The anomalous weather parameters that lead to the extreme rainfall of Kerala in August 2018

S. S. Suneela · Basil Mathew · S. Sureshkumar

1 Kerala University of Fisheries and Ocean Studies, Panangad, Ernakulam 682506, India

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Abstract
Extremely heavy rainfall occurred over Kerala, southwest coast of India, during mid-August 2018 resulting in devastating floods. This flood may be called “the flood of the century” as the state has not experienced a flood of this magnitude since the 1924 flood. The rainfall over Kerala during June, July and August 2018 was 15%, 18% and 164% above normal. To examine the reasons for this anomalous phenomenon, the meteorological conditions during this period are studied by analysing different parameters, such as wind, rainfall, potential evaporation, latent heat, outgoing longwave radiation, etc., and it is found that a combination of several rain favouring conditions prevailed at that time. The positive phase of Madden–Julian Oscillation (MJO) coupled with a monsoon depression in the Bay of Bengal and a weak trough in the south-eastern Arabian Sea strengthened the monsoon Low-Level Jet (LLJ) bringing moisture-laden winds over Kerala. The rising limb of Walker and Hadley circulations was also found over Kerala, which gave favourable updraft for cloud formation. In addition, the core of the Tropical Easterly Jet (TEJ) was found over the Kerala and Karnataka region. The cyclonic circulation in the mid-troposphere observed around the monsoon depression extended up to the west coast of India. Spatial variation of different weather parameters and their anomalies showed that many of the parameters were anomalously high during the second week of August 2018, when the torrential rainfall occurred. The simultaneous occurrence of all these conditions could have contributed to the extreme rainfall events and severe floods over Kerala.

1 Introduction
The Indian state of Kerala received very heavy rainfall resulting in severe floods during August 2018. Due to the floods, over 483 people lost their lives, 140 people went missing, and millions were affected (National Institute of Disaster Management (NIDM) (Walia and Nusrat 2020). The estimated loss due to the floods is over Rs 31,000 crore (~$3.9 billion). The flood of 2018 was the severest in Kerala in about a century, where the last being the catastrophic floods in the monsoon of 1924 (Rajiv Gandhi Institute of Development Studies (RGIDS) 2018). Extreme rainfall events are increasing worldwide in the recent period. Even though global warming could be one of the main reasons for the extreme weather events, the flood of 1924 occurred in Kerala during the pre-industrial era. This flood might have been caused by offshore vortices along the west coast and upper tropospheric perturbations as there were no depressions or cyclonic storms in the Arabian Sea or the Bay of Bengal during that period (Ramaswamy 1985). According to the National Oceanic and Atmospheric Administration (NOAA, 2021), the present-day annual global average atmospheric temperature is 1.04 °C warmer than that in the pre-industrial era. As the atmosphere becomes warm, potential evaporation increases enhancing the formation of cyclonic systems and associated extreme weather conditions, especially rainfall. With 1.0 °C increase in temperature, the water-holding capacity of the atmosphere increases by about 6–7%, leading to more intense and frequent extreme precipitation events (Trenberth et al. 2003; Kharin et al. 2007). The water-holding capacity of the atmosphere increases almost exponentially with temperature, and the atmospheric water content also increases with temperature (Pall et al. 2007; Santer et al. 2007; Willett et al. 2007). Using extreme rainfall data and multi-model simulations, Min et al. (2011) showed that human-induced increases in greenhouse gases influence the intensification of extreme rainfall events. A rise of 1.5 °C
in global mean temperature from the pre-industrial era can increase the three hourly rainfall maxima by 20% (Ali and Mishra 2018). Mishra (2019) also attributes heavy rainfall events to global warming, specifically to increased extreme rainfall and a decrease in moderate and light rainfall. This study shows that for a 1.0 °C increase in regional warming, about 4.98% ± 1.26% increase can occur in the precipitable water content. During the last few decades, the frequency and intensity of extreme rainfall events have increased in India, which can be attributed to global warming (Mukherjee et al. 2018; Myhre et al. 2019; Pai et al. 2015). O’Gorman (2015) discussed different physical factors influencing the response of extreme rainfall like dynamical contribution, orographic contribution, mesoscale convection and warming and concluded that rainfall extremes intensify with the warming climate.

