A diagnostic study of extreme precipitation over Kerala during August 2018

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Abstract

The state of Kerala, located on the west coast of India, experienced a record 100-year flood that resulted in major landslides from unprecedented prolonged and extremely heavy rainfall (50–480 mm day⁻¹) during August 1–19, 2018, causing extensive damage and about 500 causalities. Rainfall observations indicate that the heavy rainfall occurred over two spells (August 7–10 and 14–18) in association with an offshore trough, and a depression over the Bay of Bengal (BOB). High-resolution 38-year climatology data (5 km) and the ERA-Interim reanalysis dataset show a strong low-level jet over the Arabian Sea and a depression over the BOB with a southwestward tilt during the heavy rainfall. Very high-resolution (2-km) mesoscale model simulations suggest that this high convective instability due to the strong westerly jet along with the formation of offshore vortex, the transport of mid-tropospheric moisture under the presence of conducive vertical shear of horizontal wind, and transport of mid-tropospheric moisture from the BOB are the major factors (as shown in the schematic diagram) behind the extreme heavy rainfall over Kerala.

KEYWORDS

Heavy rainfall events, Southwest Indian Monsoon, Off-shore trough, Monsoon depression

1 | INTRODUCTION

The Indian southwest summer monsoon (ISM) is characterized by distinct spells of rainfall that occur in association with the synoptic features of the monsoon trough, off-shore troughs along the west coast of India, movement of monsoon lows and depressions, upper/mid-tropospheric cyclonic circulations, and more (Rao, 1976). The interaction between the steep topography of Western Ghats (WG) and moist winds of the ISM triggers deep convective systems, which trigger rainfall between 10 and 100 mm day⁻¹ (Sahany et al., 2010; Guhathakurta et al., 2015). The existence and position of an offshore trough over the west coast of India, the formation of depression over the Bay of Bengal (BOB), and its north-west propagation towards central India further enhances moisture convergence and leads to heavy rainfall (Rao, 1976; Francis and Gadgil, 2006). The state of Kerala, located in the southern WG, sits at the tipping point of the monsoon onset and receives seasonal rainfall of about 2,000 mm (Krishnakumar et al., 2009). The rainfall characteristics over Kerala are unique because of isolated structures with steep slopes separated by a wide mountain gap, called Palghat gap (Tawde and Singh, 2015).

From August 1 to 19, 2018, Kerala experienced exceptionally heavy rainfall that lead to extensive flooding and landslides, and caused about $5 billion worth of damage and more than 500 causalities...
This unprecedented and extreme rainfall generated a record 100-year flood that forced officials to open nearly 80 dams at once, creating havoc, landslides, and significant damage to crops and livestock (CWC report, 2018; Sudheer et al., 2019; Mishra et al., 2018). Unlike the historical and localized flood events of Mumbai in 2005 (Vaidya and Kulkarni, 2007), Utharakand in 2013 (Vellore et al., 2015), and Chennai in 2015 (Srinivas et al., 2018), the entire state of Kerala was inundated with heavy rainfall spells that lasted for several days. The India Meteorological Department (IMD) reported that the extreme rainfall over Kerala in the month of August, 2018 was the highest recorded over the past 78 years.

The formation and intensification mechanisms associated with the extremely heavy rainfall events over the west coast were studied using global and regional weather prediction models (e.g., Litta et al., 2007; Vaidya and Kulkarni, 2007; Bhanu Kumar et al., 2012), these emphasized the advantage of high-resolution regional models for capturing mesoscale features of heavy rainfall (e.g., Bhaskarrao and Hari Prasad, 2006; Bohra et al., 2006; Vellore et al., 2015; Raju et al., 2015; Umakanth et al., 2016). Diagnostic analysis of previous studies revealed that the presence of thermodynamically favorable conditions, such as strong convective instability, a conducive vertical shear of horizontal wind, a moisture-laden mid-troposphere, and the formation

![Image of rainfall data and maps](attachment:image.png)
of a mid-tropospheric cyclonic system, were possible factors leading to the occurrence of localized heavy precipitation events (Litta et al., 2007; Vaidya and Kulkarni, 2007; Srinivas et al., 2018).

