

Role of east–west shear zone and wind confluence on the occurrence of intense heavy rainfall over North Konkan during southwest monsoon season

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An attempt has been made to understand the mechanism in occurrence of intense heavy rainfall events over North Konkan and adjoining areas using observed, satellite and reanalysis datasets. Synoptic conditions associated with Dahanu heavy rainfall event, 2016, Mumbai floods, 2005 and historical heavy rainfall events over North Konkan region are considered in the present study. In presence of East–West shear zone with upper air cyclonic circulations extending up to mid-tropospheric levels located at west central Bay of Bengal, west Arabian Sea and anti-cyclonic circulation over east-central Arabian Sea were the major synoptic features observed during these events. Results suggest that the confluence of moisture-laden winds from these circulations over North Konkan lead to the occurrence of intense heavy rainfall events.

Keywords: Heavy rainfall events, monsoon season, shear zone, wind confluence.

MONSOONAL rainfall is not continuous and uniform throughout a season, as it comprises active and break spells. Most parts of India get substantial amount of rainfall with heavy to very heavy rainfall activity at some places on several occasions during active phase of the monsoon, and weak or no rainfall during break phase of the monsoon. These heavy to very heavy rainfall activities are associated with different mechanisms described in various studies^{1–6}. Rakhecha and Pisharoty⁷ have cited the following main causes of heavy rainfall over the Indian region: (i) Formation and consequent movement of cyclonic disturbances across the country. (ii) Orographic lifting of moist air as it rises along the slope of the mountain barrier across the air stream. (iii) Monsoon break period when heavy rainfall activities are confined to the Himalayan region and areas close to it. They further explain that when cyclonic systems (mainly depression) form over the Bay of Bengal (BoB), often Arabian Sea

monsoonal flow strengthens and causes orographic lifting of the moisture-laden winds.

The west coast of India gets heavy rainfall during summer monsoon season (JJAS). Occurrence of these events is more frequent during the season and causes substantial damage to lives and property. Major causes cited for these events over the region in previous studies are: offshore trough and vortices, mid-tropospheric cyclones (MTC), etc.^{2,8}. However, Francis and Gadgil⁶ using satellite-derived outgoing longwave radiation (OLR) data demonstrated that most of these events are linked with atmospheric conditions over the equatorial Indian Ocean. Roca and Ramanathan⁹ revealed that deep cloud systems contribute significantly to total cloudiness off the west coast of India. Heavy rainfall over the west coast and the Western Ghats is mostly attributed to the ascent of moist air from the Arabian Sea due to monsoonal flow over orography of the Ghats^{10,11}. Coastal regions have been observed to record greater amount of rainfall than the Ghats^{12,13}. It has been proposed that these heavy rainfall activities are linked with offshore trough and vortices^{1,3,13}. Consequent studies by Benson Jr. and Rao¹⁴, and Rao and Hor¹⁵ indicated that these vortices are embedded in synoptic-scale convective systems. Synoptic and large-scale analysis associated with heavy rainfall events by Francis and Gadgil⁶ demonstrated that majority of these events are associated with tropical convergence zone (TCZ), while systems like offshore trough, MTC, etc. account for the rest. Here, we have studied two historic, record-breaking extreme rainfall events over North Konkan and Mumbai regions and synoptic conditions associated with them. During the 2016 monsoon season, on 21 September 2016, Dahanu station in North Konkan region recorded 528 mm of rainfall in 24 h, which was an all-time record for the station. We also studied the infamous Mumbai extreme rainfall event of the 2005 monsoon season (hereafter Mumbai floods), when on 26 and 27 July 2005, Santacruz station recorded 944 mm of rainfall^{16,17}. Further, we carried out composite analysis for the historical, intense heavy rainfall events over Dahanu station and associated atmospheric dynamics to understand their mechanism of occurrence.

