface winds during the day is a manifestation of the intense down mixing of momentum from upper levels due to solar heating (Sandeep et al. 2014). During the night, radiative (nocturnal) cooling in the boundary layer reduces the eddy viscosity and momentum transfer from upper levels and thereby the wind speed (Arya, 2001). The noon maxima and early morning minima in zonal and meridional winds are seen up to an altitude of 200-300 m on both days, as evidenced by SODAR time-height velocity plots. In the height region of 200–1000 m, the diurnal cycle is significant in the zonal wind with strong westerlies in the early morning period (03:00–04:00 LT) and weak westerlies during noon-evening. Similar diurnal variation is seen on both days, albeit with different amplitudes of diurnal cycle and its vertical variation. The diurnal cycle of the wind field (and also both MLLJ and LLJ) is quite pronounced with wind speeds varying by 10 m s^{-1} during a day. Relatively large turbulence within the ABL during daytime (precisely, during the rapid growth of the ABL) increases the friction to the background flow and reduces its velocity. Following the collapse of the ABL at night, the wind speed increases in the relatively frictionless atmosphere. As a result, the LLJ peak follows the evolution of ABL height, and appears as if it caps the ABL (Sandeep et al. 2014).

Although the amplitudes of the diurnal cycle is different, but the phase of the diurnal cycle is same on both days, i.e., strengthening of westerly wind starts at 19:00 LT and attains a peak value during 03:00–05:00 LT. This kind of nocturnal LLJ variation is observed at many geographical locations and is an oft-studied phenomenon (Blackadar, 1957; Banta et al., 2002; Karipot et al., 2009; Baas et al., 2009 and references therein). These studies attributed the occurrence of nocturnal wind peak to various atmospheric processes: baroclinicity from horizontal temperature contrast caused by land-sea and/or topographic circulations and inertial oscillation due to frictional decoupling. Although the other processes like sea-breeze and topography (Gadanki is located in a complex terrain surrounded by hillocks of altitude 400–600 m) can form nocturnal peak, the diurnal variation of LLJ resembles to that produced by inertial oscillation. That is, following the collapse of convective boundary layer after the sunset, turbulence dies out and the remnant of the mixed layer will be decoupled from the surface because of stable stratification in the night. The winds increase in this frictionless-height region and form the nocturnal LLJ. In the absence of friction, the Coriolis force induces ageostrophic circulation in clockwise direction. Mohan and Rao (2016) examined several hodographs to understand the nature and source of nocturnal peak in LLJ strength at Gadanki. They noticed a clear clockwise rotation of wind, suggesting that the inertial oscillation produced by the frictional decoupling could be responsible for NLJ at Gadanki.