This study investigates the factors and physical mechanisms that lead to the extremely heavy rainfall over Kerala in August 2018 using stations and gridded observations and global and high-resolution regional reanalysis datasets. To analyze the exceptional conditions that prevailed during the month of August 2018, we used the WRF high-resolution reanalysis along with the global ECMWF reanalysis data (ERA-Interim). Furthermore, a very high resolution (2-km) cloud resolving WRF model simulation is used for the diagnostic analysis of the extremely heavy rainfall event that occurred on August 14–17, 2018. The paper is organized as follows. Section 2 describes the data and methodology. Section 3 details the observed rainfall characteristics and associated synoptic and diagnostic analysis of heavy rainfall, and Section 4 provides a summary and conclusions.

2 | DATA AND METHODOLOGY

Hourly accumulated rainfall observations from 10 automatic weather stations (AWS) of IMD are used in the study (shown in Fig. 1a). These are located at Mattanur (11.92° N, 75.57° E), Thamarassery (11.415° N, 75.940° E), Pookot (11.542° N, 76.027° E), Vellanikkara (10.545° N, 76.2740° E), Kudlu Agro (12.5299° N, 74.9881° E), Mankara Agro (10.7918° N, 76.4997° E), Vellanikkara (10.5452° N, 76.2740° E), Neelavaram (11.347° N, 75.972° E), Erimayar (10.659° N, 76.572° E), and Meenangadi (11.659° N, 76.1726° E). We also used the satellite-rain gauge merged rainfall estimates of IMD (Mitra et al., 2009, 2013) to analyze the spatial characteristics of extremely heavy rainfall (shown in Fig. 1b).

A 38-year (1980–2018) high-resolution reanalysis (Viswanadhapalli et al., 2017; Langodan et al., 2017a, 2017b; Bindu et al., 2018; Dasari et al., 2019; Viswanadhapalli et al., 2019), generated using the Weather and Research Forecasting (WRF) model (Skamarock et al., 2008) and ERA-Interim (ERA-I) reanalysis (Dee et al., 2011), was used to study the prevailing anomalous atmospheric circulation patterns over Kerala in August 2018. Generally, global reanalyses provide acts as a good source of information for studying severe weather conditions. However, recent studies (e.g., Kishore et al., 2016; Žagar et al., 2018; Nikhil et al., 2019) indicated that the global reanalyses may not represent the mesoscale features and associated precipitation characteristics of extreme events. Particularly for extremely heavy rainfall events over complex terrain regions, such as the Western Ghats, the mesoscale signatures are either smoothed out or misrepresented in the global reanalyses. These studies further suggested that the ERA-I data better reproduces the precipitation characteristics than other global reanalyses as it is generated by an advanced assimilation system incorporating all available conventional and satellites radiance datasets. We have therefore used the high resolution WRF regional reanalysis as it has the advantage of accurately representing the mesoscale flow features over complex terrains and incorporates the signature of extreme events through the frequent initialization and assimilation of data (Lo et al., 2008; Viswanadhapalli et al., 2017).

For a more detailed diagnostic analysis of heavy rainfall between August 14 and 17, 2018, we further used very high-resolution (2-km) WRF model outputs configured with three two-way nested domains resolutions of 18, 6, and 2 km, with the innermost domain of 2 km focused over the regions of heavy rainfall in Kerala for the diagnostic analysis. The adopted physics of this model were based on previous studies of heavy precipitation events over the Indian region (Srinivas et al., 2013, 2018; Srikanth et al., 2016; Attada et al., 2018; Reshmi Mohan et al., 2018). The WRF model was initialized at 0000 UTC of August 14, 2018 using NCEP Global Forecast System (GFS) 0.25 × 0.25° analysis and is integrated for 72-hr simulation period up to 0000 UTC August 17, 2018. The boundary conditions are updated at 6-hourly intervals with the GFS forecasts. The 2-km simulations stored at hourly intervals for diagnostic analysis of the heavy rainfall event.