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Mumbai floods

Various aspects of the occurrence of the Mumbai floods have been studied; most of them focused on numerical simulations^{18–22}. However, synoptic and thermo-dynamical aspects associated with the event have also been addressed^{16,17}. The Mumbai floods disrupted life in city and resulted in a large number of deaths (~400 people) as well as property loss of nearly Rs 10,000 crores¹⁶. This loss of lives and property could have been less if these events had been predicted well in advance. A variety of modelling studies could not simulate the intensity of the Mumbai floods appropriately and cited various reasons for this (e.g. sensitivity to boundary conditions, model resolution, etc.)^{23–25}. Sikka and Rao²⁶ reviewed the modelling studies on the Mumbai floods and Odisha supercyclone 1999, and found considerable variability in predicting such events. They further suggested that in order to reduce the uncertainty in dynamical prediction, it is necessary that the model dynamics, physics, resolution, boundary conditions and availability of data on land–ocean surface processes, etc. should be tuned separately to the specific event types. The high-resolution (3.6 km) weather research and forecasting (WRF) model study by Kumar *et al.*¹⁹ could simulate the Mumbai heavy rainfall event reasonably good. Despite various modelling and observational studies on the Mumbai floods, researchers could not reach a solid consensus on the reason behind the occurrence of the event. The role of large-scale dynamics on the occurrence of such events has not been addressed appropriately in previous studies. Therefore, we revisit this case using a novel approach.

Dahanu floods

Dahanu station of North Konkan (19.98°N, 72.74°E), 130 km from Mumbai, recorded 528 mm of rainfall in 24 h on 21 September 2016, and set a new record. Rainfall distribution over Dahanu and surrounding areas demonstrated the occurrence of heavy to extremely heavy rainfall at most places for the same period. The large-scale features of Dahanu floods are compared with the Mumbai floods to understand the similarities associated with the event. Here, we study the mechanism behind these extreme rainfall events over the region using various datasets.

Datasets used

Diverse datasets, including observed rainfall data for Dahanu and surrounding stations, gridded reanalysis datasets, satellite observed rainfall and outgoing longwave radiation (OLR) data were used in the present study. To study extremely heavy rainfall event over Dahanu station and its neighbourhood, we have used daily rainfall data for Palghar district, Maharashtra, which comprises 29

stations. Long-term heavy rainfall records for Dahanu station (1951–2016) were obtained from research section of Regional Meteorological Centre (RMC), Mumbai and National Data Centre, IMD, Pune to understand the large-scale composite structure of the dynamical features of such events. The Goddard Earth Sciences Data and Information Services Centre (GES DISC), in coordination with Global Precipitation Measurement (GPM) mission and the Precipitation Processing System (PPS), an Integrated Multi-satellite Retrievals for Global Precipitation measurement (IMERG) derived daily gridded data of precipitation at $0.25^\circ \times 0.25^\circ$ were used to study rainfall distribution over land as well as ocean²⁷. The IMERG dataset was downloaded from <https://pmm.nasa.gov/data-access/downloads/gpm>. High-resolution ($0.25^\circ \times 0.25^\circ$) OLR data based on Mahakur *et al.*²⁸ were used. The authors²⁸ had derived the OLR from Kalpana-1 (formerly METSAT-1). Quality-controlled high-resolution OLR at the above mentioned resolution over the Indian region ($40^\circ\text{S}–40^\circ\text{N}$, $25–125^\circ\text{E}$) from May 2004 to the present is available at the Indian Institute of Tropical Meteorology, Pune, website (<http://www.tropmet.res.KIOLR>). The atmospheric fields were obtained from National Centre for Environmental Prediction/National Centre for Atmospheric Research (NCEP/NCAR) reanalysis-1 at $2.5^\circ \times 2.5^\circ$ resolution²⁹.

Results

Synoptic conditions associated with Dahanu heavy rainfall event

Dahanu station of North Konkan (19.98°N, 72.74°E) recorded 528 mm of rainfall in 24 h on 21 September 2016. The downpour of the Dahanu heavy rainfall event hit normal life as roads were flooded, power and phone lines had snapped, schools and colleges declared a holiday, railway tracks were flooded and services delayed by 2–3 h. Daily rainfall data from 29 stations of Palghar district (Figure 1) recorded heavy to extremely heavy rainfall at most places for the same period. The synoptic conditions before, during and after this event have been studied in order to understand the origin of the event. Figure 2 *e–h* shows the OLR and mean sea level pressure (MSLP) evolution for the period 19–22 September 2016. It is interesting to note that the existence of northwest–southeast orientation of the monsoon trough on 19 September 2016. Formation of the low pressure area (LOPAR) over west central (BoB) and its northwestward movement in subsequent days can also be noted from the figure.

