



Vertical structure and evolution of monsoon circulation as observed by 205-MHz wind profiler radar

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Abstract

A wind profiler radar at 205 MHz is operational since January 2017, at Cochin (10.04°N; 76.33°E), a region lying in the west coast of Southern Peninsular India, which also is the entry point of the Indian summer monsoon. Using the radar wind profiles obtained during April to September, the detailed vertical structure of wind during the pre-monsoon and monsoon period was studied for the years 2017 and 2018. The gradual transition from pre-monsoon to monsoon season as manifested by the development of monsoon circulations in the lower and upper troposphere is well captured by the radar observations. Parameters which characterize the strength of monsoon circulations have been derived which are shown to be potential predictors for declaring the monsoon onset over Kerala in an objective manner. The monsoon circulation during the year 2018 was studied in detail in the backdrop of extreme heavy rainfall over Kerala. It is observed that there is an anomalous decrease in the core height, but with high core speed in the Low-level Jet stream (LLJ) during 2018 as compared to year 2017. Owing to this unique placement of LLJ, it can be concluded that intense orographic lifting could have played a role in causing heavy rainfall over Kerala in 2018. The transitions in LLJ prior to heavy rainfall over south-west coast are aptly captured by the radar observations which opens up the possibility of predicting heavy rainfall events through continuous monitoring of monsoon circulation using radar.

1 Introduction

The Indian summer monsoon (ISM) is a much speculated annual phenomenon which is being officially forecasted using an ensemble of statistical and dynamical models. Though, dynamical models have been observed to out-perform the conventionally used statistical methods and may soon replace the latter in real-time prediction of monsoon rainfall (DeSole and Shukla 2012), they are mostly reliable for short-range forecasts. Declaration of the monsoon onset over Kerala (MOK) by India Meteorological Department (IMD) officially marks the beginning of the summer monsoons. MOK prediction is usually done a week in advance

and is mostly accurate, though there have been instances when they have failed, like in the year 2002. It was always upheld that the onset was purely a synoptic process, but subsequent studies point to its teleconnection with other phenomena like El Niño Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), Madden–Julian Oscillation (MJO), etc. (Kane 1998; Ashok et al. 2001; Gadgil et al. 2004; Xavier et al. 2014). Likewise, the declaration of MOK also assumes a great deal of importance and timely prediction of MOK is still a challenge.

Several studies in the past have sought to study the predisposing factors behind the onset. Raju et al. (2005) using 52 years of reanalysis data show that the strength of circulation increase rapidly at the time of summer monsoon. They also observed the development of a zone of flux convergence of heat and moisture over the region of Bay of Bengal which intensifies through onset and post-onset. Joseph et al. (2006) recorded large-scale atmospheric changes around South Asian and Indian regions ahead of MOK. They also establish that large-scale convection and SST gradients pull up jets from very low latitudes to Kerala latitudes leading to MOK.

Earlier works have attempted to define MOK through empirical or objective means (Wang et al. 2009; Pai and

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Nair 2009), but these methods are not without biases. Model simulations also need improvement when it comes to prediction of monsoon onset. They remain unreliable mostly due to lack of adequate information on land–atmosphere interactions and other physical phenomena behind the monsoon onset (Sperber et al. 2001; Waliser et al. 2003). It is therefore imperative that the models require to be assessed and validated against observations.

The commencement of monsoon brings about marked changes in the atmospheric circulation and is manifested by the establishment of two well-defined monsoon circulations, the monsoon low-level jet (LLJ) in the lower troposphere and the Tropical Easterly Jet (TEJ) in the upper troposphere. The changes in the flow pattern of monsoon jet streams during active/break phase can influence the progression as well as the distribution of monsoon rainfall over the Indian sub-continent (Pattanaik and Satyan 2000; Chen and Tomassini 2015). Attributing to these factors, it becomes inevitable to monitor the vertical structure of monsoon circulation to understand the monsoon processes in detail. Moreover, observations on monsoon circulation are vital for assessing the simulation of circulation features by models.

A stratosphere–troposphere (ST) wind profiler radar operating at 205 MHz has been set up at Cochin (10.04°N; 76.33°E), Kerala to study the monsoon processes at the region of monsoon onset (Kottayil et al. 2016b; Mohanakumar et al. 2017, 2018). The ST radar can resolve wind information in three dimensions at high spatial (depending on the height, spatial resolution may vary from 175 m at 500 m to 7 km at 20 km) and temporal resolutions which makes it an ideal tool to study the atmospheric processes before, during and after the monsoon onset (the radar location is shown in Fig. 1). Wind observations over a couple of years may seem inaccurate for an in-depth understanding of monsoon processes; however, a continuous dataset throughout the monsoon season over the forthcoming years from the radar wind profiler at Cochin would provide a unique dataset

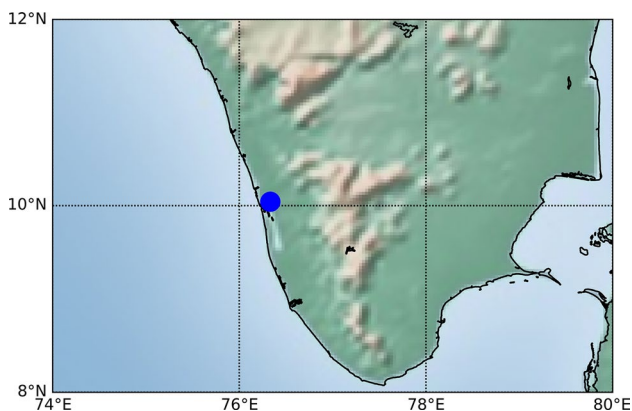


Fig. 1 Topography map showing the radar location (blue circle)

that could furnish new insights and understanding of factors leading to monsoon onset and variability.

This work utilizes unique data from the 205-MHz wind profiler radar for the first time to monitor the detailed vertical structure of wind prior and during the summer monsoon season. The data collected during April to September months for the years 2017 and 2018 would be used in the study. Specifically, the study looks into the possibility of defining predictors for the monsoon onset in an objective way. An insight has been provided for the reason behind the abnormal rainfall over Kerala in 2018, dubbed the 'rainfall of the century', by analysing the monsoon circulation features using the wind profiler radar. Further, the radar data would be used to evaluate the simulation of monsoon circulation by ERA-Interim re-analysis data and the UK Met office model.

2 Data

In this study we use data from the 205-MHz stratosphere–troposphere wind profiler radar for the period of April to September, for the years 2017 and 2018. The ST radar at 205 MHz is an active phased array radar having 619 Yagi–Uda antennas and a corresponding number of transmitter–receiver modules (TRM). Doppler beam swinging (DBS) method is used for three-dimensional wind profile estimation. The radar is very accurate in the estimation of wind for an altitude range of 315 m to 20 km. The detailed technical specification and the validation of radar are found elsewhere (Samson et al. 2016; Kottayil et al. 2016b; Mohanakumar et al. 2017). The radar has been used to understand various atmospheric phenomena (Kottayil et al. 2018; Nithya et al. 2019). Radar wind measurements from two different coded modes of operation at baud rates of 0.3 and 1.2 μ s have been combined over the altitude range of 315 m–20 km. A height range of 315 m–5 km has been taken from 0.3 μ s baud operation, which has a vertical resolution of 45 m and a height range of 5–20 km has been taken from the 1.2 μ s baud, having a vertical resolution of 180 m. The daily mean wind profiles were created by combining the data for a period of 11–17 h local time.

European Centre for Medium Range Weather Forecasts (ECMWF) Interim re-analysis (ERAInt) (Dee et al. 2011) is one of the widely used reanalysis products for studying the monsoon circulation and its variability. The profiles of zonal wind from ERA-Interim for the period of May to September, 2017 having a horizontal resolution of $0.25^\circ \times 0.25^\circ$ are used. The merged gridded rainfall data (Mitra et al. 2013) for the period May to September 2017 and 2018 available at $0.25^\circ \times 0.25^\circ$ resolution are also used in this study.

Zonal wind profiles from Met Office Unified Model (MetUM) operational analysis are also used in the present

study. The MetUM uses Global Atmosphere version 6.1 (GA6.1; Walters et al. (2017)), which underwent a major resolution upgrade on 11 July 2017 with the horizontal resolution improving from 17 to 10 km at the mid-latitudes. For the analysis of this study, the nearest grid point at the respective resolution to the location of the radar is chosen for comparison. We have also used outgoing longwave radiation (OLR) from INSAT-3D geostationary satellite during the period of August 10–20, 2018 obtained from <https://www.mosdac.gov.in/>.

3 Results and discussion

In this section, the vertical structure of monsoon circulation is analysed in detail, followed by an investigation into the anomalous increase in rainfall over Kerala in 2018. A

study of the monsoon circulation characteristics over Cochin prior to heavy rainfall events over west coast is also made and the modelled circulation features are evaluated against observations.