Extreme rainfall events and associated floods have increased recently in many parts of India. The frequency and intensity of extreme rain events show a significant increasing trend and a decreasing trend in the frequency of moderate events over central India during the monsoon season from 1951 to 2000 (Goswami et al. 2006). But another study shows, in Central and North India, extreme rainfall has decreased, whilst in southern India, it has increased (Guhathakurta et al. 2011). Trend analysis of rainfall events for Northeast India showed a significant decrease in low rainfall events and an increase in very high and extremely high rainfall events (Varikoden and Revadekar 2020). The extreme rainfall events in this region are due to the strengthening of the southerly component of low-level wind from the Bay of Bengal and the updraft due to convergence at 850 hPa level. Panda and Sahu (2019) observed a statistically significant increasing trend in annual rainfall and a decreasing trend in monsoonal rainfall over certain districts of Odisha. Varikoden et al. (2019) analysed trends in southwest monsoon rainfall over Western Ghats (WG) and observed an increasing trend of 0.3 mm/day/decade over the northern WG region and a decreasing trend of 0.039 mm/day/decade over the southern WG region. They reported that this contrasting trend is due to the northward movement of the LLJ. Trend analysis of rainfall over the West Coast Plain and Hill Agro-Climatic Region of India was done by (Sahu et al. 2020). Saini et al. (2020) has shown a significant monotonic decrease during January and July, and an increasing trend during August and September. Saini et al. (2022) examined the association of monsoon onset, length of monsoon period with rainfall amount over five homogeneous monsoon regions of India. They reported that the extreme excess rainfall showed a significant relationship with the number of rainy days, but monsoon onset and rainfall do not show any significant pattern over peninsular India.

Simulation studies for two domains, the outer domain covering the entire Indian Peninsula and the inner domain covering the state of Kerala and the adjoining coastal Arabian Sea, using Weather Research & Forecasting (WRF) model in conjunction with the hydrological (WRF-hydro) model, showed that the extreme rainfall events could be 18% lower than the pre-industrial era for the inner domain whilst considering the recent weakening of monsoon low-pressure systems (Hunt and Menon 2020). However, extreme rainfall events can be 36% more due to the moisture availability for the same domain as a result of warming. There exist large differences between contributions from the widespread (~ 80.7%) and the intense (53%) extreme rainfall events whilst considering the top 1% of extreme events in global rainfall (Kumar et al. 2019). Even though the frequency of the Bay of Bengal depressions has decreased, over Central India, widespread extreme rainfall events have increased threefold during 1950–2015 (Roxy et al. 2017). The extreme rainfall event in Chennai from 30 November to 2 December 2015 shows a positive correlation with the sea surface temperature (SST) over the southern Bay of Bengal (Boyaj et al. 2018). Kumar et al. (2009) suggest that the northern Indian Ocean warmed in recent years, especially the Arabian Sea, resulting in increased cyclogenesis and extreme weather events. Another study by Boyaj et al. (2020) in three major states of South India, namely Tamil Nadu, Telangana and Kerala, suggests that alterations in the land cover resulted in higher surface temperatures, sensible heat flux and a deeper and moist boundary layer, resulting in heavy precipitation. The state of Kerala experienced abnormally heavy rainfall during the monsoon season of 2018, which caused flooding in almost all districts of Kerala. According to Mishra et al. (2018), on 8 August 2018, most of the major reservoirs in Kerala were at more than 90% of their capacity. When another spell of heavy rainfall started on 14 August with torrential rainfall almost all over Kerala with rivers at full capacity, the reservoirs had to release water, resulting in flooding all over Kerala. However, an analysis of the flood situation in the Periyar River Basin in August 2018 showed that only 16–21% peak attenuation was possible by emptying the reservoir in advance and that the intermediate catchments which had no reservoirs to control the flow contributed large runoff to the flood event (Sudheer et al. 2019). An assessment of the Kerala flood situation in August 2018 was done by Agarwal (2018) who made suggestions to tackle the problems in the future.

