Orographic effect and multiscale interactions during an extreme rainfall event

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Abstract
Interaction of multiple oscillations of different time scales may result in severe weather events. The presence of orography can modulate the intensity of these events even further. Kerala witnessed one such heavy rainfall event in August, 2018, claiming 483 lives and damages worth INR 200 billion. This study focuses on the peak rainfall duration (13–17 August) when the departure from normal was 42%. Segregating moisture transport into its mean and perturbation terms show that an anomalous moisture channel over the Arabian Sea supplied continuous moisture to the Western Ghats (WG), whereas anomalous wind due to a monsoon depression advected moisture towards the southern peninsula. It is evident in the form of Moisture Flux Convergence (MFC) towers traversing along the Eastern Ghats before merging with the semi-permanent MFC feature over the WG. The presence of positive quasi bi-weekly oscillations and of Intra Seasonal Oscillations (ISO) aggravated the event as they complemented the anomalous moisture transport, with ISO constantly providing winds of the order of 2–3 m s⁻¹. In addition, shedding of MFC towers by the depression is accredited to the synoptic scale oscillation.

1. Introduction
Multiscale interactions culminating into extreme weather events can have detrimental impacts on the society at large (Krishnamurti et al 2017a). An extensively studied extreme event in Uttarakhand (2013), India, demonstrated the interplay between a monsoon depression and a southward penetrating mid-latitude westerly trough over an orographic region resulting in incessant rains, claiming thousands of lives and damaging property worth billions (Rajesh et al 2016, Ranalkar et al 2016, Vellore et al 2016, Krishnamurti et al 2017b). Krishnamurti et al (2017b) described it as streams of buoyant elements marching through a moist boundary layer towards the extreme orographic region, while Rajesh et al (2016) held potential vorticity shedding from both upper air westerlies and northerly moving monsoon depression that merged over Uttarakhand responsible for the catastrophic event. Baisya et al (2018) have also found the role of enhanced low–mid tropospheric moisture in facilitating the rainfall intensity of monsoon depressions over the Indian region in surrogate climate change experiments. The extreme precipitation event causing flood over the Indus valley of Pakistan in late July, 2010, exemplified yet another multiscale interaction between the Russian heat wave, convective outflow associated with the active phase of the Madden–Julian Oscillation (MJO), and a low level barrier jet in conjunction with a monsoon depression (Houze et al 2011, Galarneau et al 2012). Over the Mediterranean region, the synoptic scale steering flow subjected to the Alps creates a secondary cyclone on the lee side, drawing moisture from the adjacent western Mediterranean Sea and precipitating heavily in the nearby areas (Reale and Atlas 2001, Rudari et al 2004).

In northeast India, extreme precipitation events have been linked to quasi-biweekly oscillations and ISO coupled with local topography (Prokop and Walanus 2015). Goswami et al (2010) speculated southward
proporting gravity waves with strong updrafts, generated by the interaction of mesoscale circulation with local topography to create deep convective extreme rainfall. Analyzing 100 extreme rainfall events over the west coast of India, interactions between one or more of tropical convergence zone, offshore convective system, mid-tropospheric cyclone and offshore vortex were found (Francis and Gadgil 2006). Similar findings confirmed the contribution of ISO and quasi-biweekly oscillation components in facilitating the moisture supply during Chennai floods in 2015 (Krishnamurti et al 2017a). The 30–60 days oscillations linked to MJO have been deemed important for the Indian summer monsoon (ISM) and an intense MJO phase assists faster advancement of the ISM (Seetharam 2008, Singh et al 2017).

From 1 June to 19 August, 2018, Kerala received 2346.6 mm of rain, as opposed to a normal of 1649.5 mm, thus creating the most devastating floods in 100 years (India Meteorological Department 2018, Padma 2018). In this study, we will be focusing on the intense rainfall that lasted from 13 to 17 August, 2018, when the departure from normal was 42% (supplementary figure S1 is available online at stacks.iop.org/ERC/1/051002/mmedia). The prominent synoptic features during this period include (1) a monsoon depression with a southwestward tilt that traversed west-northwestward from its genesis location in northwest Bay of Bengal (BoB), (2) an anticyclonic circulation at 200 hPa over the Tibetan Plateau, and (3) a phase 6 MJO (Cyclone Warning Division - India Meteorological Department 2018). In this study we unravel the interactions between the cross-equatorial monsoonal flow and the monsoon depression along with presence of positive phases of synoptic, quasi-biweekly oscillations and ISO.