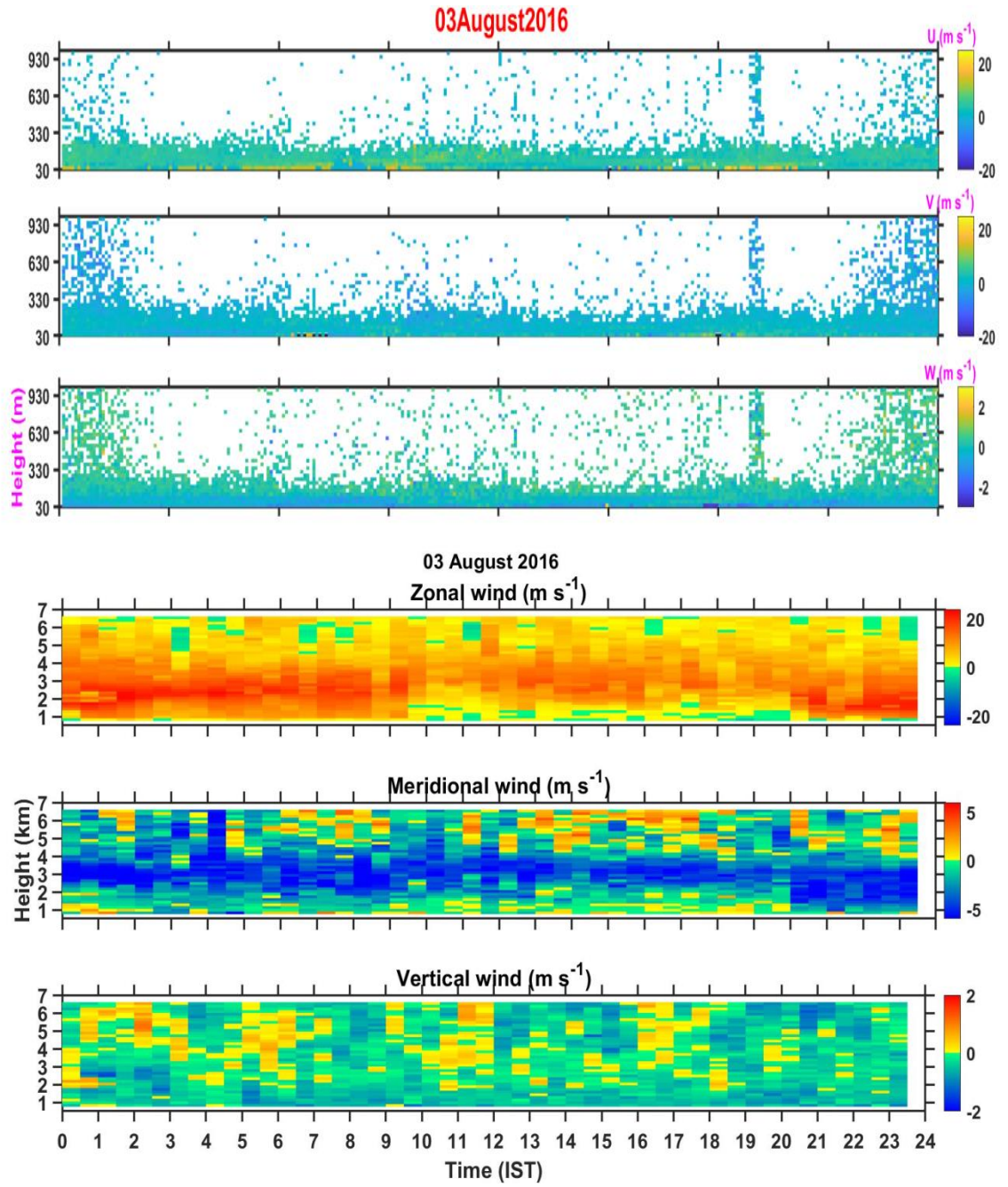


Figure 6: Time height variation of u , v and w on 03 August 2016 as measured by Sodar (top panel) and UHF wind profiler (bottom panel)

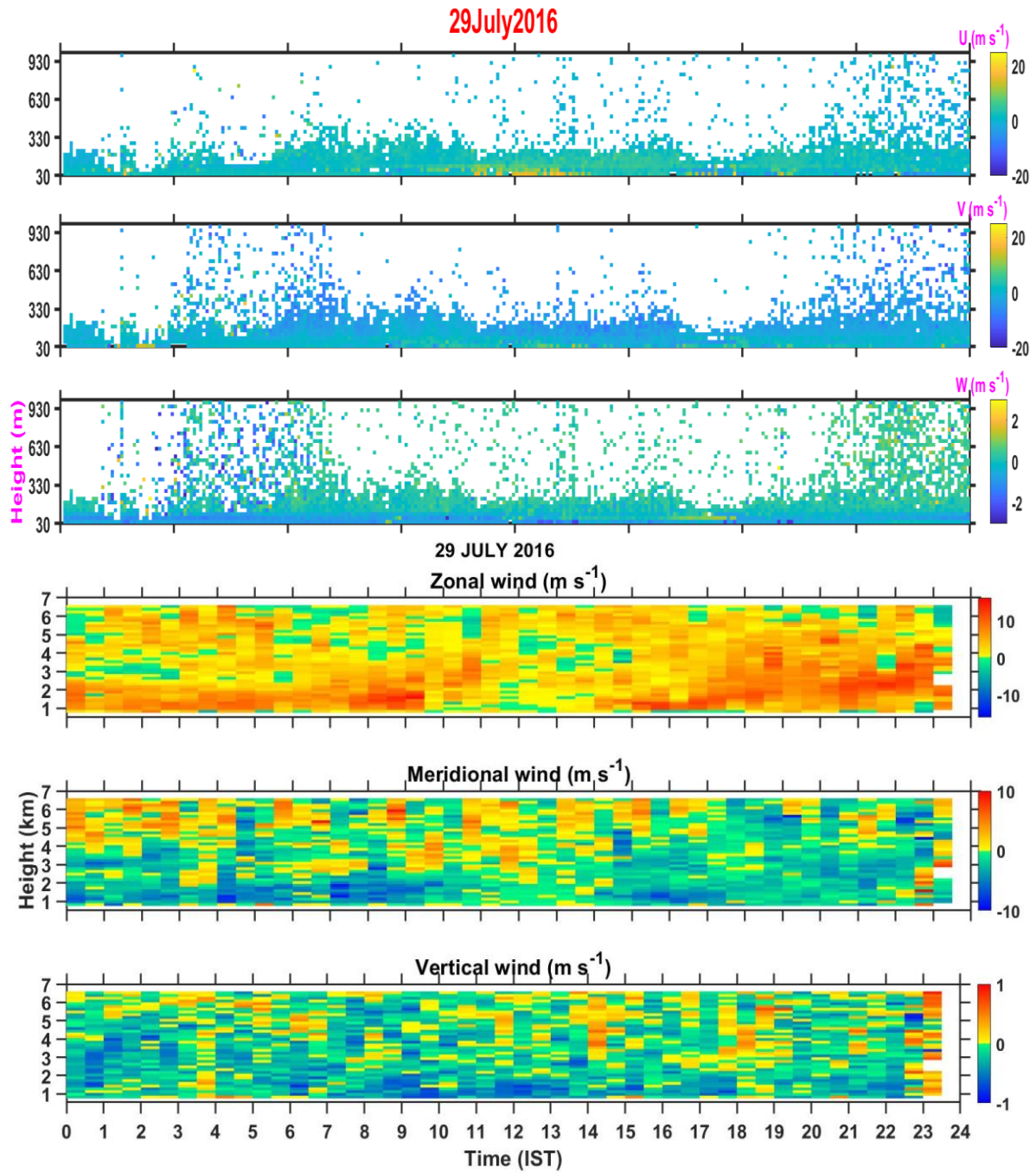


Figure 7: Same as Figure 6, but for 29 July 2016

3.3. Statistics of MLLJ Occurrence

To examine how frequently or rarely that these jets occur in different climatic regimes, the spatial distribution of occurrence statistics of MLLJ and LLJ are estimated. If the wind speed (obtained from ERA5 reanalysis) at a grid on 850 hPa level exceeds 8 m s^{-1} , the MLLJ is considered to be present at that grid (Findlater 1969). The same threshold is used to obtain LLJ statistics, but on a different pressure level, i.e., 925 hPa. As seen in Figures 4-7, both MLLJ and LLJ magnitudes exhibit strong diurnal variation, linked with ABL dynamics. The occurrence statistics of MLLJ and LLJ, therefore, are estimated at each hour. Figure 8 shows the occurrence statistics at two selected timings, at 21 UTC (02:30 IST, representing time for midnight-early morning) and 08 UTC (01:30 IST, noon time) when the winds are strongest and weakest during a day, respectively.