The extreme weather event in August 2018 in Kerala was investigated by many. This extreme event was attributed to anomalous weather conditions rather than the warming trend in the atmosphere by Mishra and Shah (2018). According to Viswanadhapalli et al. (2019), high convective instability, offshore vortex, moisture transport from the mid-troposphere due to horizontal wind shear and mid-tropospheric moisture transport from the Bay of Bengal played major roles in this extreme rainfall event. The synergic interaction between a
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propagating Low-Pressure System (LPS) in the Bay of Bengal, an intrusion of dry air into the mid-troposphere and the offshore trough are the main reasons for the extreme rainfall (Kumar et al. 2020). The performance of Numerical Weather Prediction (NWP) models used at the National Centre for Medium-Range Weather Forecasting (NCMRWF) in the prediction of the extreme rainfall of Kerala during August 2018 was evaluated by Ashrit et al. (2020). They found that the deterministic NWP models were accurate at shorter lead times of up to three days and the ensemble-based probabilistic forecasts performed better at higher lead times beyond three days. Another study by Mohandas et al. (2020) suggested that a large amount of moisture from the tropical cyclones in the western North Pacific was transported to the upper troposphere over Kerala by a conveyor belt-like flow, which they termed the ‘Remotely Aligned Intense Tropical Circulations’ (RAITC). Mukhopadhyay et al. (2021), whilst evaluating the performance of three global models, found a significant increase of moisture convergence over Kerala during the extreme rainfall event in August 2018 and that the extreme event was associated with a westward propagating barotropic Rossby wave. The present study investigates the different weather parameters and systems that influenced the peculiar weather conditions in Kerala during the 2018 monsoon season.

In Sect. 2, the sources of the data used and the methodology are described. The spatial distribution of different atmospheric parameters and their anomalies during the study period are analysed and different atmospheric systems like MJO, Hadley and Walker circulations, etc., in the context of extreme rainfall are discussed in Sect. 3. The results of the analysis are summarized in Sect. 4.

2 Data and methods

For this study, the data for 2018 is used to determine spatial distribution. To compute anomalies, data for a period of 30 years, (1990–2019) is used. Data of different meteorological parameters like, vertical wind profile, vertical temperature profile, vertical velocity, zonal gravity wave stress, precipitable water, Outgoing Longwave Radiation, latent heat flux, potential evaporation rate and precipitable water were downloaded from the NCEP gridded climate data set (2.5° × 2.5°) available from PSL (Physical Sciences Laboratory; https://psl.noaa.gov/) (Kalnay et al. 1996). High-resolution (12.5 km × 12.5 km) ERA-Interim reanalysis data of wind and rainfall are taken from the site https://www.ecmwf.int. Besides this, gridded daily rainfall data (0.25° × 0.25°) developed by IMD (Pai et al. 2014) was downloaded from the site, https://www.imdpu.net/Climate_Pred_LRF_New/Grided_Data_Download.html.

Lapse rate (-dT/dz) is computed using NCEP temperature data. Horizontal divergence ((∂u/∂x) + (∂v/∂y)) and horizontal vorticity ((∂v/∂x)−(∂u/∂y)) are computed with the help of NCEP wind data.