3.1 Monsoon circulation features

The features of monsoon circulation are more discernible in zonal wind profiles and therefore for depicting the changes in the circulation pattern, we use the zonal wind profiles obtained from radar. The height–time variations in zonal wind for the years 2017 and 2018 are shown in Figs. 2 and 3. These show the fluctuations in the zonal wind structure within the height range of 315 m to 20 km, beginning from April to the end of September. The evolution of monsoon circulation is clearly evident in the radar data. For both the years, the wind starts off as south-westerly at lower levels

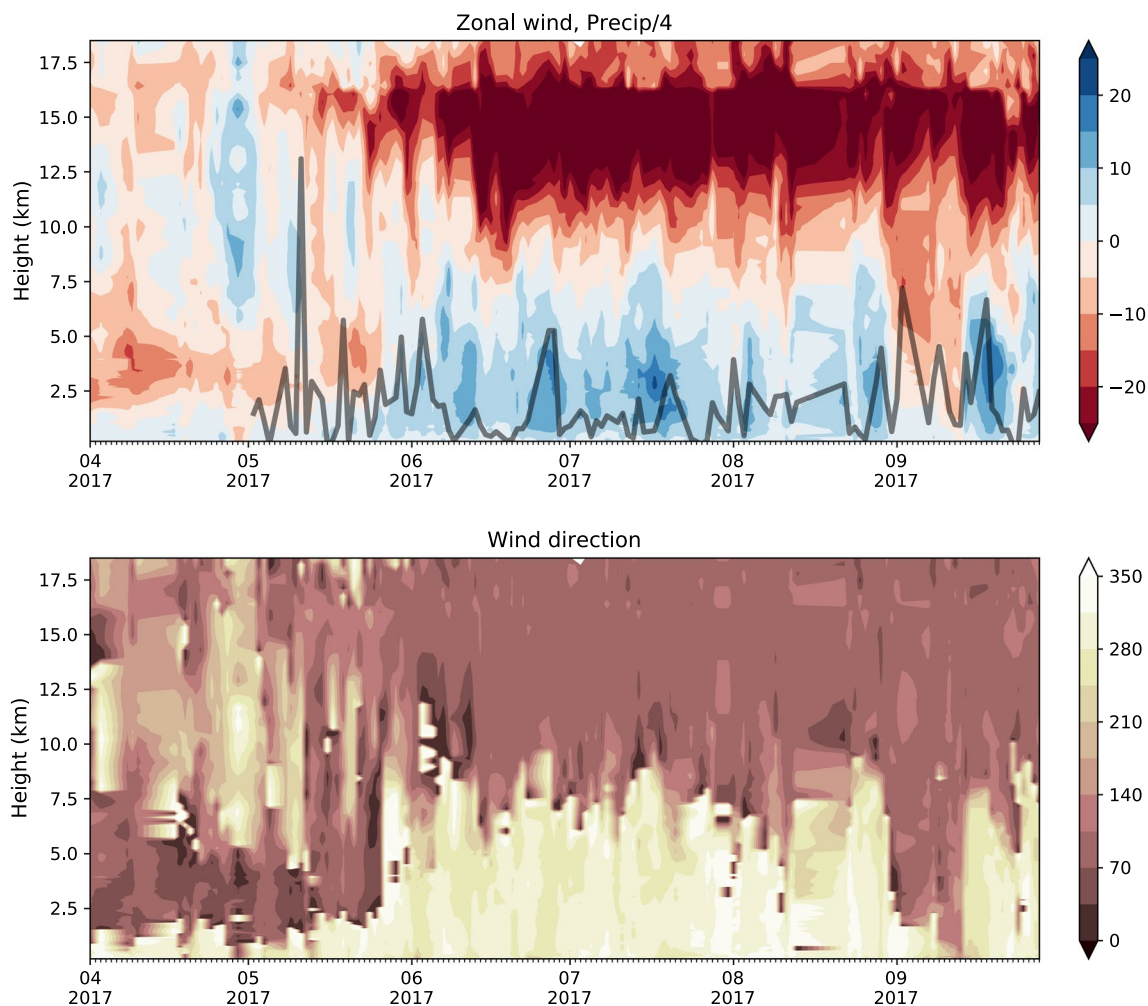


Fig. 2 Time–height variations in the zonal wind (m s^{-1}) (top) and wind direction ($^{\circ}$) (bottom) from ST radar observed over Cochin during April to September 2017. Wind direction is represented as northerlies = 0° , easterlies = 90° , southerlies = 180° and westerlies

= 270° . The rainfall (divided by a factor of 4 for the convenience of plotting) observed over Kerala ($8\text{--}12^{\circ}\text{N}$; $76\text{--}78^{\circ}\text{E}$) during May to September is also shown as black solid line

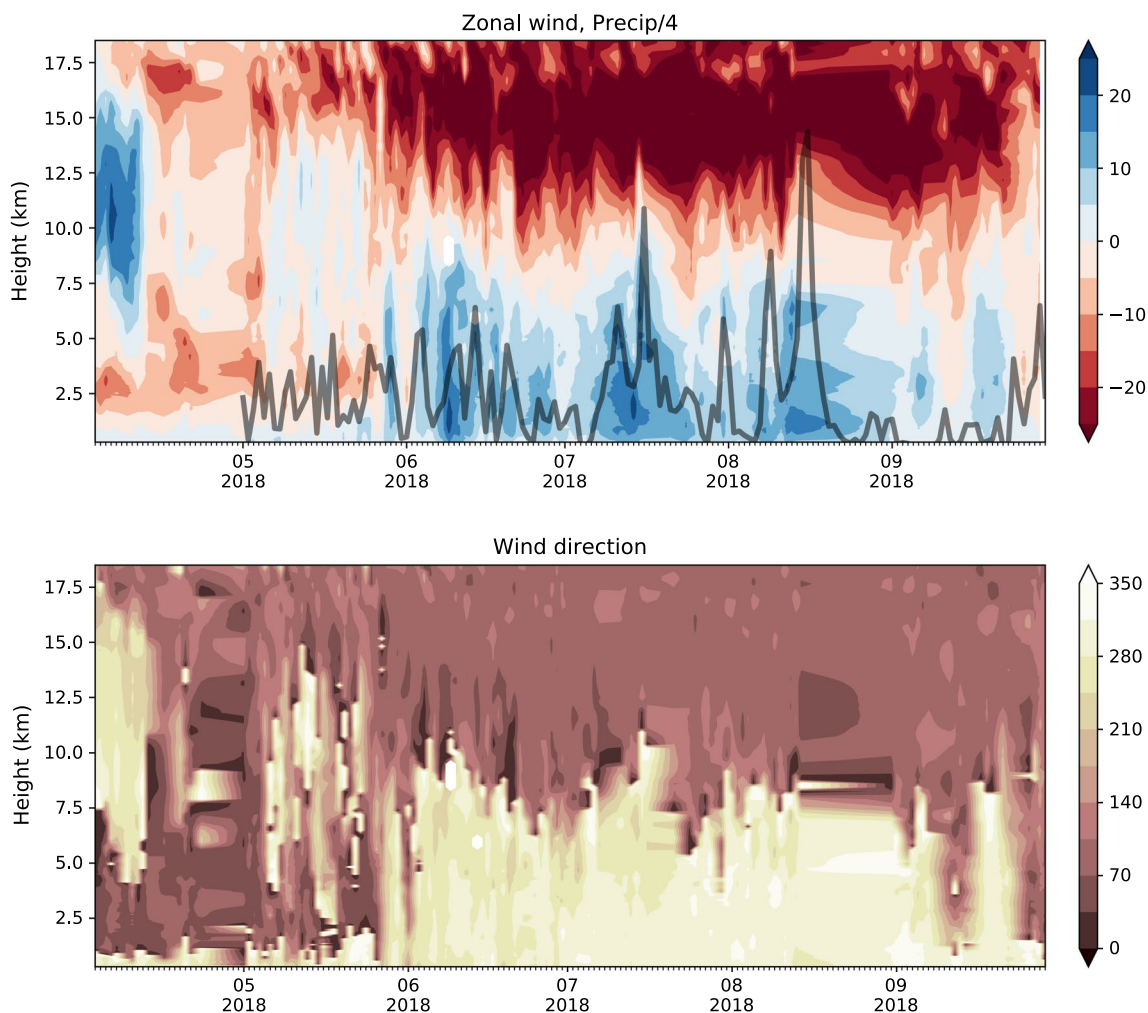


Fig. 3 Same as Fig. 2 but for the year 2018

(below 2 km) in April, later becoming intermittent and lacking in directional consistency. By the first quarter of May, the scenarios change with winds turning south-westerly at lower levels, and maintaining directional consistency thereafter. This marks the establishment of monsoon low-level jet. As evident from the figure, south-westerly flow spans up to an altitude of 8 km once monsoon onset begins, exhibiting a day-to-day variability with the progression of monsoon. The MOK for the years 2017 and 2018 were declared on 30 May and 28 May, respectively, by the IMD. Both the years show a similar vertical span in LLJ with a height of about 2 km by mid-May and increasing thereafter, before reaching a height of 8 km on 29 May 2017 and 30 May 2018, the respective dates when MOKs were declared. As monsoon progresses further, fluctuations in the altitude range of LLJ are observed which can be related to the variability in the monsoon rainfall. The rainfall observed during May to September 2017 over Kerala is also shown in figure as solid black line. The rainfall variability is synchronous with the development of