The prevalence of MLLJ exceeds 90% all the time in the Arabian Sea along the path of jet, discussed in Section 3.1. Major difference in occurrence statistics is seen over the peninsular India, where the occurrence of MLLJ is much higher during midnight-early morning period than that of noon time. The occurrence statistics of MLLJ estimated for mid-night are larger than that of those occurring for noon by 20-30%. The reduction is much more strikingly apparent in southeast peninsular India. Occurrence of MLLJ is mostly confined to south of 20° N and reduces northward to 10-20% in the monsoon trough region.

The spatial distribution of LLJ occurrence resembles to that of MLLJ, except for few changes. For instance, the occurrence of LLJ is lower (higher) than that of MLLJ over southern peninsular

India (monsoon trough region). Also, the occurrence frequency is very less during noon, because of stronger friction it experiences because of daytime thermals in the boundary layer.

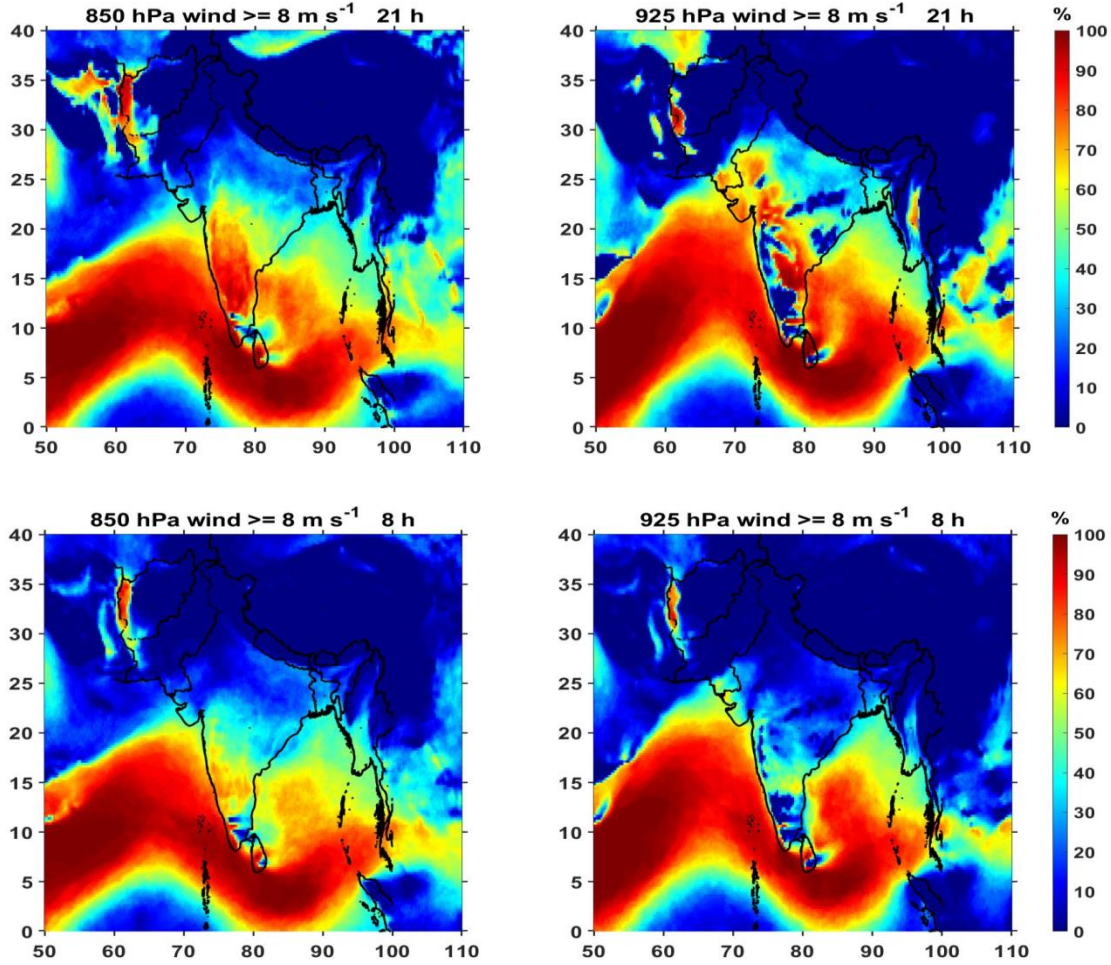


Figure 8: Occurrence statistics of MLLJ on 850 hPa level and LLJ on 925 hPa level at maximum and minimum occurrence times of the day.

4. MLLJ and LLJ during active and break spells:

4.1. Identification of active and break spells:

The rainfall in southwest monsoon doesn't occur continuously, rather occurs in spells (so called active spells) punctuated by scanty rainfall (referred to here as break spells). Numerous studies exist on the characteristics and variability of active and break spells and the underlying mechanisms causing the variability. It is also possible now to predict these spells with reasonable

accuracy. However, most of these studies primarily focus on active and break spells with reference to the rainfall in monsoon core zone (as it shows good correlation with all India rainfall) (Rajeevan et al. 2006). The active and break spells are not coherent throughout India rather they exhibit large spatial variations. Earlier studies clearly demonstrated that there exists an anticorrelation in the rainfall pattern between the core monsoon zone and southeast peninsular India (and also northeast India). During the break monsoon period, the core monsoon zone hardly gets any rain but good amount (~20-40 % of seasonal rainfall) of rainfall occurs over southeast India, northeast India and parts of Jammu and Kashmir (Ramamurthy 1969, De et al. 1998, Gadgil 2003, Goswami 2005, Rao et al. 2009, Rajeevan et al. 2010; Mohan and Rao 2016). Also, rainfall increases near the foothills of Himalayas, following northward movement of the monsoon trough. As active and break spells associated with these ISOs show large spatial variability, we have to identify these spells separately for each region. Several studies from southeast peninsular India followed this approach to characterize active and break spells and understand the underlying processes responsible for these spells (Rao et al. 2009; 2016; Sandeep et al. 2014; Mohan and Rao 2016). Identification of active and break spells for southeast India is described below.