3 | RESULTS AND DISCUSSION

The spatio-temporal variability of rainfall at 10 AWs across Kerala and the IMD satellite-merged rainfall estimates are first analyzed. The analysis of synoptic meteorological conditions and the anomalous atmospheric conditions associated with the Kerala heavy rainfall event are then studies based on a regional high-resolution reanalysis. A diagnostic analysis of the event using the cloud resolving (2-km) mesoscale model simulations is finally presented.

3.1 | Observed rainfall distribution and synoptic meteorological conditions

The time-series of daily accumulated rainfall observations during the study period (Fig. 1a) reveals that the heavy rainfall occurred across two spells on August 7–10 and 14–18, 2018. The gridded rainfall estimates (Fig. 1b) suggest a southward movement of rainfall bands during both spells from the northern mountainous regions to the coastal areas of Kerala. The highest amount of rainfall occurred on August 9, 14, and 15, and the isolated heavy rainfall during the first spell (>100 mm-day⁻¹) was concentrated over the mountainous region and spread over the entire state during the second spell with a maxima over the central and south-central Kerala. The highest daily cumulative rainfall of 450 mm was observed in Pookot (450 mm) during the first spell, and about 950 mm was recorded over four consecutive days during the second spell over the south-central station, Valparai.

Our analysis suggests that a prolonged heavy rainfall occurred during the second spell of August 14–17, leading to severe flooding and landslides caused by the excessive rainfall over a relatively longer period at all locations. The IMD synoptic charts shown in Fig. 2 explain the atmospheric conditions of the prolonged heavy rainfall during the second spell. The synoptic surface charts at 0300 UTC, August 14, 2018 (Fig. 2a) indicate the simultaneous existence of low pressure over the northwest BOB, off the northern Odisha coasts on the east coast of India, and over southern Pakistan and western
Rajasthan. A weak offshore trough at mean sea level from south Maharashtra to Kerala is also apparent. A well-marked cyclonic circulation is present in the upper levels (Fig. S1) on August 14, extending to 7.6 km, with a southwestward tilting and a monsoon low pressure trough from Himachal Pradesh to the east-central BOB passing through Uttar Pradesh, Madhya Pradesh, and Odisha, and an anti-cyclonic circulation over Kerala at 7.6-km ASL. On August 15 (Fig. 2b), the low-pressure system near the Odisha coast further intensified, and the offshore trough over the west coast strengthened and extended from Karnataka to Kerala. The upper-air charts (Fig. S2) on August 15 show a well-organized monsoon trough with a vertical extension of up to 3.1 km from the head BOB to central India and the upper level cyclonic circulation with a southwestward tilting extending to 7.6 km in the vertical direction and spatially up to Kerala coast. At 0300 UTC, August 16 (Fig. 2c), the depression over Odisha moved westward and positioned over south Chhattisgarh, and the offshore trough over the west coast further intensified (indicated by a pressure gradient). By the evening of August 16 (Fig. 2d), both the low pressure over Pakistan and the BOB depression moved further west, whereas the offshore trough over the west coast moved slightly northward. These synoptic features persisted from 0300 UTC, August 14, to 0300 UTC, August 16, 2018, then moved westward. The major synoptic systems associated with the heavy rainfall included the depression over coastal Odisha, the intensified offshore trough over the southwest coast, and a well-organized monsoon trough from the head of the BOB to central India. The CIMSS satellite merged product of low-level convergence and vorticity, and upper tropospheric divergence shown in Figure S3 clearly supports the gradual intensification of low-level convergence and cyclonic vorticity over Kerala along with increase in the upper tropospheric divergence off the coast of Kerala between August 14 and 15, 2018. These three parameters gradually increased their respective strength when the depression moved the westward (eastern part of Maharashtra) on August 16. Moreover, the water vapor images of INSAT-3DR show the presence of mid-tropospheric moisture over Kerala between August 14 and 16 (Figure not shown).