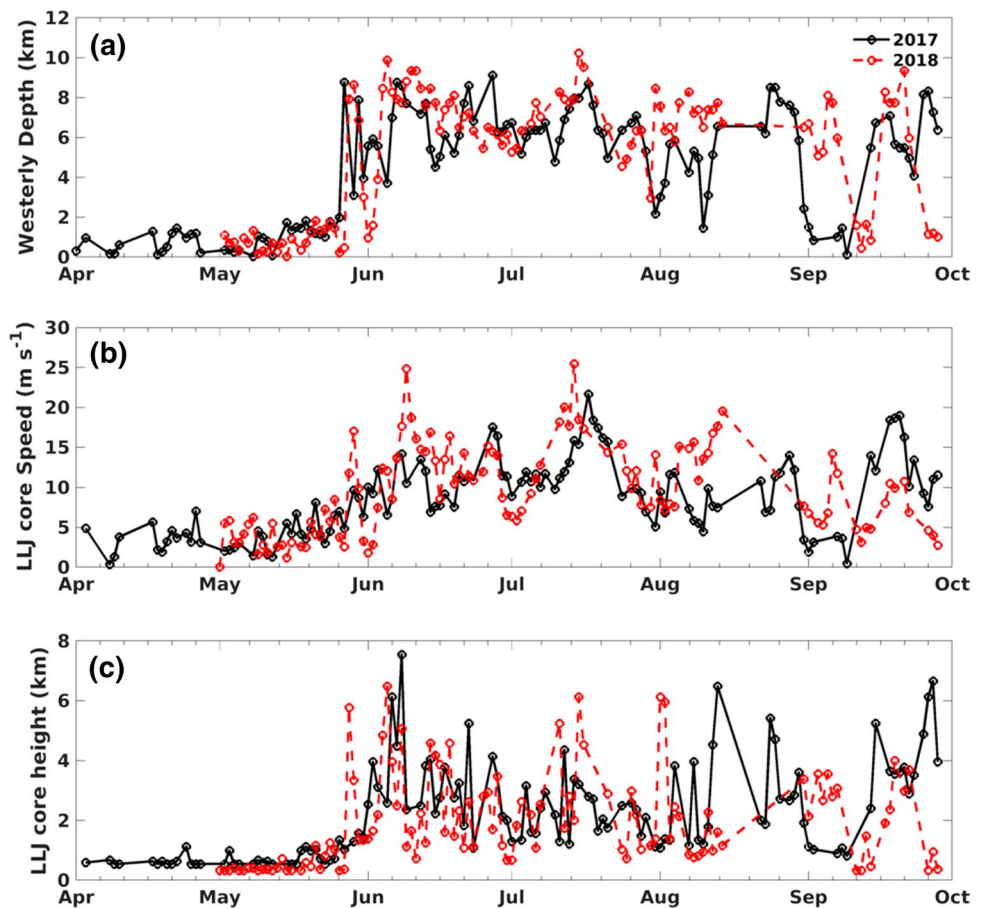
low-level jet flow. There is an abrupt increase in the rainfall, similar to the trend in LLJ at the time of MOK. There are also days when troposphere is dominated by easterlies (middle of September). During this time the rainfall recorded over the region is also low as illustrated in the figure. The development and progression of the Tropical Easterly Jet in the upper troposphere, another important component of monsoon circulation, is also clearly seen. As seen in the figure, a weak TEJ forms in the first week of May, intensifying gradually but attaining a sharp gain in strength at MOK.

It is well established that LLJ and TEJ are strongly linked to the large-scale distribution and variability of monsoon rainfall over the Indian sub-continent (Chen and van Loon 1987; Joseph and Sijikumar 2004). Here, we trace the various characteristics of these monsoon circulations and how they vary before and during the monsoon season. The LLJ structure is analysed to understand its characteristics such as the depth of westerly flow (referred to as westerly depth), LLJ core speed and height. Westerly depth is the vertical

extent of the westerly wind, core speed is its maximum speed and the height corresponding to core speed is the core height. The progression of westerly depth from pre-monsoon to monsoon season for the years 2017 and 2018 is shown in Fig. 4a. During the beginning of May, the westerly depth was below 1.5 km with an invariant trend in its value. However, with the establishment of low-level monsoon circulation in the middle of May, the depth is seen to increase gradually but gaining rapidly during the last week of May. At the time of monsoon onset over Kerala, the depth of westerlies reach up to a value of 8 km and also recorded a rapid increase in the rainfall over Kerala. It is also to be noted that Kerala recorded heavy showers during the first week of May. Simultaneous observations of rainfall and westerly depth observed during May suggest that the heavy rainfall that has occurred prior to the commencement of monsoon may not be directly linked to the large-scale monsoon circulation, but most likely due to convection arising from local convective systems. During June to September, the westerly depth shows variability, without any significant trend. The maximum and minimum westerly depth observed during 2017 are 9.3 and 0.13 km, respectively, with a mean value of 5.88 ± 4.12 km, whereas the corresponding values for 2018 are 10.23 and 0.26 km, with a mean value of 6.37 ± 2.37 km.

The core speed and height of LLJ are shown in Fig. 4b, c. The core speed and core height show similar variations as that of westerly depth, where their values remain low during the first week of May without any trend. This situation changes when the core speed and height show an increase in the trend from mid-May onwards. The core speed and core height reach values of 10 m s^{-1} and 3.5 km, respectively, at the time of MOK in 2017. In 2018 the value of core speed and height reached a value of 17.02 m s^{-1} and 3.3 km during MOK. The maximum value of LLJ core speed observed during 2017 and 2018 monsoon seasons (June to September) are 21.6 m s^{-1} and 25.45 m s^{-1} , respectively. The mean values of the LLJ core speed with one σ standard deviation are $10.61 \pm 4.12 \text{ m s}^{-1}$ and $11.36 \pm 5.09 \text{ m s}^{-1}$, respectively, for the years 2017 and 2018 while the values of the core height for the respective years are 2.88 ± 1.49 and 2.32 ± 1.51 km. Based on re-analysis data, Joseph and Sijikumar (2004) have shown that LLJ core speed lies at 850 hPa (approximately 1.7 km) throughout the Indian sub-continent. The study by Joseph and Sijikumar (2004) use re-analysis data of coarser vertical resolution obtained at fixed pressure levels, which may account for any discrepancies with our results. The value of core height determined using radar data is in agreement with an earlier study by Narayanan et al. (2016) where

Fig. 4 Temporal evolution of westerly depth (a), LLJ core speed (b) and core height (c) during April to September for the years 2017 and 2018



they have used high vertical resolution GPS radiosonde data to determine the same.

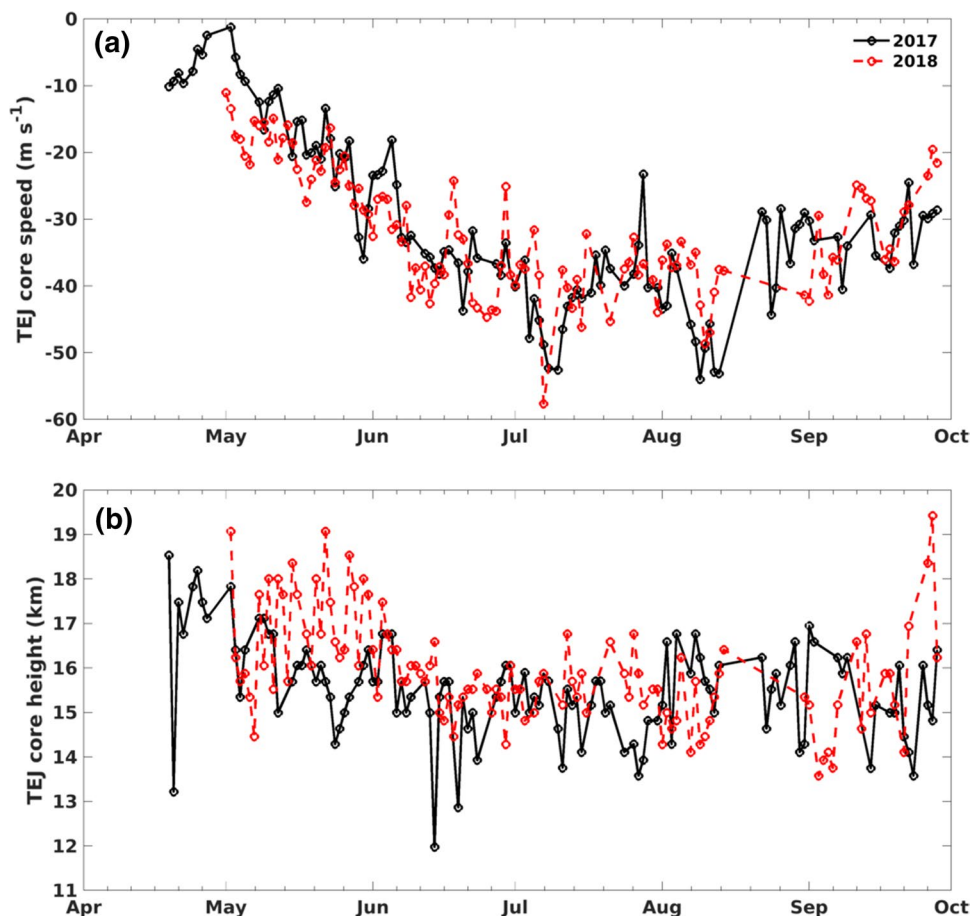
Monsoon, like many other tropical phenomena is strongly a baroclinic system. It is therefore highly relevant to understand the coherent variations of the tropical easterly jet (Sathiyamoorthy et al. 2007) in relationship with LLJ and monsoon rainfall. The evolution of core speed and core height of TEJ is shown in Fig. 5. The easterly jet starts building up by the beginning of May, slowly gaining strength by middle of May and thereafter there is a sharp increase in its core speed when monsoon onset occurs over Kerala. The core speed of the TEJ observed during MOK in 2017 and 2018 are 35 m s^{-1} and 28 m s^{-1} , respectively. After the onset of monsoon, TEJ shows significant day-to-day variability. The mean values of TEJ core speed observed during June to September are $-36.4 \pm 7.2 \text{ m s}^{-1}$ and $-36.4 \pm 7.27 \text{ m s}^{-1}$, respectively for the years 2017 and 2018. Contrary to TEJ core speed, TEJ core height does not show any sharp transition at the time of monsoon onset, with the mean value of core height being $15.22 \pm 0.93 \text{ km}$.