The active and break spells are discerned from time series of rainfall data obtained from the GSMaP gauge-adjusted precipitation rate (Kubota et al. 2020). To identify the active and break spells for southeast peninsular India, rainfall in the shaded region in Figure 2 is averaged and time series of daily rainfall for the shaded region is generated. The shaded region is a coherent rainfall zone in which rainfall at each grid correlates well with the area averaged rainfall (Mohan and Rao 2012). This regional daily rainfall dataset is used to identify active and break spells, following Rajeevan et al. (2010), Mohan and Rao (2012), Rao et al. (2016). From

the regional daily rainfall data, daily standardised rainfall anomaly is calculated using the following formula:

$$\text{Standardised rainfall anomaly (SRA)} = \frac{r - \mu}{\sigma} \quad (1)$$

where r denotes the regional daily rainfall for a particular day in a given year, μ and σ represents the average rainfall and standard deviation of a particular day, respectively, estimated using all the years. 18 years of GSMaP rainfall measurements are used for obtaining climatological μ and σ . If the SRA anomaly is greater (less) than 0.5 for at least three consecutive days, then those days are classified as active (break) spell days. Figure 9 demonstrates the procedure adopted and identified active and break spells during 2016 monsoon period. Both number and duration of break spells is large and longer, respectively, than active spells. A total of 3 active spells of duration 3-5 days are observed, while the number and duration of break spells are 8 and 4-20 days. Longest break spell is observed during August and the nearest long active spell is in late July. These periods are taken as representatives for break and active spells, respectively. They are considered as typical representatives, as they lie in the middle of the monsoon season.

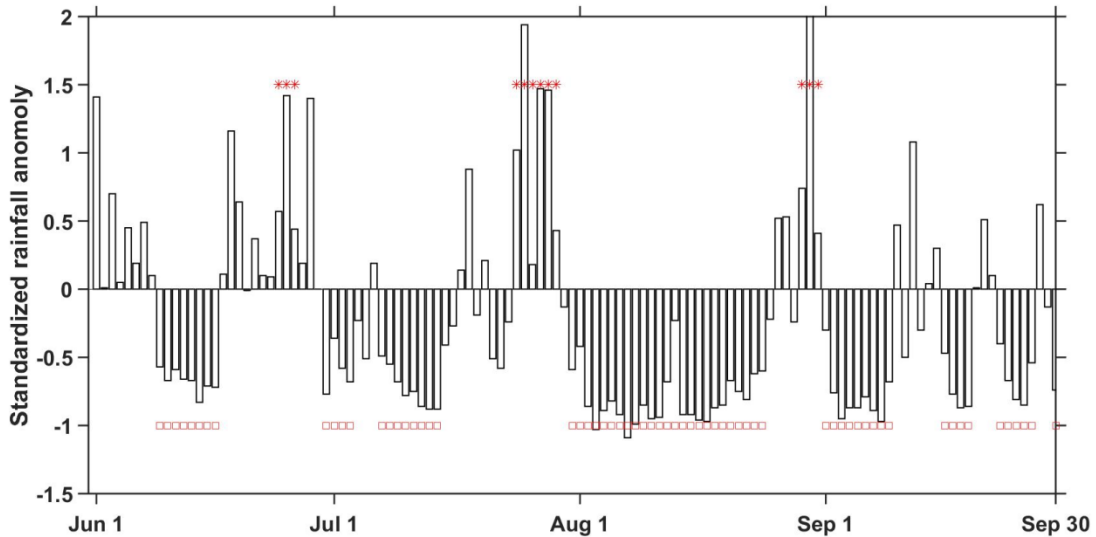


Figure 9: Time series of standardized daily rainfall anomalies during monsoon 2016, depicting the procedure adopted for identifying active and break spells over southeast peninsular India and identified spells (symbols).

4.2. Synoptic variation of MLLJ and LLJ during active and break spells:

To understand the prevailing synoptic situations during active and break spells, ERA5 horizontal winds during 24-29 July and 3-12 August 2016 are averaged and are considered as their representatives, respectively. Spatial maps of mean horizontal wind patterns on 850 hPa level and 925 hPa levels, similar to Figure 3, are shown in Figures 10 and 11, highlighting the MLLJ and LLJ variations during break and active spells, respectively. Distinct wind differences are noted between the active and break spells. The first notable difference is that the winds are much stronger during the break spell ($12-18 \text{ m s}^{-1}$) than in active spell over the ocean as well as land. Also, stronger winds over the Arabian Sea and branching of MLLJ near the west coast of India are strikingly apparent during the break spell. Further, cyclonic rotation of winds near the head Bay of Bengal and monsoon trough region is also visible clearly, providing conducive environment for monsoon low-pressure systems in that region. Stronger winds with large shears are detrimental for the growth of precipitating systems, which is the case for southeast peninsular India during the break spell. On the other hand, the branch passing over the peninsular India weakened considerably and wind speeds over this region falls to $6-10 \text{ m s}^{-1}$ during the active spell. In the presence of such weak winds, the precipitating systems generated along the west coast propagate towards east and produce copious rain in the southeast peninsular India. Several recent studies have shown that the rainfall peaks in the mid-night over Gadanki and surroundings using measurements from satellites and network of rain gauges (Rao et al. 2016; Sunilkumar et al. 2015; Rao and Mohan 2020 (under review)). During the active spell for southeast peninsular

India, the cyclonic circulation over the monsoon trough region shifts from east to western part of trough region. Also another branch of winds (though weaker in magnitude) blows towards northwest India from the Arabian Sea and produce some rainfall in that region.