The LOPAR/depressions during monsoon are synoptic-scale cyclonic circulations that occur over the northern BoB and sometimes over central India during the summer monsoon season. They generally give abundant rainfall in the southwest sector¹. Commonly, a persistent spell of

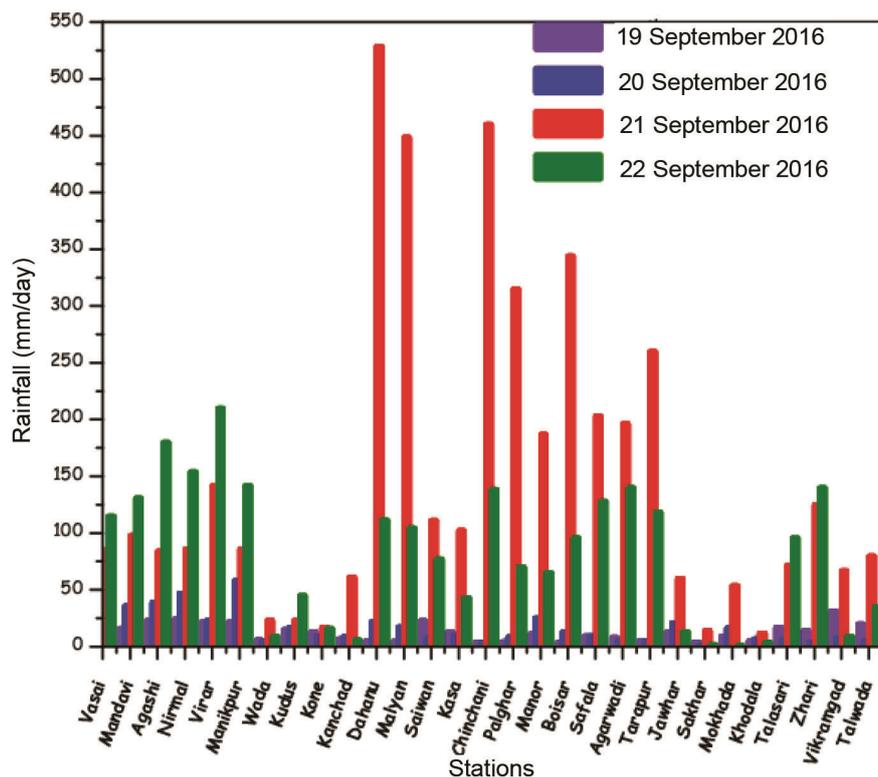


Figure 1. Rainfall (mm day^{-1}) recorded at 29 stations in Palghar district, Maharashtra on 21 September 2016.

dry weather during the monsoon season is broken by the formation of monsoon synoptic-scale systems (LOPAR/depressions). Several studies on the cause of intensification of low-pressure systems into depressions have been carried out^{30–32}. Some of the cited are as follows: the association of the interaction between lower tropospheric convergence and upper tropospheric divergence³⁰. These features are also linked with upper-level positive vorticity and advection which help in the upward motion and lower-level convergence in the northern BoB. However, Daggupati and Sikka³¹ have argued that during several occasions, development of depression takes place without adequate changes in the upper tropospheric circulation prior to the time of intensification. They further explain that the presence of strong monsoon westerlies to the south of the genesis area as well as strengthening of the lower tropospheric westerlies over peninsular India is one of the reasons for LOPAR formation over the region. Saha and Chang³² demonstrated that most of the depressions that form at the head BoB are associated with pressure disturbances coming from the east. The vertical wind shear and convective instability of second kind (CISK) are the reasons cited for LOPAR formation and intensification³³.