3 Results and discussion

According to India Meteorological Department, Kerala received 2346.6 mm of rainfall from 1 June 2018 to 19 August 2018, whereas the normal rainfall is only 1649.5 mm (IMD 2018). The rainfall was about 42% above normal, and in August, it was 164% above normal. Because of continuous rainfall from 1 June onwards, several reservoirs in the state were at their full reservoir level. The heavy rainfall of August 2018 caused severe floods in 13 out of the 14 districts of Kerala. On the 8th and 9th August, the first spell of heavy rainfall was experienced at several places, following a monsoon depression in the Bay of Bengal (Kashyap et al. 2019). The second spell of heavy rainfall in August started on 14 August and lasted till 17 August, causing disastrous flooding as gates of the 35 reservoirs had to be opened to release water whilst torrential rainfall was occurring almost over the entire state of Kerala. As per the Central Water Commission report (CWC 2018), the huge quantity of runoff within the period 15 to 17 August 2018 was beyond the carrying capacity of most of the rivers in Kerala and resulted in overbank flows in most of the rivers and caused a severe flood situation all over Kerala.

3.1 Weather elements and atmospheric systems

Various weather parameters and atmospheric systems that are favourable for the occurrence of extreme rainfall events are analysed in this study. Strong winds can enhance evaporation and increase the water vapour content in the atmosphere. Higher zonal gravity wave stress can increase the zonal wind speed. Vertical velocity transports water vapour to the upper levels and helps condensation and cloud formation. Rising limbs of Hadley and Walker circulations can enhance the vertical motion in the atmosphere. Easterly Jet is another factor that helps the upward transport of moisture due to high wind shear. The active phase of Madden–Julian Oscillation (MJO) can increase the intensity of rainfall. These factors and the associated parameters are examined in detail to understand the extreme rainfall event that lead to severe flood in Kerala during the monsoon month of August 2018.

3.1.1 Spatial variation of rainfall, area average rainfall and rainfall anomaly

Spatial variation of rainfall using IMD data (Fig. 1(a)) shows intense rainfall in the southwest coastal region of India on
15 August 2018. On this day, intense rainfall of more than 220 mm occurred at Idukki in the Western Ghats region. After 15 August, there was a gradual decrease in rainfall. Figure 1(b) & (c) shows the rainfall and rainfall anomaly averaged over the area, 75ºE–77ºE & 5ºN–12ºN. In the Kerala region, rainfall is at its peak on 14 and 15 August (Fig. 1(b)). From 7 to 17 August, continuously, there was above-normal rainfall (Fig. 1 (c)). On 14 and 15 August, anomalous values of rainfall + 85 mm and + 75 mm respectively were observed. Roca et al. (2014) suggested that around 75% of tropical rainfall occurs from mesoscale systems that last for more than 12 h, whereas 60% of the rainfall is due to systems that travel more than 250 km. The monsoon depression which formed in the Head Bay on 14 August 2018, persisted till 17 August and travelled more than 600 km in the west–northwest (WNW) direction before dissipation. This monsoon depression augmented the conditions for heavy rainfall over Kerala.

To study the extreme weather phenomenon of August 2018 over Kerala, different weather parameters are analysed on a daily basis at different atmospheric levels. The results are presented in Fig. 2 for a typical day, 15 August 2018, at 850 hPa level.

### 3.1.2 Wind

Wind speed and direction at 850 hPa on 15 August 2018, as shown in Fig. 2(a) indicate that the LLJ is prominent with its core passing through southern India. The southern parts of India were experiencing strong winds of more than 16 m/s, and southern Kerala to central Kerala experienced more than 18 m/s. The strong winds at this level indicate the active phase of the monsoon (Joseph and Sijikumar 2004). The wind anomalies presented in Fig. 2b indicate that along the southwest coast of India, the wind was 6–8 m/s stronger than the normal values. A monsoon depression that formed on 14 August in the Head Bay of Bengal intensified on 15 and persisted till 17 August. The cyclonic circulation associated with the depression extended up to 400 hPa level, and the area of coverage became wider with height. The axis of the circulation is found to tilt towards the south–south-west (SSW) direction with altitude. The cyclonic vorticity and convergence associated with the depression extended to the Kerala coast in the lower levels and further westward in the upper levels up to 500 hPa level. The strong westerlies brought in much moisture to the whole west coast of India.