Over the years, several methods have been developed to determine the monsoon onset over the southern tip of India both using subjective and objective methods (Ananthakrishnan and Soman 1988; Joseph et al. 2006; Pai and

Nair 2009; Wang et al. 2009). Traditionally, IMD's declaration of monsoon onset is based on the surface rain rate observed from several stations in the southern tip of India (Ananthakrishnan and Soman 1988). However, since 2006 they have adopted different criteria for determining the monsoon onset based on an objective method. In addition to using surface rain rate, strengthening of lower tropospheric monsoon circulation as proposed in Joseph et al. (2006), was also considered before onset declaration. Though several studies allude to the fact that changes in the lower tropospheric circulation features can be used as proxy for declaring the MOK, these inferences have been made mostly from re-analysis data whose vertical resolution is rather poor. Whether wind information from re-analysis data can be relied upon as a robust predictor of monsoon onset is the obvious question to ask.

There is mutual consistency in the behaviour of monsoon circulation during monsoon onset time for the 2 years studied. This indicates the possibility of using radar data as a reliable means for affirming the monsoon onset over Kerala. Owing to the synoptic nature of monsoon circulation in terms of scale, it is therefore quite likely that large-scale events get captured by the radar as well. Considering the fact that monsoon onset occurs over entire Kerala, it would

Fig. 5 Same as Fig. 4 but for TEJ core speed (a) and core height (b)



be more appropriate to analyse the vertical profiles of zonal wind over the entire Kerala region and also over Cochin during the monsoon onset time. This would be helpful in indicating whether the transition of monsoon circulation during monsoon onset over the whole of Kerala is mirrored over Cochin too. With this rationale, we have composited the profiles of zonal wind during the monsoon onset dates for a period of 1982–2007 from the ERAInt data over the entire Kerala and Cochin (radar location) regions separately and the differences were investigated. The result is shown in Fig. 6. It is obvious that the transformations occurring in monsoon circulations during the onset period over Kerala is well captured over the radar location. These results show that radar observations can be used for understanding the monsoon onset features to a certain extent.

By examining the characteristics of monsoon circulations for 2 years it becomes obvious that the derived parameters which represent the strength of monsoon circulations can be used as indicators for declaring monsoon onset. On examining the various characteristics of monsoon circulation from ST radar, there emerges a possibility of defining parameters with a higher likelihood of defining the monsoon onset date. This however would require ST-radar data acquired over several monsoon years before being used as general criteria.

The following observations were made by ST radar during monsoon onset over Kerala.

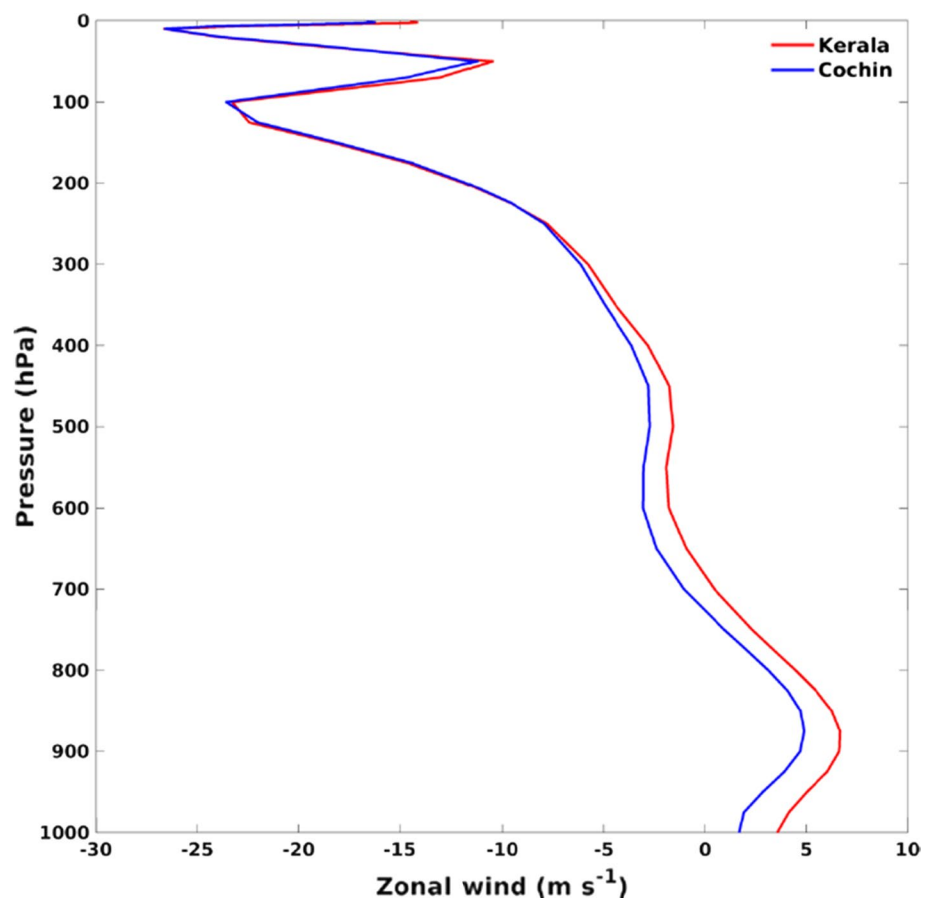
- LLJ core speed reached a value which is equal to or greater than 10 m s^{-1} .
- Westerly depth attained a value of 8 km.
- TEJ core speed attained a value greater than 25 m s^{-1} .

However, it is to be noted that conditions observed from radar at the time of monsoon onset may also occur during bogus monsoon onset time. Under such circumstances, it may not be advisable to use wind profiler data alone to confirm the onset features but rather, the radar observations should be supplemented with other observations.

3.2 Relationship between monsoon rainfall and circulation

Figure 7a shows the daily average rainfall over Kerala ($8\text{--}12^\circ\text{N}$; $76\text{--}78^\circ\text{E}$) for the years 2017 and 2018. In 2017, the south-west monsoon rainfall over India was 95% of the long-term average and Kerala received around 1085 mm of rainfall during the period from 1 June to 20 September. The 2017 rainfall is a typical example of a normal monsoon. The

Fig. 6 Composite of zonal wind profiles during monsoon onset period (1979–2007) over Kerala from ERAInt data