We have discussed various mechanisms for the occurrence of LOPAR over northern BoB during SW monsoon season. The northwestward movement of these disturbances leads to widespread rainfall along the path, with

high rainfall activity over SW sector of it^{1,31}. Deep convective clouds are usually identified by their cold cloud tops which emit low values of OLR. A minima in OLR is the proxy for deep convective clouds. $\text{OLR} < 240 \text{ Wm}^{-2}$ is considered as convective clouds. Therefore, negative anomalies of the OLR suggest the presence of convection/cloudiness over the region. Figure 2 *a–d* shows plot of the Kalpana satellite-derived OLR for the period 19–22 September 2016 (ref. 28). Systematic west-northwestward movement of the convective cloud bands corroborates well with the streamline and vorticity analysis (Figure 3).

Figure 3 *a–d* depicts the anomalies in streamline and vorticity at 850 hPa level for 19–22 September 2016. Northwestward movement of LOPAR from west-central BoB and associated upper air cyclonic circulation extending up to 500 hPa (Figure 4 *c*) have been observed during the period. The remarkable synoptic features before and during this event are as follows: (i) Upper air cyclonic circulation over southwest Madhya Pradesh, adjoining Gujarat and north Maharashtra persisted on 19 September 2016. (ii) Upper air cyclonic circulation (Figures 3 and 4 *b, c*) over west central and northwest BoB and adjoining coastal areas of south Odisha and north Andhra Pradesh persisted on 20 September 2016. (iii) Anomalous anti-cyclonic circulation at 850 hPa over east to east-central Arabian Sea extending up to 500 hPa (Figure 4 *b* and *c*). (iv) Presence of anomalous, strong E–W wind shear