### 3.1.3 Vertical velocity

Vertical velocity and its anomalies at 850 hPa on 15 August 2018 are plotted in Fig. 2c and d. It is observed that in the lower levels up to 850 hPa, the vertical velocity is maximum along the west coast of India. The strong westerlies can bring in a lot of moisture towards the land and the above-normal low-level upward velocities (+ 0.005 to + 0.01 m/s), as shown in Fig. 2d, help in condensation and cloud formation. However, above 850 hPa level, the maximum (up to + 0.018 m/s) is in the Head Bay and the nearby eastern coastal area of India due to the presence of the monsoon depression, although positive anomalies prevail all over central and southern India up to 500 hPa level. As time progresses, along with the cyclonic circulation, the vertical velocity maxima shift in the northwest direction. A gradual decrease in rainfall can be seen after 15 August with a decrease in the intensity of vertical motion.
3.1.4 Zonal gravity wave stress

The convective activity influences the cloud-top wave stress, and hence it is found to be concentrated over the inter-tropical convergence zone. Even though the zonal gravity wave drag is maximum at the lower stratosphere, this parameter shows higher values in the lower troposphere also, during the monsoon months of June, July and August 2018. Figure 2e shows that in August 2018, the maximum values of zonal gravity wave stress of 0.2 to 0.3 N/m² at 850 hPa level is found near the Anamudi Mountain region, the highest peak of the Western Ghats, due to the orographic effect, which is 0.15 N/m² above normal (Fig. 2f). This anomalously high value can intensify the zonal wind speed, and hence the LLJ became stronger. Gravity waves can quickly transport the latent heat released (Adames and Maloney 2021).

3.1.5 Precipitable water

Figure 3 shows the spatial distribution of (a) precipitable water on 15 August 2018, (b) its anomaly, and (c) time series during 1 June to 31 August 2018. Precipitable water is the total amount of water vapour present in the entire column of the atmosphere over unit area. Rainfall is closely related to column water vapour in the tropics (Muller et al. 2009; Neelin et al. 2009). An increase in temperature enhances the
water vapour holding capacity of the atmosphere. Deep convection in the troposphere is enhanced by the water vapour content (Adames and Maloney 2021). Precipitable water is maximum on 15 August 2018 (> 65 kg/m²) in the northern Bay of Bengal due to the presence of the monsoon depression. Spatial variation of anomalies shows that almost the entire Indian region experiences positive values. Most parts of Kerala exhibit positive anomalies of precipitable water (> 6 kg/m²). Under favourable conditions, this can produce torrential rainfall in the area. The time series of precipitable water (Fig. 3(c)) shows a peak on 15 August, which accounts for the extreme rainfall. According to Rangarajan and Mani (1982), the highest values of precipitable water over India (between 50 & 64 kg/m²) is observed during July–August. Our observation agrees with their results.

3.1.6 Madden–Julian oscillation

Madden–Julian Oscillation (MJO) is one of the factors that affects the intraseasonal variability of the monsoon. During the active phase of MJO, precipitation intensity can increase considerably (Roxy et al. 2019; Peng et al. 2019; Anandh and Vissa 2020). Analysis of wind speed anomalies, cloudiness and rainfall elucidates the presence of an active phase of MJO. Time series of area averaged Outgoing Longwave Radiation (OLR) and wind speed anomalies during June to September 2018 are displayed in Fig. 4a and b, respectively. The OLR values were consistently low during the second week of August 2018, which indicates the presence of deep clouds during these days associated with moisture convergence. Wind speed anomaly estimates show consistently
high values during these days. Variations in OLR and wind speed anomalies suggest the presence of an active phase of Madden–Julian Oscillation during this period. This active phase can generate extreme rainfalls and strengthen the LLJ.