3.2 | Exceptional meteorological conditions during the month of August 2018

To analyze the exceptional synoptic conditions that favored the extreme precipitation event in Kerala, we have calculated the anomalies in monthly mean winds and geopotential heights. These anomalies are calculated by subtracting the monthly mean fields of August 2018 from a corresponding monthly mean of 38 year (1980–2017) WRF (5-km) and ERA-I reanalysis datasets. In the lower atmosphere (925 and 850 hPa), strong westerly-to-southwesterly winds with low geopotential height values are observed over the Arabian Sea (AS) and southern parts of India. Along with the increased low-level westerlies, an enhanced channel flow from the Red Sea and Gulf of Aden and an increased intensity of Shamal winds is also noticeable over the northern Arabian Peninsula. The comparison of anomalies estimated from ERA and WRF reanalyses at lower levels (925 and 850 hPa) indicates large differences in geopotential height and circulations, with stronger and northward extension of south-westerlies winds and geopotential anomalies in WRF reanalysis. The northward extension of south-westerlies enhances moisture transport towards the west coast, leading to higher rainfall. In the upper atmosphere (450 hPa), the wind and geopotential height anomalies from both the WRF and ERA datasets clearly indicate
an anomalous strong cyclonic circulation over the west-central BOB off coast of the northern Andhra Pradesh, extending over a larger area from the eastern AS, Kerala, Karnataka, and Maharashtra states. It also provides a clear indication of stronger northwesterly winds and lower geopotential heights, suggesting an increase in the cyclonic flow pattern over the west coast. Though both datasets suggest similar patterns, the WRF reanalysis shows a more intensified Shamal jet over the Arabian Peninsula, a stronger offshore trough, and strong winds over the west coast. The wind and geopotential height anomalies at 450-hPa level indicates a cyclonic flow positioned over the west-central BOB, extending over a larger area, covering all of southern India and eastern AS, while the strength of the upper level easterly jet is increased by 3 ms$^{-1}$ over the southern Peninsular India in the upper troposphere at 150-hPa. WRF reanalysis indicates enhanced cyclonic circulation features over the BOB, anti-cyclonic conditions over Iran and Afghanistan, and amplified cyclonic circulation over the Arabian Peninsula. This suggests that the heavy precipitation was triggered by the strong interaction of moist westerly/southwesterly monsoon winds from the AS with the steep topography of WGs (>1,500 km) over Kerala under the presence of an intensified offshore trough over the west coast and a depression over the BOB.

The meridional cross-section (averaged within the latitude band of 8–13°N) of the wind (calculated as in Fig. 3) from WRF and ERA is displayed in Figure S4. It shows stronger anomalous winds in the lower atmosphere between 925 and 850 hPa, indicating stronger westerly-to-southwesterly monsoon flow over the AS and the west coast of India during the second spell of heavy precipitation. The maximum northwesterly winds (4 ms$^{-1}$) are found between 850 and 700 hPa over the Indian Peninsula. The core of the maximum winds extended vertically up to 500 hPa over the BOB, suggesting an increased cyclonic flow over Peninsular India and the BOB during the heavy rainfall episode. The WRF reanalysis dataset (not the ERA-I dataset) shows relatively stronger monsoonal flow over the AS and cyclonic circulation over the BOB. An enhanced vertical extension of intense winds near the west coast, an intensification of the East African jet, and a westward shift of the winds associated with the cyclonic circulation over the BOB was also noticeable in the WRF reanalysis, compared to the ERA data. The wind flow of August 2018 suggests that both enhanced monsoonal circulation and the location of cyclonic circulation over the BOB played a major role in the prolonged occurrence of heavy rainfall over Kerala.