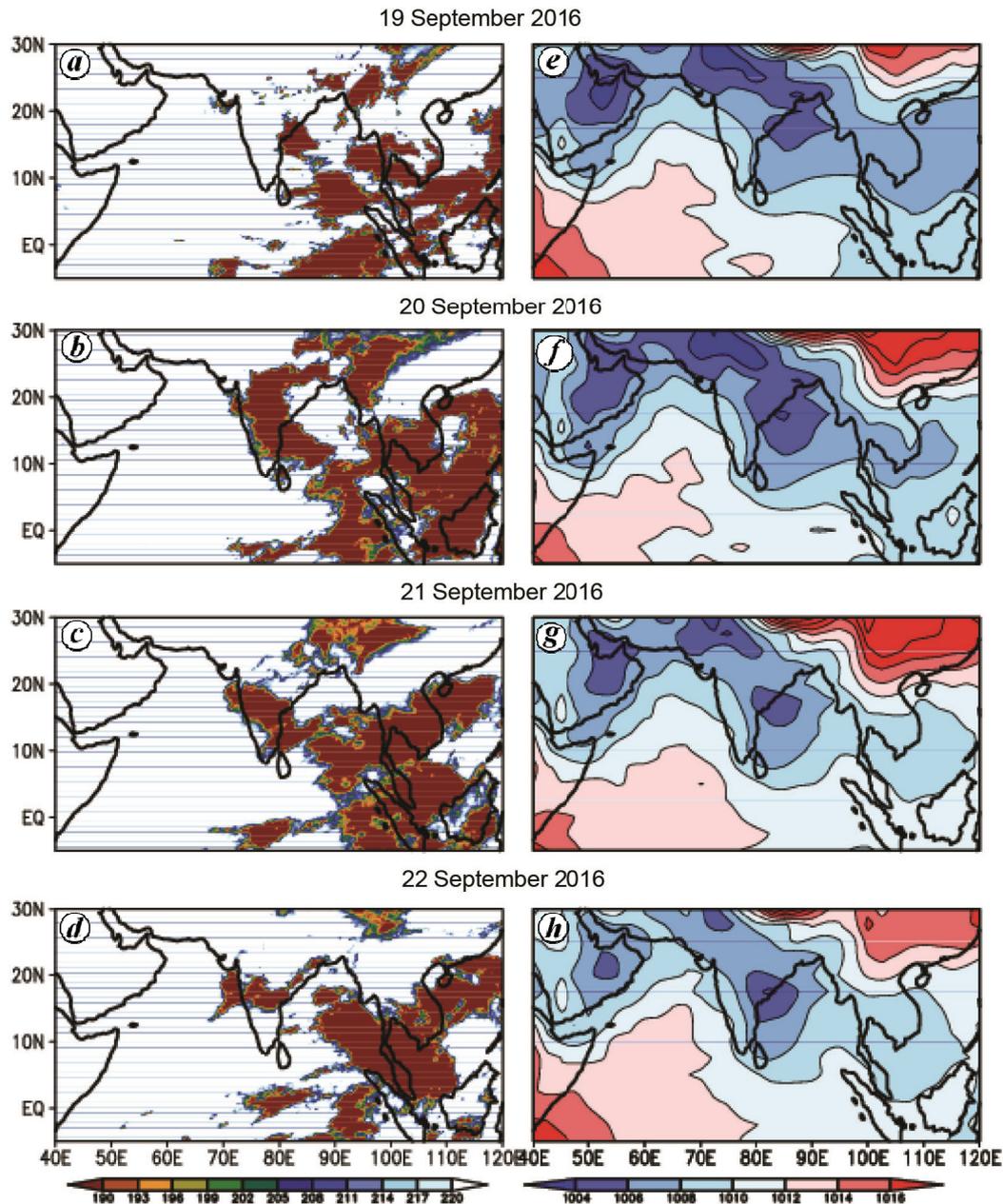


Figure 2. Evolution of (a–d) Kalpana satellite-derived outgoing longwave radiation (W m^{-2}) and (e–h) mean sea-level pressure (hPa) for the period 19–22 September 2016.

embedded with upper year cyclonic circulations extending from 850 to 500 hPa. (v) Anomalous cyclonic circulation over western Arabian Sea near Oman coast extending from 850 to 500 hPa.

Similarity with the Mumbai floods

The Tropical Rainfall Measuring Mission (TRMM) satellite-observed rainfall, 850 and 500 hPa streamline and relative vorticity (shaded) are plotted in Figure 5 for 26 July 2005, when the heavy rainfall event occurred over

Mumbai and adjoining regions. It is worth mentioning that synoptic features present during the Dahanu heavy rainfall case study are similar to the Mumbai heavy rainfall event. However, position of the vortices embedded in E–W shear zone is located more northward compared to the Dahanu event. Also, anti-cyclonic circulation in the Mumbai event was found to be near the equator, while it was located in east-central Arabian Sea in the earlier case. Therefore, position as well as strength of these systems determine the region of heavy rainfall. Hence, it may be concluded that embedded vortices in E–W-oriented

wind shear in the lower levels, anti-cyclonic circulation in the Arabian Sea, cyclonic circulation over eastern Arabian Sea and LOPAR over west-central BoB play an important role in the transport of moisture and occurrence of heavy to extremely heavy rainfall events over North Konkan and adjoining regions.

Historical intense heavy rainfall events over Dahanu and associated synoptic conditions

Heavy rainfall (64.5–114.5 mm day⁻¹) events are common over the west coast of India during monsoon season. However, frequency of occurrence of very heavy rainfall (>115–204.5 mm day⁻¹) events and above categories is comparatively less⁶. Therefore, we selected only events

when rainfall over Dahanu station was greater than or equal to 150 mm/day for our analysis. Table 1 shows the rainfall records and occurrence date. Composite analysis for these events was carried out to find similarities, if any of these events with the Dahanu extremely heavy rainfall event. Figure 6 depicts composite anomalies of the rainfall, streamline and relative vorticity at 850 and 500 hPa. It is interesting to note that the main features observed from Dahanu and Mumbai case studies, i.e. E–W wind shear, anti-cyclonic circulation over east–central Arabian Sea, cyclonic circulation over western Arabian Sea and BoB are also observed in composite analysis. This finding further confirms the synoptic conditions essential for the occurrence of intense heavy rainfall over North Konkan and adjoining regions, apart from its possibility of occurrence from offshore trough, MTC, etc.