### 3.1.7 Meridional mean of vertical velocity

Vertical profile of the mean meridional vertical velocity between 5ºN & 15ºN and its anomalies are shown in Fig. 5a and b. Upward motion prevails between 70ºE & 80ºE from 1000 to 150 hPa levels. The vertical velocity is found to be maximum between the longitudes 70ºE & 80ºE and between the pressure levels 850 & 700 hPa which is 0.015 m/s above average. This band of maximum vertical velocity shifts westward from 16 August onward and lies between 60ºE & 70ºE on 25 August. There was a gradual decrease in rainfall over Kerala from 16 August onwards with the shift of the band of high vertical velocity.

### 3.1.8 Hadley and Walker circulations

Hadley and Walker circulations on 15 August 2018 are shown in Fig. 6. During 12–16 August, the rising limb of Hadley (10ºN–20ºN) and Walker (70ºE–80ºE) circulations coincide over the Kerala region which enhances the vertical motion. The vertical limb of both Hadley and Walker circulations reaches above 200 hPa level, which helps in the vertical transport of moisture from the lower troposphere to the upper troposphere. Since the relative humidity is found to be greater than 90% over the Kerala region, the vertical motion enhances cloud formation and rainfall.

### 3.1.9 Wind at 500 hPa and 100 hPa levels

Interaction between low-pressure systems, offshore troughs, or secondary cyclonic vortices and intrusion of cold dry air to the mid-troposphere can help to develop static instability and consequently extreme rainfalls (Nikumbh et al. 2020; Kumar et al. 2020). The present analysis shows the advection of cold dry air at 500 hPa is mainly from the northern side, beyond the Himalayas (Fig. 7 (a)). A weak advection of dry air occurs from the Middle East. Figure 7 (b) shows the upper tropospheric wind pattern at 100 hPa level. The tilt in the axis of the circulation of the monsoon depression towards SSW direction with altitude must have brought much moisture in the mid-troposphere from the Bay of Bengal towards the southwest coast of India. The core of the TEJ occurs over Kerala/Karnataka. The high wind shear due to this jet enhances the upward transport of moisture and cloud formation.

### 3.1.10 Latent heat and Lapse rate

Figure 8a shows the daily variations of net latent heat flux averaged over the area, 75ºE–77ºE & 5ºN–12ºN. From 14 to 17 August, net latent heat flux values are highest in the month, coinciding with the maximum rainfall. The latent heat released by convective activity is quickly distributed spatially by gravity waves. In the southern peninsula, conditional instability prevails in the lower levels with the maximum at 925 hPa level (Fig. 8b). There the lapse rate is more than the moist adiabatic rate of 6 ºC/km but less than the dry adiabatic rate of 9.8 ºC/km. In the presence of saturated air, this condition is conducive to the formation of rain-producing cumulonimbus clouds.

### 3.1.11 Potential evaporation, divergence and vorticity

The ability of the atmosphere to remove water from the surface, if enough water was available, through the evaporation process is known as potential evaporation. The major factors influencing evaporation are temperature and wind.

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![Fig. 4](image_url) Daily time series of (a) OLR (W/m²) and (b) wind speed anomaly (m/s) averaged over an area between the longitudes 75ºE & 77ºE and the latitudes 5ºN & 15ºN during June to September 2018
Temperature provides the energy for evaporation, and wind removes water molecules from a surface through eddy diffusion. The more the wind speed, the more the process of evaporation. In Fig. 4, we saw that the wind speed anomalies are maximum in August. Potential evaporation closely follows this pattern (Fig. 9a). A dip in potential evaporation during the third week of August is due to the lower atmospheric temperature resulting from cloud cover and rainfall. Figure 9b shows divergence (shaded) and vorticity (contours) on 15 August 2018 at 850 hPa level. The cyclonic vorticity associated with the monsoon depression extends up to the southwest coast. In the upper levels, cyclonic vorticity is observed over a wider area. In the lower levels up to 850 hPa level, two convergence maxima are observed, one in the coastal Arabian Sea and another in the Head Bay. The low-level convergence and the above-average vertical velocity and relative humidity enhance condensation and cloud formation.