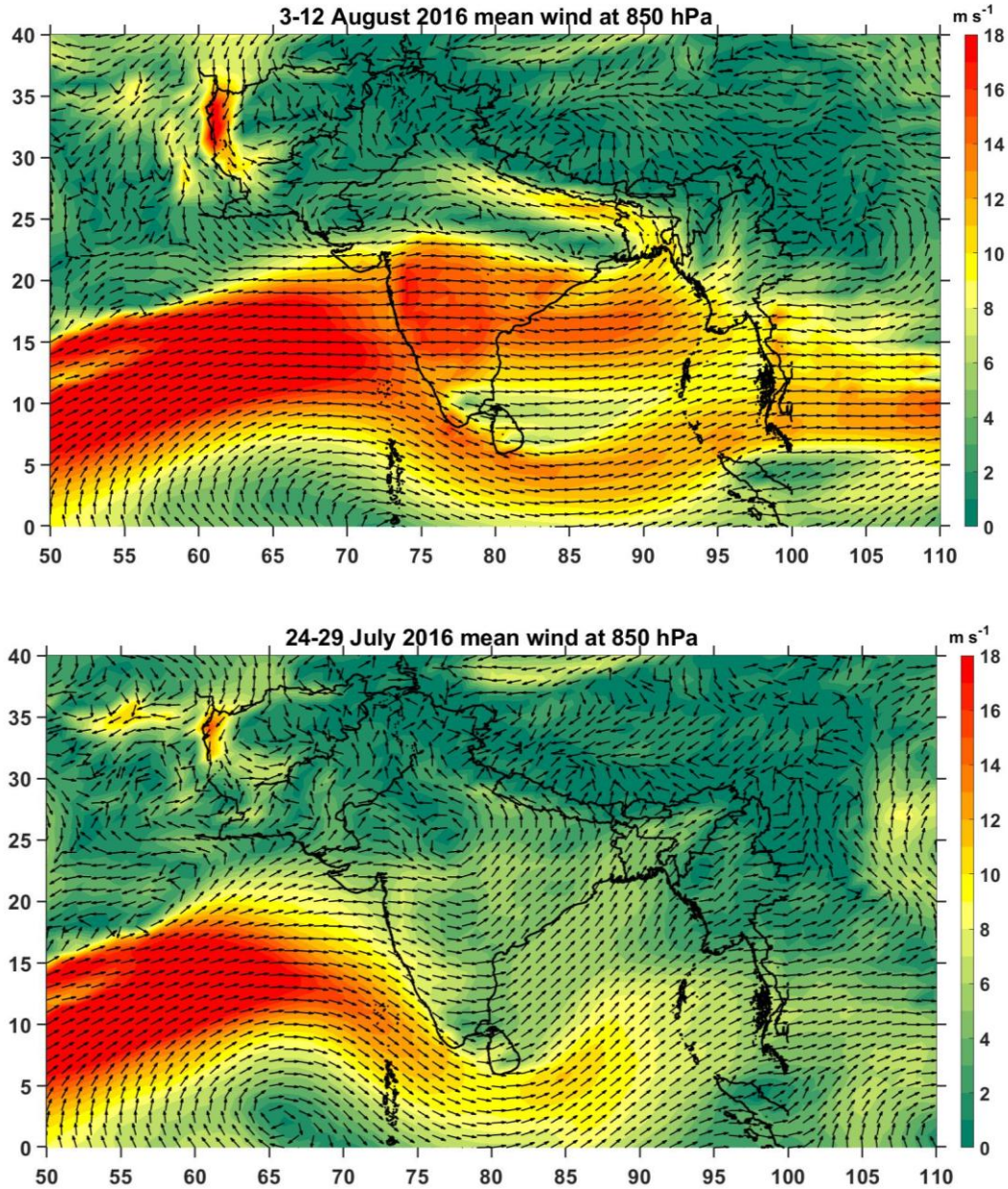


Figure 10: Spatial variation of MLLJ during break (top panel) and active (bottom) spells, depicting the synoptic situation during those spells.