The above analysis was performed considering only intense heavy rainfall events (rainfall >150 mm day⁻¹). Here question arises whether similar synoptic conditions prevail for no rain (0.0 mm day⁻¹), light (2.5–15.5 mm day⁻¹) and moderate rainy days (15.6–64.4 mm day⁻¹). In order to quantify this, we performed composite analysis for the above categories. The quantification of rainfall categories mentioned above is according to IMD’s forecasting circular³⁴. Figure 7 shows composite anomalies of the no rain, light rain and moderate rain categories. The

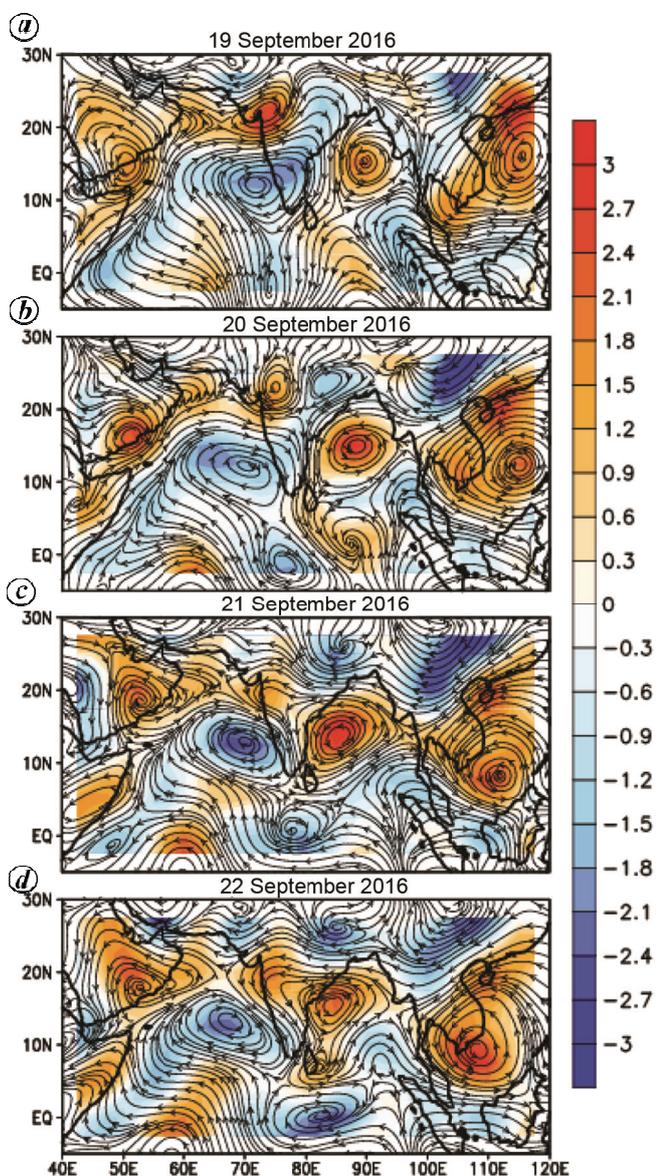


Figure 3. Evolution of 850 hPa relative vorticity (10⁻⁶ S⁻¹, shaded) and streamline (vectors) for the period 19–22 September 2016.

Table 1. Intense heavy rainfall over Dahanu station and the respective date of occurrence

Date (dd/mm/yyyy)	Rainfall recorded (mm day ⁻¹)
16/07/1965	293.2
26/07/1965	197.2
06/08/1968	191.8
23/06/1970	216.4
01/06/1971	220.8
12/06/1973	185.8
04/07/1974	301.0
21/06/1978	169.0
23/06/1980	195.0
24/09/1981	239.0
07/08/1983	296.7
02/08/1985	193.0
15/07/1988	192.3
23/06/1992	281.2
17/09/1993	154.0
18/07/1995	191.2
22/07/1996	204.6
28/06/1998	199.0
07/07/2000	183.8
15/06/2001	195.4
28/07/2003	219.4
03/08/2005	164.7
04/08/2007	178.3
24/06/2010	236.0
12/06/2011	158.0
04/09/2012	359.6
24/09/2013	267.2
05/07/2014	267.6
21/09/2016	528.6