The Meteorological parameters that we investigated, namely wind, vertical velocity, relative humidity, precipitable water, potential evaporation and zonal gravity wave stress, showed anomalously higher values in the second week of August 2018. Daily variations of OLR, wind speed anomaly and rainfall indicated the active phase of an MJO during the second week of August 2018. Meridional mean values of vertical velocity between 5°N & 15°N were maximum in the band of 70°E–80°E longitude. Another feature noticed during this period is the coincidence of the rising
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limbs of Hadley and Walker circulations over Kerala. The combined effect of all these factors enhanced the rainfall over Kerala and resulted in a devastating flood situation. Hence, it seems the anomalous weather conditions are more responsible for the extreme rainfall event of August 2018 over Kerala, and the warming of the Arabian Sea might have influenced the development of the anomalous weather conditions.

4 Summary and conclusions

Heavy rainfall events are becoming more frequent and more intense in many parts of the world. The extreme rainfall and the consequent flood of August 2018 in Kerala affected many lives and property. Different weather parameters during that period were investigated in this study. Most of the weather parameters showed anomalously high values during the period 14–17 August 2018. Wind speeds greater than 16–18 m/s occurred over Kerala, which was 6–8 m/s above normal. This anomalous wind is mainly due to the monsoon depression that formed in Head Bay during 14–17 August 2018. The anomalously high gravity wave stress intensified the zonal wind speed by which the LLJ became stronger. Vertical velocity showed positive anomalies of 0.015 m/s and precipitable water showed above-normal values of 50 kg/m² during this period over most part of Kerala. The presence of higher vertical motion and humidity helped condensation and the formation of clouds.

During the second week of August, OLR values are consistently low. However, the wind speed anomalies are consistently high for more than a week, confirming the active phase of a MJO during that period. Higher zonal gravity wave stress helped in the distribution of released latent heat and the occurrence of the high amount of water vapour content during these periods enhanced the MJO activity. This active phase of MJO enhanced the intensity and duration of the heavy rainfall. This anomalous rainfall can be observed
from the above-normal values from 13 to 17 August. The high wind speed and shear near the surface improved the moisture transport to the atmosphere. Another important feature observed during the period is the Hadley and Walker circulations. The ascending limb of both the circulations was observed over Kerala, which helped the transportation of moisture to the upper levels. Potential evaporation is maximum in August, except a few days, and the occurrence of the higher amount of precipitable water vapour coincides with extreme rainfall events.

The weather parameters and atmospheric systems that we investigated in the present study indicate a favourable situation for heavy rainfall during 13–17 August 2018. This study suggests that the extreme rainfall event and the associated flood over Kerala in August 2018 are more likely due to the anomalous weather conditions that persisted during that period. These include a positive phase of the MJO, which triggers an active monsoon phase, a strong LLJ, a near stationary monsoon depression over the Bay of Bengal and a weak offshore trough in the southeast Arabian Sea. The coincidence of the ascending limbs of Walker and Hadley circulations over Kerala, the occurrence of TEJ with its core over Kerala/Karnataka and the wider extent of the mid-tropospheric cyclonic circulation with its western extent over Kerala was also favourable for heavy rainfall. A combination of all these factors resulted in a strong ascending motion of high-humidity air resulting in extremely heavy rainfall over Kerala and resultant catastrophic floods.
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Author contributions
SSS: conceptualization, data curation, investigation, writing and funding acquisition. BM: conceptualization, investigation and writing. SK: Supervision, review.

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Availability of data and materials
The data used for this study are readily available from the sites. https://psl.noaa.gov/, https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets, https://coastwatch.noaa.gov/https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html.

Code availability
GrADS, CDO, Adobe illustrator and Inkscape.

Fig. 9  a Time series of daily potential evaporation rate (W/m²) area averaged between the longitudes 75ºE & 77ºE and the latitudes 8ºN & 12ºN from June to August 2018 and b spatial distribution of divergence (s⁻¹) (shaded) and vorticity (s⁻¹) (contours) at 850 hPa on 15 August 2018
Declarations

Conflicts of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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