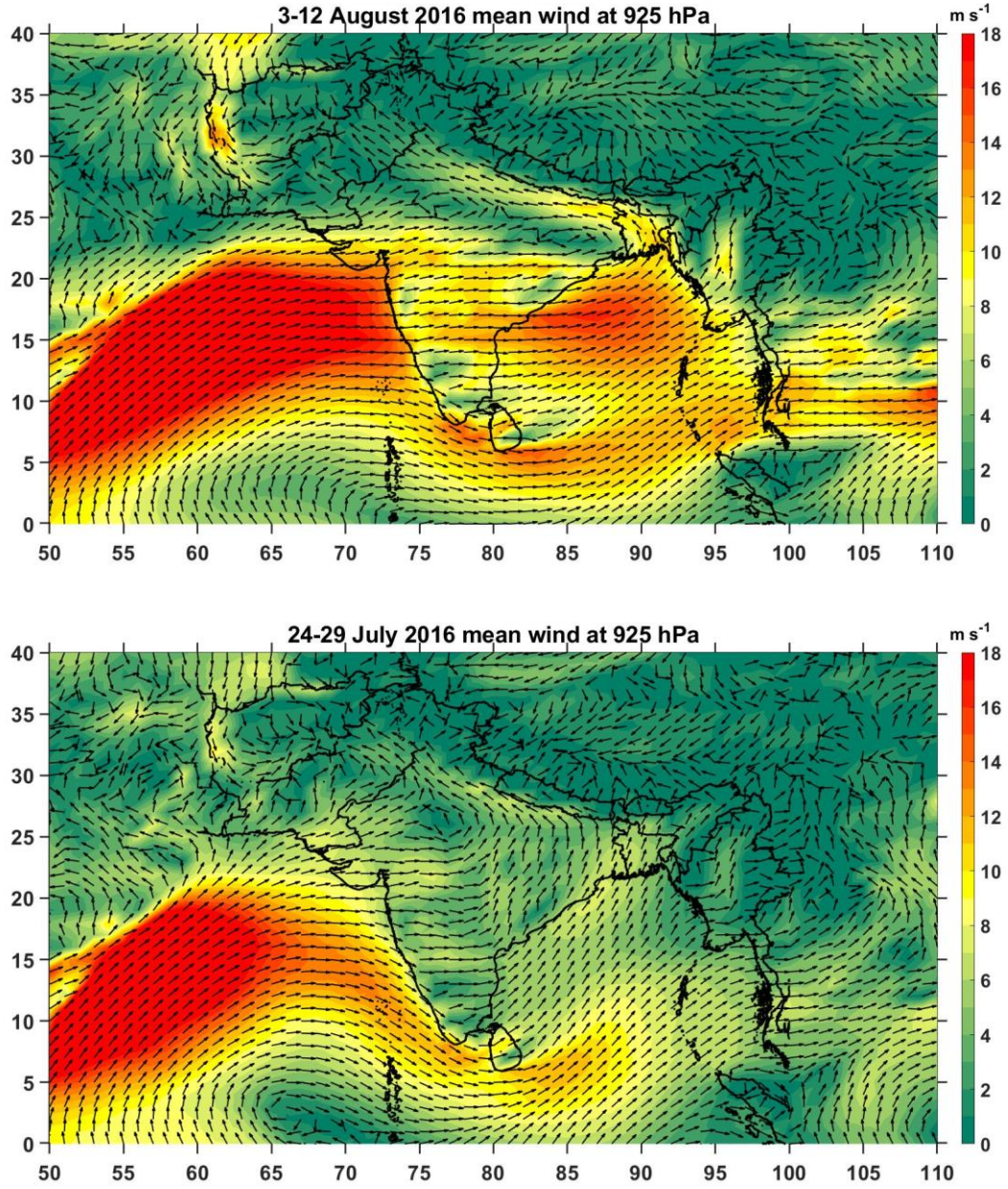


Figure 11: Same as Figure 10, but for LLJ.

Spatial distribution of LLJ during active and break spells resembles to that of MLLJ, except that the winds are much weaker over peninsular India (land region). However LLJ is found to be much stronger and wider than that of MLLJ in the Arabian Sea. As mentioned above, over the land region, winds are considerably lower than their counterparts of MLLJ (by 6-8 m s⁻¹),

because LLJ experiences stronger frictional force as it forms at a lower height. Except for wind magnitude, all the changes observed in MLLJ between active and break spells are seen in LLJ also. For instance, weaker winds and weakening of branch over southern peninsular India, westward shift in cyclonic circulation in monsoon trough region, etc during active monsoon periods are clearly seen in LLJ plots also.

4.3. Mean diurnal and vertical variation of winds during active and break spells:

To quantify and understand the diurnal variation of winds within the ABL during different monsoon spells, half-hourly composites of horizontal wind speed and direction for wet and dry spells are estimated. Figure 12 shows the diurnal variation of wind speed during the dry and wet spells. These plots resemble to the wind variation seen in case studies, with strong winds during midnight-early morning and weak winds during the day time, particularly during noon-evening in both spells. There exist some striking differences in winds between the spells. 1) The mean winds during the break spells are stronger than that of in active spells by nearly $6-8 \text{ m s}^{-1}$. 2) The depth of westerlies is also higher in break spells. Westerlies are seen in the entire observational heights during the break spells, while they are confined to lower heights (3-4 km) during active spells. 3) The heights of strong winds are also different. While strongest winds are seen in the height range of 1.5-2.5 km during the break spells, in the night when wind magnitudes are higher, they are observed at a lower height (1-2 km) during the active spell. During both spells, largest wind variations in a day occur within the ABL above the surface layer. Since the wind variations (and both MLLJ and LLJ) are tightly coupled with ABL dynamics, it is important to understand how ABL evolves in these spells. Sandeep et al. (2014) studied ABL evolution in both spells using a suite of in-situ and remote sensing instruments to understand their variation

and factors causing those variations. They have shown that the ABL evolution during these spells is different. The ABL is not shallower during the active spell, but also its evolution delays by 2-3 hours. Most of the available net radiation is consumed to evaporate soil moisture, available abundantly during the active spell, leaving limited energy for thermals (sensible heat flux). Weaker sensible heat flux and thermals do not have much energy to rise to greater height and these factors are primarily responsible for the observed differences.