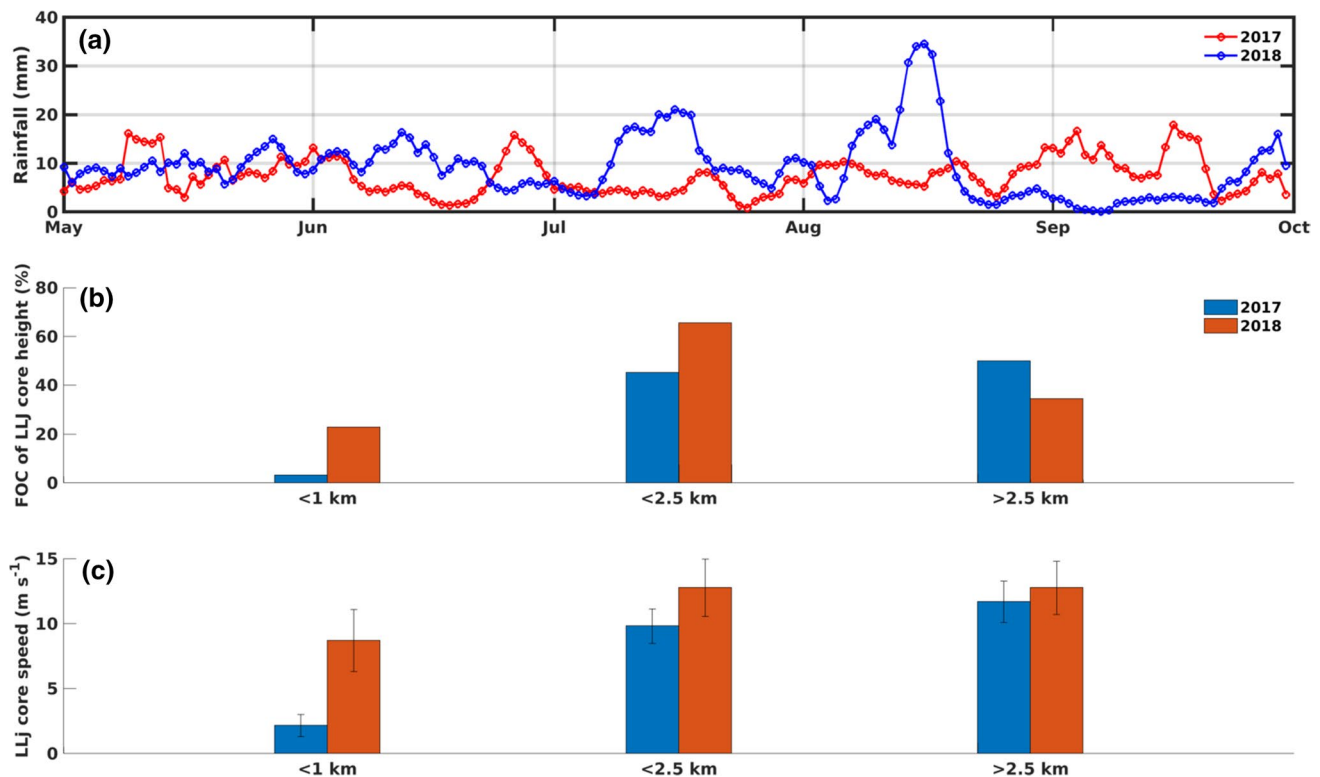


Fig. 7 **a** Daily mean rainfall (mm) over Kerala (8–12°N; 76–78°E) during the years 2017 and 2018. **b** The frequency of occurrence of LLJ core height at different altitude ranges for the years 2017 and

2018. **c** The median of LLJ core speed when LLJ core height lies at different altitude ranges for the years 2017 and 2018. The error bars represent median absolute deviation

2018 rainfall, in contrast to 2017, shows stronger variations with three clear spells in each month. It is clear from the figure that the mean rainfall in 2018 shows three, five, and sevenfold increase from 2017 for the months of June, July and August, respectively. The third week of August 2018 witnessed an intense rainfall spell causing unprecedented floods wreaking havoc across the state. The 2018 monsoon flood in Kerala has been considered the worst since 1924. The cumulative rainfall for Kerala between 1 June and 15 August was 2087.67 mm, a departure of nearly 30 per cent from the normal (1606.05 mm) rainfall. The torrential rains during 14–18 August led to Kerala's dams and rivers reaching their full capacities. Few locations received 300–400 mm rain in a day between 15–17 August. The first 3 weeks of August alone witnessed a rainfall of 758 mm, the highest since 1931 (<https://www.imdtvm.gov.in/rainfall>).

Kerala's unique geographic location is an underlying factor determining monsoon incidence. It is a region lying between the Arabian Sea and the Western Ghats, a range of mountains lying parallel to the west coast of India. The average elevation of Western Ghats is around 1.2 km with a maximum of 2.6 km. The copious monsoon rain in Kerala can be attributed to this unique placement, where orographic lifting plays a significant role in the formation of rain bearing

clouds during the monsoon season. With extreme weather events on the rise in a warming world, intense rainfall in these regions are predicted to be a norm. The consequences can be more damaging when such disasters strike amidst unpreparedness. Under these circumstances, the underlying factors which trigger extreme weather conditions need to be isolated and studied in detail for future preparedness and aversion of calamities.

The rainfall over south-west coast is largely controlled by moisture flux from the Arabian Sea due to the LLJ (Joseph et al. 2006). Following this line of contention, we compare the frequency of occurrence of LLJ core height for different height ranges for 2017 and 2018 and the results are shown in Fig. 7b. The figure depicts that in about 30% of the cases, the LLJ core height lies at 1 km or below and for more than 60% of the cases, the LLJ core height lies within 2.5 km for the year 2018. The occurrence of LLJ core height above 2.5 km is less than 40% in 2018. In contrast, in 2017 when the monsoon rainfall is normal over Kerala, the presence of LLJ core height below 1 and 2.5 km is less than 4% and around 45%, respectively. About 50% of the time, the LLJ core height occurred above 2.5 km in 2017. Figure 7c shows the median values of the core speed of LLJ occurring at different height ranges. As evident from the figure, the core speed of LLJ

in 2018 is higher than that of 2017 with values reaching 15 m s^{-1} for LLJ core heights below 2.5 km. It is thus obvious from our analysis that for most cases analysed during 2018 monsoon, the LLJ core height lies below 2.5 km with high values of LLJ core speed as compared to 2017 (see Fig. 4). The above observations clearly suggest an enhanced moisture influx (humidity data is not available for the period at the time of analysis and hence not shown) towards the Western Ghats in 2018 compared to 2017. Since the LLJ core was recorded below 2.5 km for most of the days in 2018, the consequent enhanced moisture influx up on interacting with Western Ghats may have caused intense orographic uplift and thereby an anomalous increase in rainfall in 2018.

To have a deeper insight into the processes behind the extreme August rainfall and consequent Kerala flooding, it was imperative to look into the transitions that occurred over the Arabian Sea prior to it. We have therefore analysed the evolution of OLR before and during the heavy rainfall event. The OLR observed over the Indian sub-continent and Indian Ocean during 10–20 August 2018 is shown in Fig. 8. The low OLR values (200 Wm^{-2}) indicate the presence of a low-pressure system over the Bay of Bengal on the 10 August 2018 around $8\text{--}12^\circ\text{N}$ and $88\text{--}96^\circ\text{E}$. A similar low-pressure region was also prevalent over the west coast of India which may be due to the barotropic instability occurring during the monsoon season. The depression seemingly traveled north westward over the Bay of Bengal in the subsequent days (11–12 August 2018) causing a low-pressure region over central India. At the same time, the low-pressure area is found to extend over a small region over the Arabian Sea surrounding the west coast. However, on 14 August 2018, the low-pressure system is seen to engulf a large area over the Arabian Sea ($0\text{--}12^\circ\text{N}$; $66\text{--}80^\circ\text{E}$) and this condition prevailed until 18 August 2018. This can be concluded as the

triggering mechanism for enhanced LLJ winds which may have caused the extremely heavy rainfall over Kerala.

We also analysed the changes in monsoon lower level circulation observed at Cochin in the backdrop of the depression over Arabian Sea in August. The monsoon rainfall over Kerala and the LLJ core speed and height from radar during 10–14 August 2018 are shown in Fig. 9 (It is reminded that continuous heavy rainfall over Cochin after 14 August 2018 had caused serious electrical power failures in the region and hence hampered the wind estimation from ST radar). There is a gradual increase in the LLJ core speed from 10–14 August 2018 and in concurrence, the rainfall values also increase. It is also clear from the figure that the LLJ core height also decreases from about 2.2 km in 11 August 2018 to about 1 km in 14 August 2018. The strengthening of LLJ was in accordance with the intensification of low-pressure area around the vicinity of west coast (see Fig. 8) and the core speed of the LLJ reached a value of 20 m s^{-1} on 14 August 2018. An important observation from the figure is that rainfall over Kerala is high when the LLJ core speed is high and the core height is low. Since the low-pressure system had been prevailing from 14–18 August 2018 over the west coast, it can be assumed that LLJ remained strong during the said time period with a lower core height. Usually when the west coast receives heavy rainfall, it is seen to continue for 3–4 days with the characteristics of LLJ most likely remaining unchanged (Xavier et al. 2018).