2. Results and discussions

2.1. Moisture transport
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Torrential rains during the month of August 2018 brought havoc and chaos in the state of Kerala. The large scale flow can give us a clue about how the moisture was advected to Kerala. In order to do so, moisture transport is separated into both the mean and the perturbation terms (Hunt et al 2016):

\[ qv = \bar{q}v + q^\prime v + q^\prime v', \] (1)

where \( q \) is specific humidity (Kg Kg\(^{-1}\)) and \( v \) is the wind vector. The climatological value or the overbar is calculated using 39 years (1979–2017) of data, whereas the prime represents the perturbation from climatology.

In this study, European Centre for Medium-range Weather Forecasts six-hourly reanalysis dataset (ERA-Interim) is used unless specifically mentioned (Dee et al 2011).

As seen in figure 1(a), the climatological moisture advected by the climatological wind shows the mean southwesterly moisture transport over the Indian subcontinent. In addition to the mean flow of moisture, a moist stream of anomalous moisture advected by the climatological wind provides continuous supply of moisture to the WG (figure 1(b)). On the other hand, the depression was sustained by the climatological moisture advected by the anomalous wind (figure 1(c)), and is nearly 3 times greater than the moist stream of moisture advected from the Arabian Sea. The least contribution is seen from the anomalous moisture advected by the anomalous wind (figure 1(d)). Interestingly, the anomalous circulation due to the monsoon depression (head BoB) advected climatological moisture of the order of 0.05–0.075 Kg Kg\(^{-1}\) ms\(^{-1}\) to the southern peninsula, and could be one of the triggering mechanisms for such an intense and sustained rainfall over Kerala.

2.2. Cloud ice and cloud liquid water
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The long spells of heavy rain had direct implications on cloud properties, and are important parameters to be examined alongside precipitation (figure S2). Figure 2 shows the daily averaged cloud liquid water (CLW) in shading (Kg Kg\(^{-1}\)), cloud ice water (CIW) in dots (Kg Kg\(^{-1}\)), and vertical velocity in contours (m s\(^{-1}\)). Each panel is drawn along the latitude of maximum rainfall for that day. A strong updraft near the foothills of the WG force the moisture brought in by the cross-equatorial flow to ascend, thus accumulating CLW; on the contrary, the leeward side exhibits downdrafts with little or no CLW (Stockham et al 2018). Another region of low-mid-tropospheric updraft between 78°–82°E is associated with enhanced CLW, and positive anomalous moisture transport, calculated using 39 years of climatology (figure S3). Proliferation of CIW along with CLW from 13–15 August, suggests intense convective precipitation as confirmed by the daily accumulated rainfall plots (figure S2; Huffman 2016), but creates ambiguity whether these low-mid-tropospheric clouds are generated by upward propagating gravity waves, or being fed by the west-northwestward moving depression (Jiang and Smith 2003, Houze 2012).

2.3. Moisture flux convergence towers
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Discerning the dominant mechanism is crucial to understand the cause of the event, so moisture flux convergence (MFC), an excellent precursor of heavy precipitation (Baisya et al 2017) is examined. MFC is
calculated as defined by Banacos and Schultz (2005):

\[ MFC = - \nabla \cdot (\bar{q} \mathbf{V}_h) - \frac{\partial}{\partial p} (q_\omega), \]  

where \( \nabla = \hat{i} (\partial / \partial x) + \hat{j} (\partial / \partial y) \), \( \mathbf{V}_h = (u, v) \), and \( \omega \) is vertical \( p \) velocity (Pa s\(^{-1}\)).

Isosurfaces of \( 2.5 \times 10^{-5} \) s\(^{-1}\) MFC (figure 3, shown in red) break-up from the depression and propagate in a northeasterly fashion, precipitating over Odisha, Andhra Pradesh and Telangana before starting its ascent over the WG, and merging with the semi-permanent MFC feature over the WG (975–900 hPa). The southwestward tilt of the depression and the anticyclonic circulation over the Tibetan Plateau could be the reason for the generation of these MFC towers (Cyclone Warning Division - India Meteorological Department 2018).