3.3 Diagnostic analysis of the heavy rainfall event using mesoscale model simulations

The previous analysis of the observations and high-resolution datasets shows that the extreme precipitation during August 1–19, 2018 over Kerala was associated with a monsoon low-pressure trough, an intense offshore trough over the west coast of India, and a deep depression over the BOB. To investigate the major factors contributing to the formation, intensification, and sustenance of the rainfall, we carried out a diagnostic analysis using the very high resolution (2-km) WRF model simulations.

3.3.1 Analysis of moisture transport and vorticity

The availability of moisture and its source regions is crucial to the development and intensity of convective systems (Brimelow and Reuter, 2005; Huang and Cui, 2015). The anomalous low-level moisture transport (calculated as in Fig. 3) during August 14–17, 2018, based on the very high-resolution (2-km) model simulations, shows a strong moisture transport (>20 kg m$^{-1}$ s$^{-1}$) over the south-eastern AS (Fig. 4) which comes from the cross-equatorial flow and the southern Red Sea through the Gulf of Aden. The contribution of the moisture from

![FIGURE 3](image-url) Anomalies in horizontal winds (ms$^{-1}$, shown in vectors) and geopotential heights (in m; color shading) at 925, 850, 450, and 150 hPa from ERA-I and WRF reanalysis datasets. The anomalies in the monthly fields are computed by subtracting monthly mean parameters of August 2018 from 38-year’s climatology
the depression over the BOB was concentrated mainly over the southern Indian Peninsula and the Central and Southern BOB. The inflow of dry desert air from the eastern AS towards the west coast of India is seen in the lower and mid-tropospheric levels (850–700 hPa) enables to maintain the conditional instability. Previous studies (e.g., Sabin et al., 2013; Parker et al., 2016) indicated that the intruded dry air at mid-tropospheric levels enhances the low level cold and moist winds. The presence of strong low-level westerly jet cools the lower temperatures and increases the moisture content, lead to enhanced $\theta_e$ and reduced convective inhibition levels. The intrusion of mid-level dry air, on the other hand, increases the CAPE, which provides the ideal conditions to increase the convective instability due to the low CIN and high CAPE values along with a negative gradient of $\theta_e$. The cyclonic circulation over the BOB extending southwest to the northeast towards Kerala coast resulted in enhanced moisture transport (<7 kg m$^{-1}$ s$^{-1}$ at 450 hPa) in the upper levels along the west coast. Therefore, the three major factors that played a critical role in the formation of Kerala heavy rainfall event were the strong low-level westerly jet on the hilly topography, the subsequent mechanical uplifting of air and moist convection, and the advection of dry continental winds at mid-tropospheric levels (700 hPa). These factors maintained static stability while the transport of moisture from the BOB facilitated the prolonged occurrence precipitation over the southwest coast.

The strength of the low-level trough and its location can be identified from the geopotential height, and we use vorticity to quantitatively assess the intensity of the low-pressure system. The spatial distribution of relative vorticity and geopotential clearly show a strong offshore trough off the coast of Kerala (Fig. 5) associated with a strong low-level convergence with the positive vorticity. A cyclonic circulation at mid-tropospheric levels is clearly seen at 450 hPa, which confirms the monsoon depression over Odisha and adjoining BOB, with a vertical tilt towards the north coastal Andhra Pradesh. The cyclonic flow extended up to 450 hPa (approximately 6.5 km), enhancing the low-level convergence and further strengthening the low-level monsoon winds. A weak anti-cycloic vorticity was also noticeable above 450 hPa. The spatial distribution of winds and relative humidity clearly indicate strong westerly winds (approximately 40 ms$^{-1}$) at low levels, with a saturated atmosphere (RH > 95%) over Kerala and coastal Karnataka. Northwesterly winds with relatively dry air were apparent in the layer of 700–600 hPa, compared to the conditions in the lower levels (1,000–700 hPa). At 450 hPa, north-to-northwesterly winds with relatively high humidity (RH > 90%) extended from the BOB’s cyclonic flow to coastal Karnataka and northern Kerala. The wind, vorticity, and humidity analyses at different levels clearly illustrate an altered flow pattern and moisture accumulation caused by the enhanced low-level convergence and vorticity.