3.3 Circulation characteristics prior to heavy rainfall events

Rainfall and circulation are inter-related during monsoon season, it is shown in Joseph and Sijikumar (2004) that rainfall and associated convective heating over India/Bay

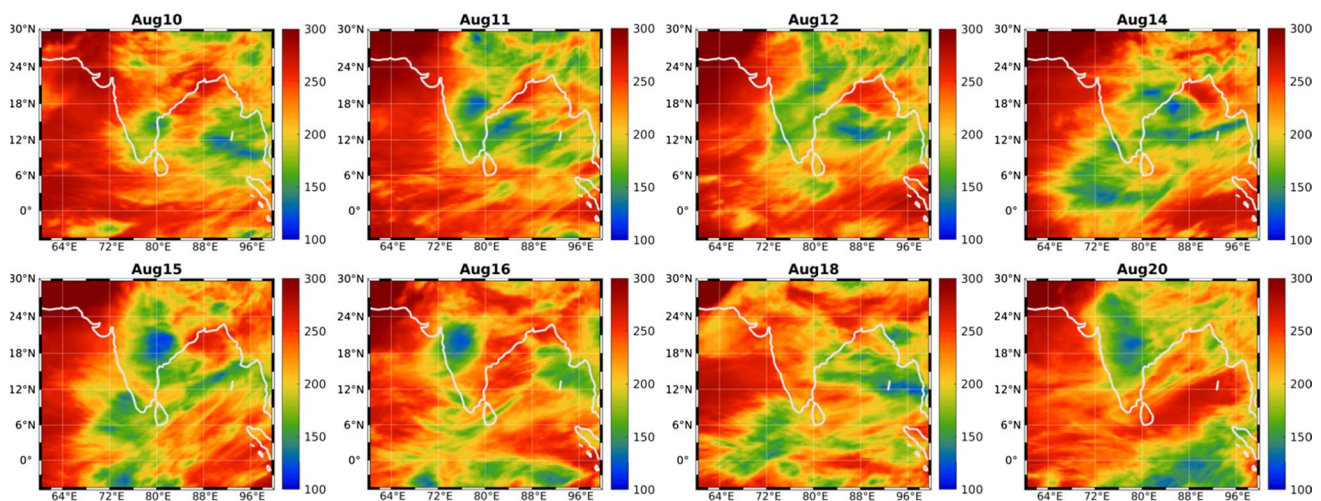


Fig. 8 Evolution of OLR (Wm^{-2}) observed over Indian Ocean and Indian sub-continent during August 10–20, 2018 from INSAT-3D satellite observations

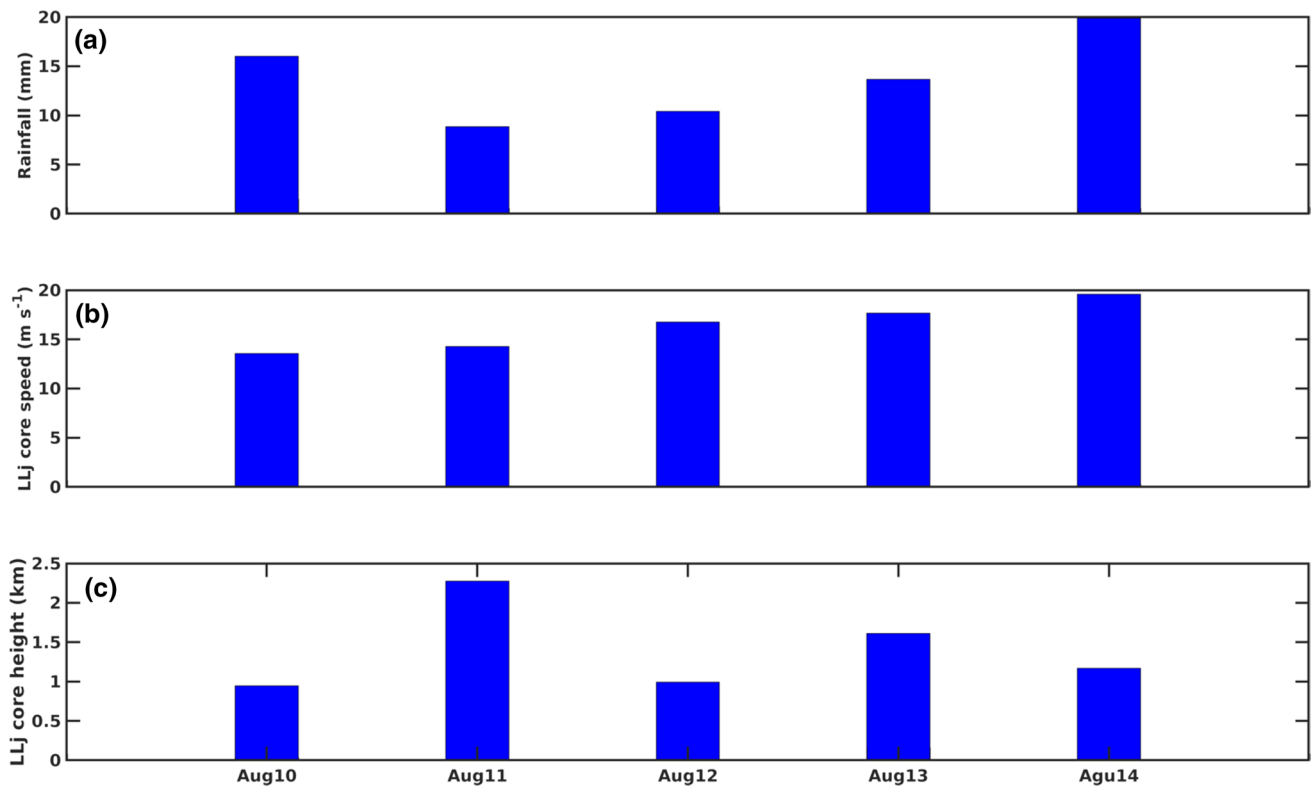


Fig. 9 The daily mean rainfall (mm) over Kerala (a), LLJ core speed (b) and core height (c) observed from ST radar at Cochin during August 10–14, 2018

of Bengal strengthens the monsoon low-level jet. A direct relationship between strength of LLJ and rainfall observed over Cochin is shown in Fig. 10. The observed correlation and the linear regression slope of the relationship are 0.52 and $0.44 \frac{\text{mm}}{\text{ms}^{-1}}$, respectively, both of which are statistically significant at 5% level.

It is well established that strengthening of monsoon circulation can render greater rainfall during monsoon season over the Indian sub-continent. The amount of rainfall increases through strengthening of LLJ and TEJ, where the former advects more moisture into the Indian sub-continent and TEJ is instrumental in maintaining the large-scale upper level outflow from the convective regions which relates to tropical and extra-tropical teleconnections related to monsoon (Goswami and Xavier 2005; Xavier et al. 2007). It is a known fact that rainfall variability over south-west coast can be well explained by variations in the strength of monsoon low-level circulation. As the lower level circulation strengthens, i.e., as the westerly depth and LLJ core speed increases the rainfall also amplifies over the south-west coast. This can be attributed to the build-up of moisture over this region brought about by the zonal water vapour transport by LLJ. The zonal moisture flux is strongly dependent on the strength and vertical extent of LLJ (Narayanan et al. 2016).

Heavy rainfall events during monsoon do not occur abruptly but occur as a result of certain preconditioning factors in the atmosphere. Factors that lead to heavy rainfall can be identified and can be traced few days in advance. The role of monsoon low-level jet in regulating heavy rainfall has been studied in Xavier et al. (2018). They have shown that there is gradual increase in the strength of LLJ prior to heavy rainfall days and LLJ achieves its peak at the time of heavy rainfall event over the west coast of India. This study has clearly shown that heavy rainfall days may have some predictability provided continuous monitoring of lower level monsoon circulation is achieved. To check this we have chosen the region lying in the south-west coast ($9\text{--}20^\circ\text{N}$; $72\text{--}77^\circ\text{E}$). The daily mean rainfall values observed over this region during June to September, 2017 and 2018 are classified into different intensities based on the percentile. Daily rainfall values below the 25th percentile are classified as low rainfall; those between 50 and 75th percentile are considered as medium rainfall; between 75 and 95th percentile as high rainfall and above the 95th are considered as heavy rainfall. We have identified 3 days when heavy rainfall had occurred over west coast and studied the characteristics of LLJ observed at Cochin 4 days prior to these events.