Isosurface of \( -5 \times 10^{-5} \) s\(^{-1}\) MFC (shown in blue) is seen near the foothills of the WG on the leeside where strong downdrafts were present. A similar pattern is also observed in the wind convergence and divergence.
The presence of the semi-permanent MFC feature is due to the fact that the WG act as an obstacle to the cross-equatorial flow, forcing the moisture laden winds to rise, thereby creating a strong convergence zone near the foothills of the WG. In addition to MFC shedding by the depression, strong wind convergence zones are also identified along the eastern coast of India, confirming the fact that the low-mid-tropospheric clouds on the leeward side of the WG were being fed by the monsoon depression.

2.4. Scale interactions

The presence of multiple scales over a location can aggravate extreme events (Krishnamurti et al 2017a). To assess the impact of each of these oscillations, sixth-order Butterworth bandpass filter is applied to 850 hPa wind to extract the synoptic scale (3–7 days), the quasi bi-weekly oscillations (10–20 days), and the ISO (30–60 days; Russell 2006). National Center for Environmental Research–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data at 2.5° resolution for the period 1 Jan–2 Dec, 2018 is used for this analysis (Kalnay et al 1996).

Clearly the quasi bi-weekly oscillation and the ISO complement the cross-equatorial monsoonal flow, and the anomalous moisture advected by the climatological wind closely follows the positive phase of the ISO pattern between 0°–20° N (figures 4(b), (c)). Thus, the ISO provides a background for the continuous supply of moisture from the Arabian Sea towards the WG. Analyzing the time series for point locations in and around Kerala shows that ISO consistently provides strong winds of the order of 2–3 m s⁻¹ throughout the study period (figure S5). In addition to the transport of moisture towards the WG due to onshore winds, the quasi-biweekly oscillation supports the synoptic scale by supplying moisture through the BoB channel of the monsoonal flow (figures 4(a), (b)). This assures the continuous supply of moisture from the BoB translated through the synoptic scale oscillations to the monsoon depression. It is worth mentioning that the climatological moisture advected by the
anomalously high wind that sustains the depression follows the positive phase of the synoptic scale oscillation (figures 1(c), 4(a)).

As discussed earlier, another facet of the Kerala event was the shedding of MFC towers by the depression while traversing west-northwestward. As seen in figure 4(a), a strong southward flow on 14 August, forced MFC towers to separate out and propagate along the east coast before merging with the semi-permanent MFC feature over the WG. Similarly, a strong southwestward flow on 15 August, and a return flow from the monsoon depression on 16 August, guaranteed a continuous flow of moisture from the depression to the southern peninsula. Thus, on one hand the bi-weekly and the ISO provided moisture from the Arabian Sea to the WG, on the other hand the synoptic scale oscillation provided moisture to the WG in the form of MFC towers from the monsoon depression.

3. Conclusions

Kerala witnessed one of the worst floods in the month of August, 2018, due to sustained incessant rains. In this study the most intense phase of the event (13–17 August, 2018) is investigated, when the rainfall was 42% above the climatological value. Decomposing the large scale moisture transport into its mean and perturbation terms, we found that the mean flow sustained the continuous supply of anomalous moisture to the WG (figure 4(b)), whereas, climatological moisture advected by the anomalous wind maintained a west-northwestward propagating depression (figure 4(c)).

Streams of MFC towers marched along the east coast of India and merged with the semi-permanent MFC feature over the WG, which consequently enhanced CIW and CLW on the leeward side of the WG, and precipitated heavily in the nearby areas. Another speculation for augmented CIW and CLW on the leeward side of the Western Ghats is the upward propagating gravity waves (Jiang and Smith 2003, Houze 2012).

Assessment of multiple oscillations revealed the fact that the quasi-biweekly oscillation and the ISO facilitated the continuous supply of moisture from the Arabian Sea to the WG, and the synoptic scale oscillation provided moisture to the depression from the BoB, in addition to being a key player in separating MFC towers from the depression. Interestingly, locations upstream of the Kerala coast exhibited positive phase for all the oscillations with ISO constantly providing winds of the order of 2–3 m s⁻¹ during the heavy rainfall period (figure S5). Thus the perfect synchronicity of multiple oscillations aided in the development of the catastrophic event in Kerala.

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