3.3.2 | Analysis of mesoscale characteristics

A vorticity budget analysis (e.g., Dasari et al., 2017; Srinivas et al., 2018) was conducted to examine the life cycle of the convective system and its associated dynamical features using the very high resolution WRF simulations (2-km). The time–height section of the area located between 11 to 12$^\circ$N and 75 to 76$^\circ$N, averaged for vorticity budget analysis is presented in Fig. 5 and shows that the vertical
Advection and stretching terms mainly contributed to the intensification of cyclonic vorticity. The vertical advection (Fig. 5d) reached its highest values between 0000 UTC on August 15 and 0000 UTC on August 16, as the term originates from the convective motions that developed in the lower and middle layers of the troposphere. The corresponding stretching term (Fig. 5b) also achieved its maximum values between 1800 UTC on August 14 and 0000 UTC on August 15, indicating deepening areas of convection and vortex vertical extension/stretching with a lower radius at the surface. The tilting term is also stronger than that of the horizontal advection up to 500 hPa, and the abrupt reduction in strength thereafter reflects the role of strong shear on the vorticity in the lower levels. The maximum negative horizontal advection and positive vertical advection were between 850 and 400 hPa from 1800 UTC, August 14 to 0600 UTC, August 16, 2018, suggesting the simultaneous occurrence of strong vertical transport of moisture and maximum rainfall. The positive values in the lower troposphere suggest a strong contribution of the tilting term in the separation of updrafts and hailstones from the low-moisture convergence.

The time–height vertical section of equivalent potential temperature ($\theta_e$), horizontal winds, potential temperature ($\theta$), and vertical wind over central Kerala (11°–12°N and 75°–76°E) from WRF (2-km) simulations are shown in Fig. 6. The high values (>352 K) of $\theta_e$ in the lower levels, a gradual decrease of $\theta_e$ to low values (approximately 340 K) in the layers 500–600 hPa, and a steady increase of $\theta_e$ to the highest value (approximately 360 K) at the top of the troposphere indicate unstable/dry/unstable conditions in the lower/middle/upper levels. The presence of strong westerly winds, peaking about approximately 25 ms$^{-1}$ at 700 hPa, gradually decreases in strength to about 8 ms$^{-1}$. 

**FIGURE 5** Time–Pressure cross-sections of different terms in the vorticity budget equation. (a) Relative vorticity ($10^{-8}$ s$^{-1}$), (b) Stretching term ($10^{-8}$ s$^{-2}$), (c) Tendency term ($10^{-8}$ s$^{-2}$), (d) Vertical advection term ($10^{-8}$ s$^{-2}$), (e) Horizontal advection term ($10^{-8}$ s$^{-2}$), (f) Tilting term ($10^{-8}$ s$^{-2}$). Each term is computed at every model grid point and averaged over Kerala (11°–12° N and 75°–76° E)
at 400 hPa. The transition of winds between 200 hPa (easterly) to 300–400 hPa (westerly) indicates the presence of strong shear between 300 and 200 hPa layers and the strengthening of the easterlies in the layers between 150 and 100 hPa. The radiosonde data plotted at Cochin and Trivandrum stations (shown in Fig. S6) also confirms the presence of strong upper level easterly jet with core winds of about 48 m s$^{-1}$ that prevailed on August 14 and 15 and elevated core height of the jet by 1.5-km compared to the mean conditions. The upper level easterly jet was stronger by about 10 m s$^{-1}$ from mean conditions, producing favorable conditions for a stronger low-level westerly jet during the event. Additionally, the time–height cross-section of winds (Fig. 6c) and the RH (Fig. 6b) suggest an abrupt increase in the strength of moisture-laden northwesterly winds between 1800 UTC, August 15, and 1200 UTC, August 16, 2018, increasing the moisture transport from the BOB, and coinciding with the maximum rainfall over central Kerala, as discussed in Section 2. The high $\theta_e$ in the upper atmosphere above 400 hPa led to the formation of a highly convective unstable layer above a relatively dry layer. The strong shear suggests the development of convective overturning, as noticed first at 1200 UTC on August 14. The difference in $\theta_e$ propagated to higher levels (up to 300 hPa), and the maximum difference in $\theta_e$ developed between 1500 and 1800 UTC, August 15, indicating the development of favorable conditions for deep convection, eventually leading to precipitation. Strong vertical velocities in the order of 0.2 to 1 m s$^{-1}$ with a fully saturated atmosphere (RH > 98%) suggest an increased low-level convergence and the vertical transport of moisture on the windward side of the mountains. The high-resolution WRF (2-km) simulations clearly show strong low level westerly jet in the 800–400-hPa layer associated with a higher equivalent potential temperature (>2.5 K), stronger vertical velocities (by 0.1–0.2 m s$^{-1}$), and a fully saturated atmosphere (>98%).