Figure 11 shows the rainfall observed over west coast and the LLJ core speed observed over Cochin on and 4 days

Fig. 10 Relationship between monsoon circulation and rainfall observed over Cochin

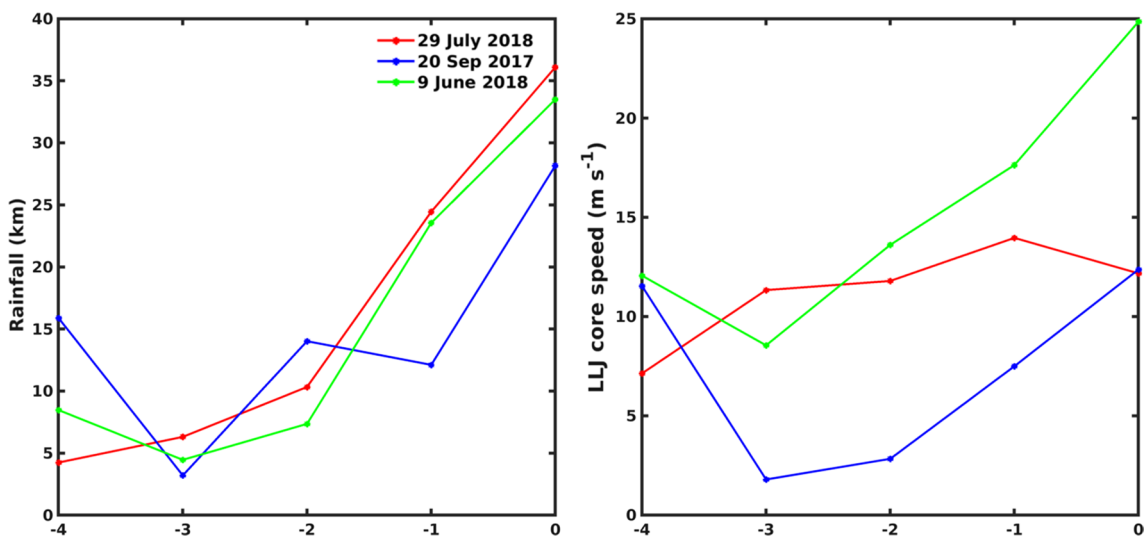
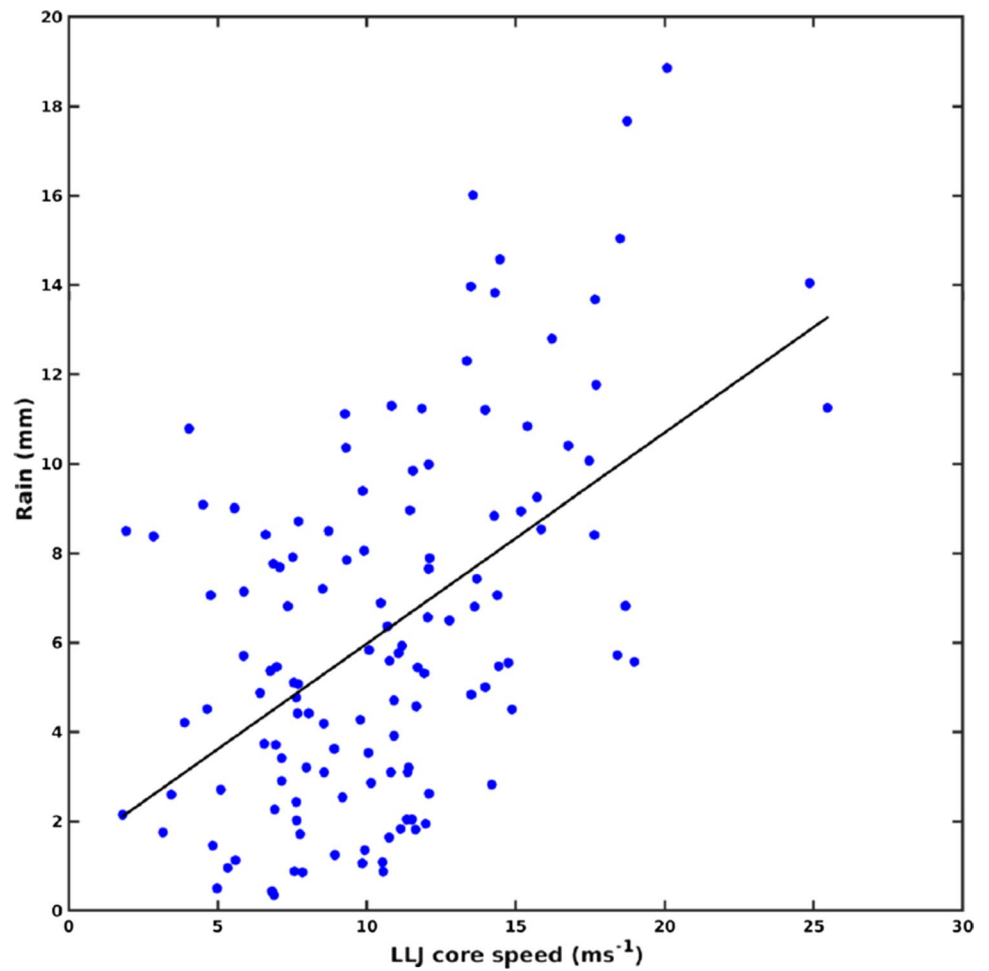


Fig. 11 Left: the rainfall over the south-west coast on (0) and prior to heavy rainfall events. The days of the heavy rainfall are indicated in the legend. Right: the core speed of LLJ observed over Cochin on and prior to heavy rainfall events over west coast

prior to heavy rainfall events. In concurrence with the LLJ core speed increase, rainfall also increase. This relationship between wind enhancement and rainfall increase can be related to enhanced water vapour transport from the Indian Ocean to the Indian sub-continent via LLJ intensification. The resulting enhanced convection over central India and the associated upward momentum transport can increase the TEJ speed. A higher vertical wind shear can intensify the convection, as convection becomes organized into linear mesoscale systems as revealed by cloud-resolving simulations (Robe and Emanuel 2001; Anber et al. 2014). Since, over the southwest coast, there is a concomitant increase in the strength of LLJ with the intensity of rainfall, it can be concluded that LLJ has a strong control on the distribution of rainfall over this region. It is to be noted that the strengthening of lower level circulation not only brings in large amount of moisture but also triggers convection (Xavier et al. 2018). It is therefore conclusive that by monitoring the factors indicating the strength of monsoon lower level circulation at Cochin there is a strong likelihood of predicting heavy rainfall events in advance. This would be one of the important practical applications of the wind profiler radar at Cochin.

3.4 Comparison of observed and modelled monsoon circulation

Models are important tools in forecasting the onset and variability of the Indian summer monsoon. However, models need to be compared against observations to assess their reliability (Kottayil et al. 2016a). Studies comparing the modelled monsoon circulation against continuous observations right at the region of Indian summer monsoon onset have not been attempted so far. In the present study, we have used the zonal wind profiles from ST-radar data to evaluate the representation of monsoon circulation in ERAInt data and MetUM global model analysis. These two modelling systems assimilate radiosonde and other observations available for the region and an independent validation of these analyses with ST radar can provide valuable information on the model biases as these datasets are widely used for monsoon studies.

For ease of comparisons with models, the radar wind profiles originally available at altitude grids are converted into equivalent pressure grids. The result is shown in Fig. 12. The monsoon circulations are reasonably well represented