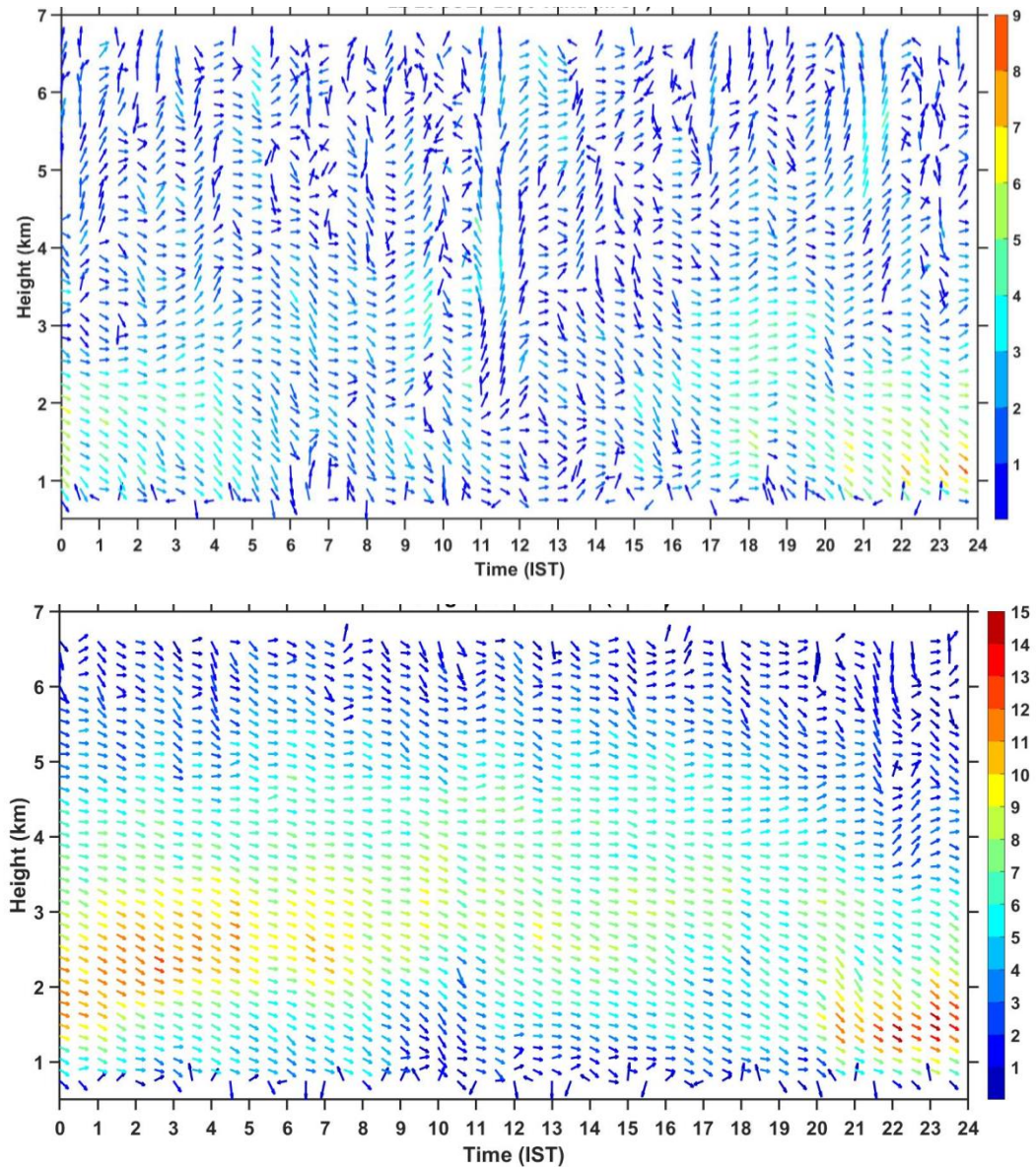


Figure 12: Typical time-height variation of speed and direction of horizontal winds during active (top panel) and break spell (bottom panel).

4.4. Occurrence of MLLJ during active and break spells:

As seen in case studies and also in composite wind plots, the MLLJ and LLJ are strikingly different in both spells. Therefore, CFAD's for wind speed are plotted for the total data (figure 13 top panel) as well as for the data during 00-06 LT (the time when these jets are strong) (bottom panel of figure 13). In both spells, the wind variation is very large (varies from meagre wind speeds to those exceeding 20 m s^{-1}) within the season. During break spell, the CFAD's for total data shows that large winds ($> 22 \text{ m s}^{-1}$) are seen in the height region of 1 km to 3 km, whereas such large winds are confined to 1-2 km height region in the active spell. The mean and mode of the distributions are also different in these spells. The mean wind speed at any height below 3 km is larger in break spell than in active spell by $3 - 4 \text{ m s}^{-1}$. Also, the 24 hour mean profiles and 6 hour (00-06) mean profiles look different in different spells. They do not vary much in active spell, but vary by $2-3 \text{ m s}^{-1}$ in break spell, particularly in the height region of peak MLLJ (i.e., 1.5 km).

If we consider the threshold of 8 m s^{-1} for the presence of jet, like in Section 3.3, 75%-80% of total observations during the break spell show the presence of jet in the height region of 1-3 km. The percentage occurrence increases to $>80\%$ when data during midnight-early morning is considered. The MLLJ and LLJ are hardly present above 4 km. On the other hand, during active spell, jets are present only for about 50% of total observations. Also the strongest winds are seen in the limited height region during the active spell. The height variation of maximum occurrence (mode of the distribution) is also different between the spells. While the break spells show large height variation with a peak at $\sim 1.5 \text{ km}$, the active spells do not show much variation with height.