**4 | SUMMARY AND CONCLUSIONS**

This study investigated the anomalous atmospheric conditions that lead to the extreme rainfall events over the state of Kerala (southwestern India) from August 1 to 19, 2018 using high-resolution regional and global reanalysis datasets. High resolution (2-km) cloud resolving WRF mesoscale model simulations were further analyzed to investigate the dynamics and thermo-dynamical factors behind the heavy rainfall. The main conclusions are as follows.

1. Station observations showed the heavy rainfall occurred in two spells (August 7–10 and 14–18) with the presence of an offshore trough and a depression over the BOB.
2. The spatially rainfall distributions observed from IMD gridded data suggests that the first spell was concentrated mainly over the northern mountainous region of Kerala. The rainfall then spread all over Kerala during the second spell with maxima over central and south-central Kerala.
3. The high-resolution WRF reanalysis and ERA-interim data suggest an increased low-level westerly jet accompanied by increased upper level easterly jet during the extreme rainfall episodes. The presence of strong and stationary cyclonic circulation over the BOB that extended up to the mid-troposphere might have played an important role in the prolonged occurrence of heavy rainfall over Kerala.

4. A strong low-level westerly jet along with the formation of the offshore vortex, the transport of mid-tropospheric moisture under the presence of conducive vertical shear of horizontal wind, and the transport of mid-tropospheric moisture from the BOB are the major factors contributing to the extreme rainfall.

5. A vorticity budget analysis based on the very-high resolution WRF model simulation indicates that the presence of strong positive vorticity is supported by horizontal advection in the lower levels and vertical advection in the upper levels. The stretching term dominates in the initial hours of heavy rainfall, whereas the tilting term contributes significantly to prolonged sustainment of the mature stage of heavy rainfall.

6. The indication of highly negative gradient of $\theta_e$ from the mid-to-the upper atmosphere (up to 400 hPa) suggests the existence of highly convective and unstable air above relatively dry air. This thermodynamically unstable layer with the strong shear suggests the development of convective overturning that favored the deep convection followed by the precipitation of August 14–16.

7. The prolonged occurrence of heavy rainfall was mainly caused by the stagnant nature of the strong synoptic force from the BOB depression with southwestward tilting up to the mid-troposphere and strengthening of moist-laden northwesterly winds near the Western Ghats. This accentuated the cyclonic circulation and low convergence, leading to sustained deep convection and producing extremely heavy rainfall.

The formation of wind confluence near surface over Kerala, the shear zones in mid and upper troposphere along with the enhanced upper air circulation are the major factors for the exceptionally heavy rainfall over Kerala. The results of the present study are highly useful for operational forecasting purposes as high resolution models are regularly employed by the national weather forecasting centers across the globe. The model diagnostics on the location of troughs, unusual circulation patterns, such as the low-level and mid-tropospheric circulations, meso-vortices and unusual low-level convergence/upper air divergence features will be highly useful for effective prediction of the exceptionally heavy precipitation events.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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