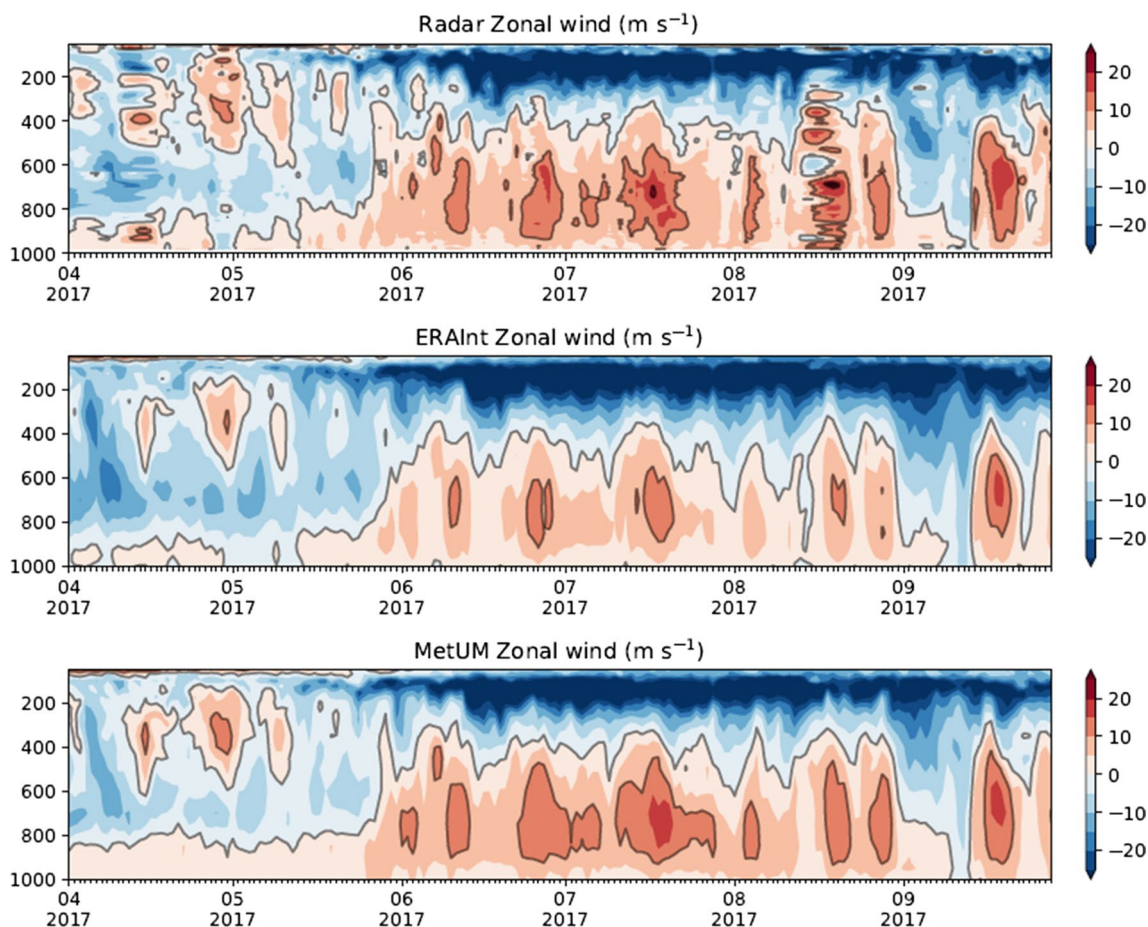


Fig. 12 Evolution of monsoon circulations in observation and models

in the models compared to observations, but they are unable to pick up the fine scale vertical variability of wind owing to their coarse vertical resolution. Although an abrupt increase in the strength of lower level monsoon circulation is seen both in ERAInt and MetUM, the day when the LLJ attains its strength differs from that of observations. In ERAInt the strengthening of LLJ occurs 4 days later as compared to observations whereas in MetUM the strengthening occurs 2 days earlier. Therefore, the models are seen to pick the MOK a bit earlier or later as compared to the actual onset date. Recall that the actual MOK was when the monsoon low-level jet attained strength, as obvious from the radar observations on May 30. The intra-seasonal strengthening and weakening of LLJ and their timings are also well captured by the model, despite the weaker amplitudes. Generally, both models produce a weaker monsoon circulation as compared to observations. Owing to these factors it is necessary to make a careful evaluation before model data is used for defining predictors of monsoon onset over Kerala.

To provide a quantitative estimate of the differences in the modelled wind compared to observations, the correlation and root-mean-square error (RMSE) of the zonal wind between observations and models have been calculated and

are given in Fig. 13. In general, the agreement between observations and models are good which is indicated by a correlation coefficient above 0.8 in most of the pressure levels. The biases in the zonal wind when compared with observations seem to be higher in ERAInt as against MetUM. The biases in zonal wind in MetUM is seen to be well below 3 m s^{-1} in almost all pressure levels, however in ERAInt the bias is more than 3 m s^{-1} with a maximum value of 6.5 m s^{-1} in the upper troposphere. Larger wind biases in the upper troposphere may be linked to the uncertainties in parametrized convection in the two models which affects the large-scale convective outflow and upper level winds. These biases in the monsoon circulation together with the lack of its detailed vertical structure in the models could lead to biases in the monsoon rainfall estimate via under prediction of the zonal water vapour transport.

4 Summary and conclusions

The coastal city of Cochin in Kerala hosts a unique wind profiler radar at 205 MHz set up to study the processes leading to the south-west monsoon right at the region of

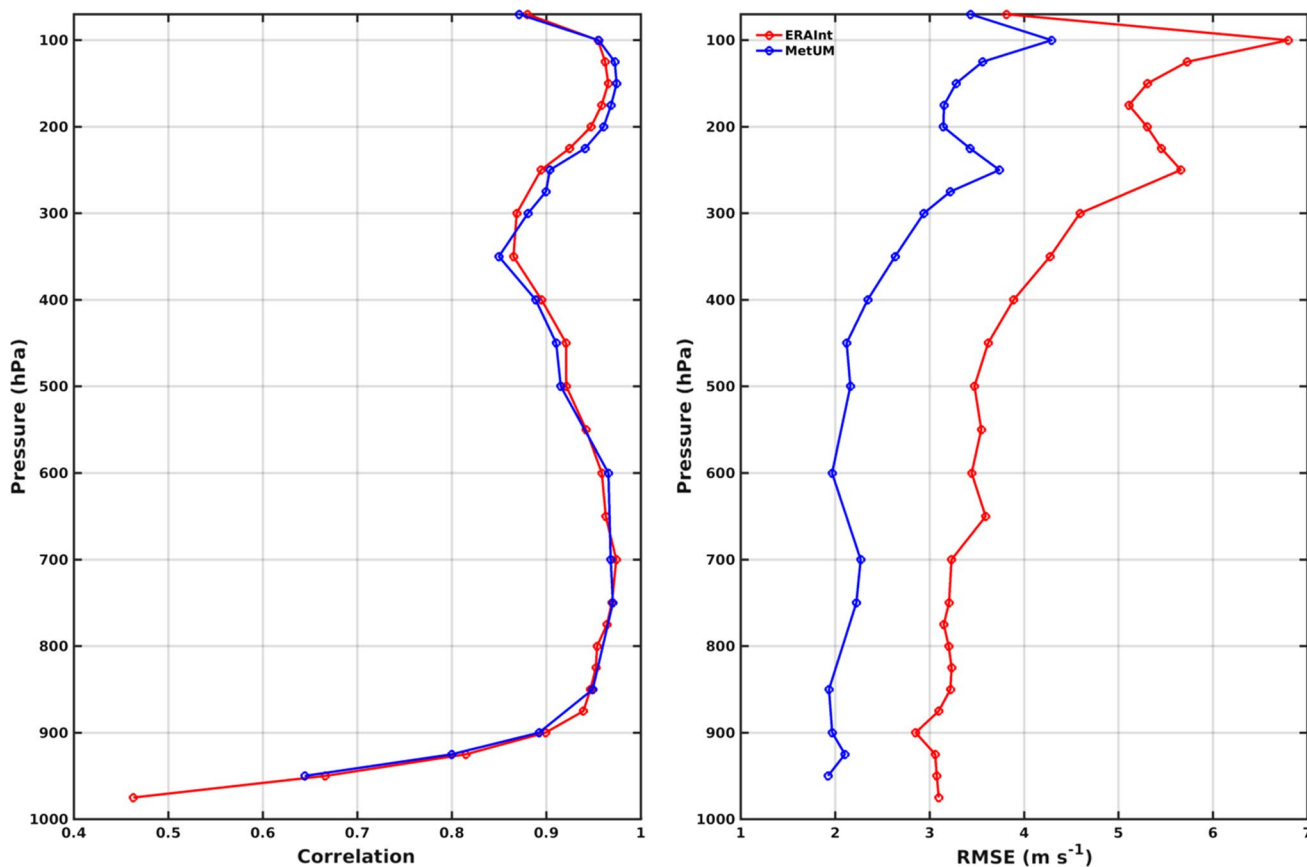


Fig. 13 Pearson correlation coefficient and RMSE in zonal wind between observations and models

its entry. Information from this radar is being used for the first time to study the characteristics of monsoon circulation for the years 2017 and 2018. The radar provides an unprecedented amount of information on the evolution of monsoon circulation. By examining the wind profiles from April to September, the development of monsoon circulation has been studied in detail. It is observed that by the middle of May the monsoon low-level and the tropical easterly jet have started developing in the lower troposphere and upper troposphere, respectively, which gradually intensifies thereafter. There is a sharp increase in the strength of LLJ and TEJ when the monsoon onset over Kerala occurs. The parameters which represent the characteristics of LLJ and TEJ such as westerly depth, LLJ core speed and core height and TEJ core speed and height are derived and it is shown that these parameters can be used as predictors for monitoring the monsoon onset over Kerala. A preliminary analysis shows that objective criteria for MOK can be developed from the 205-MHz wind profiler observations which can be used for verifying the monsoon onset features.

The radar observations have been used to understand the conditions that lead to heavy rainfall over Kerala in 2018. It is found that in 2018, for most of the times, the core of LLJ was positioned below 2.5 km with high values of core speed as compared to 2017. In general, radar observations point to an anomalous decrease in the core height of LLJ in 2018 compared to 2017, thus implying the significant role of mountain effect in the formation of heavy rainfall in 2018. The orographic lifting had been very intense and thus resulted in heavy rainfall over Kerala in 2018. We show that the wind profiler radar can ideally capture the transitions in the monsoon circulation before heavy rainfall events and there is a possibility of predicting extreme rainfall at least 2 days in advance through a continuous monitoring of the monsoon low-level jet observed over Cochin. Furthermore, the wind profiles from ST radar can be used to assess the representation of monsoon circulation in the widely used analysis and reanalysis products. The initiation and progression of monsoon circulation observed from the radar has been used to evaluate the same in models. Through this comparison we bring out the areas that need improvement in the models as far as simulations of monsoon features are concerned. These observations from the radar can serve as reference dataset for model assessments.

This study makes use of wind profiler information for the first time from Cochin to study the commencement and progression of the Indian summer monsoon circulation. More process studies which look into the detailed vertical structure of monsoon circulation during the onset are warranted for advancing our understanding of one of the most challenging phenomena to model. With the advent of 205-MHz wind profiler radar, it may now become possible to accurately

monitor and eventually improve our understanding of the conditions that lead to monsoon onset and its progression.

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