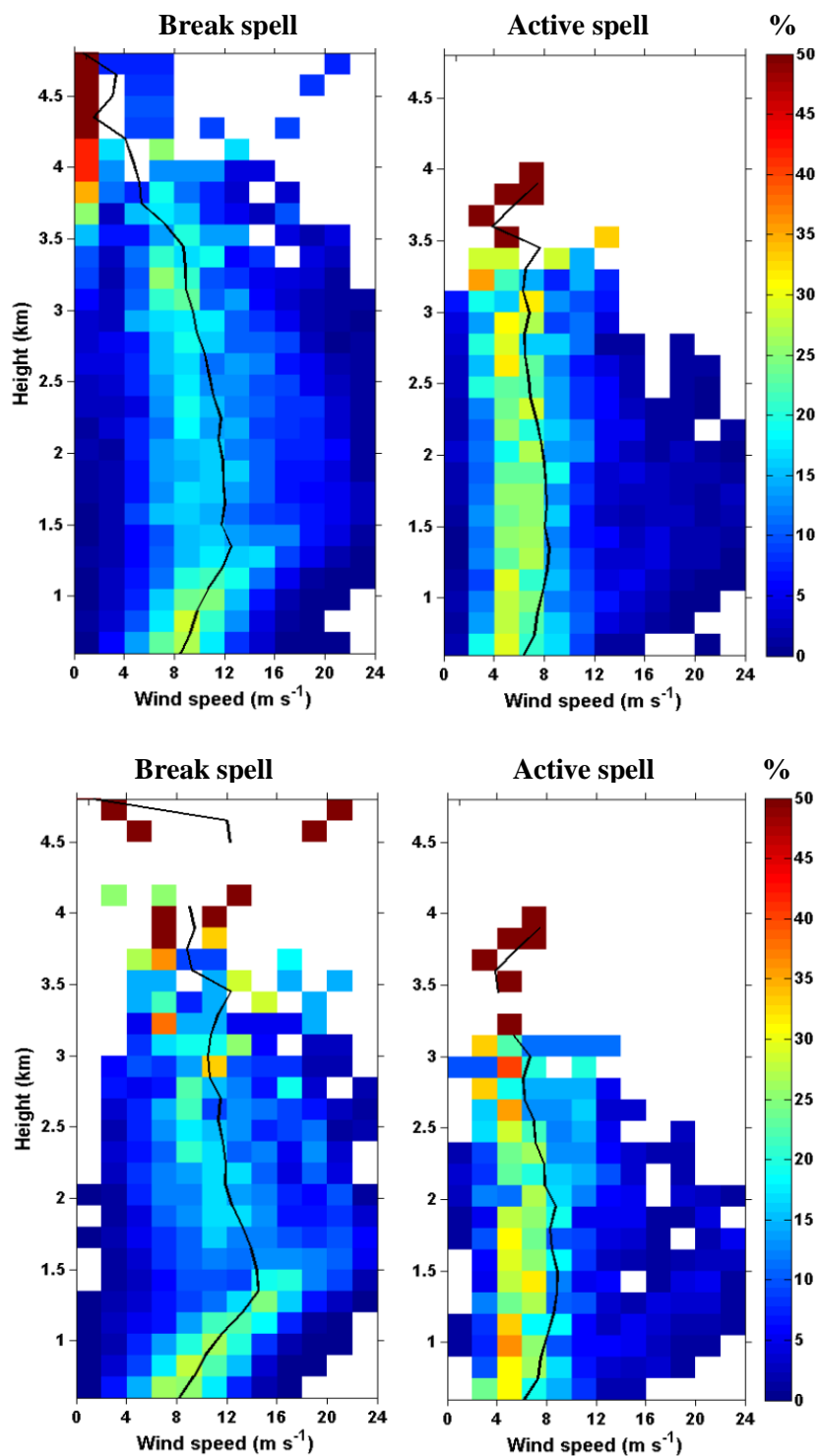


Figure 13: Occurrence statistics of wind speeds at different heights during active and break spells using total data (top panel) and also during midnight-early morning data (bottom panel). The black line superposed in each panel indicates the mean wind speed.

5. Summary and Conclusions:

A variety of data sets for monsoon 2016 are employed, comprising of reanalysis, multisatellite precipitation, Sodar and wind profiler data, to understand the characteristics of LLJ and MLLJ. Important findings from this study are summarized below.

1. Spatial patterns of both MLLJ and LLJ look similar with both of them showing their maximum strengths in the western Arabian Sea and also branching into two channels over Indian longitudes. However, the axis of MLLJ and LLJ are found to be slightly different in the Arabian Sea. Also, the LLJ strength is found to be much weaker than that of MLLJ over the Indian landmass, due to surface frictional drag.
2. Both LLJ and MLLJ show similar phase variations (or diurnal variations) during the monsoon period and is somewhat difficult to discern them and study in isolation. It appears to be a part of MLLJ, as it is found well within the width of MLLJ. Nevertheless, it is easy to identify LLJ in other seasons.
3. It is found that the vertical variation of horizontal winds at Gadanki and its diurnal variation is dictated by these jets. For instance, the vertical variation of diurnal cycle of horizontal winds is quite complex within the ABL. At lower heights (up to 300-500 m), strong winds are observed during the day time owing to downward transport of turbulence-induced momentum. Also the thermals in the ABL cause lot of friction to the flow and reduce the wind speeds during the day time. After the cessation of these thermals (post sunset) the winds start increasing again in a frictionless ABL (above the surface layer). It dramatically increases the wind velocities during midnight-early morning. Both LLJ and MLLJ peaks are observed during this period. Also, the

amplitude of diurnal variation is found to be quite large (in fact largest in the entire the ABL) at the height of MLLJ (1.5-2.5 km).

4. The MLLJ (and to some extent LLJ) exhibits large spatial variation between active and break spells (identified for southeast peninsular India). During the break spell, the branching of MLLJ is strikingly apparent with one branch of MLLJ passing over southern peninsular India, while the other curve anticlockwise (runs almost parallel to the coast) and merge with the first branch in Bay of Bengal. The first branch, i.e., the one over the southern peninsular India, weakens considerably allowing propagation of precipitating systems from the west coast during the active spell.

5. During the break spell, MLLJ is prevalent nearly 75% of time in the entire ABL over Gadanki, but the strongest winds are observed in the height region of 1.5-3 km with wind speeds exceeding 20 m s^{-1} in about 10% of total observations. On the other hand, only for about 50% of time only MLLJ occurs (wind speed exceeds 8 m s^{-1}) during active spell. Maximum winds are also noted at a slightly lower altitude range (1.5-2.5 km).

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