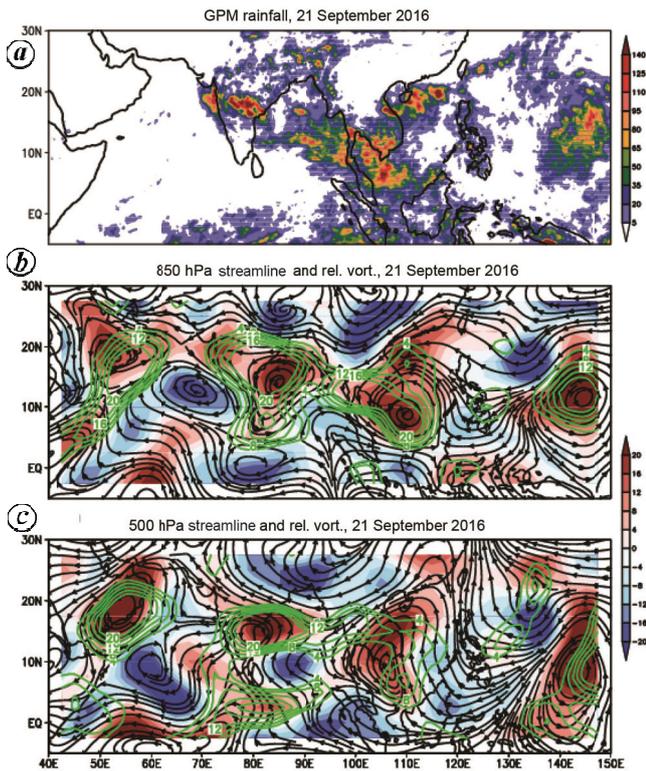


Figure 4. *a*, GPM satellite-derived rainfall for the 21 September 2016. *b*, Anomaly maps of 850 hPa relative vorticity (10^{-6} S^{-1} , shaded) and streamline (vectors) for 21 September 2016. *c*, same as (*b*), but for 500 hPa. Green contours show the actual relative vorticity (10^{-6} S^{-1}).

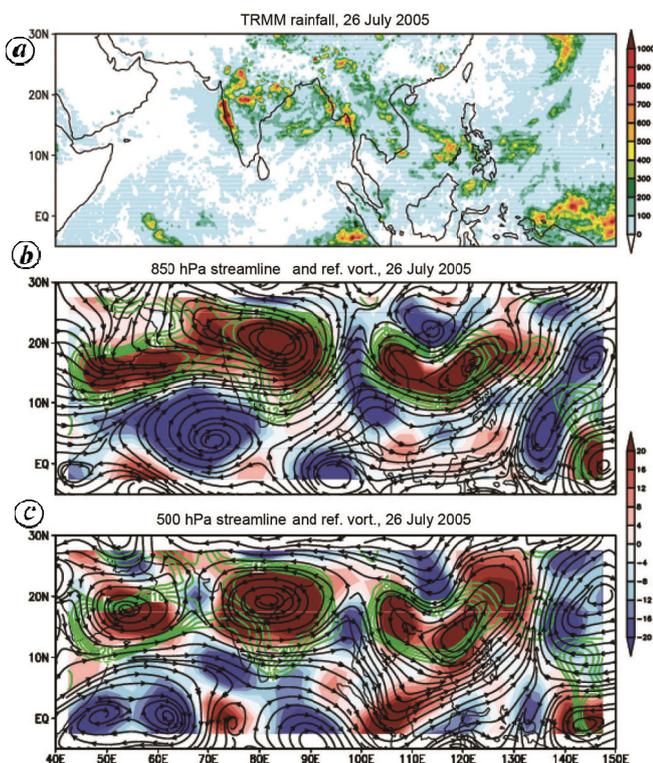


Figure 5. Same as Figure 4 but for 26 July 2005. Green contours show the actual relative vorticity (10^{-6} S^{-1}).

following points can be noted from the above analysis: (1) No rainy days composite anomalies shows anomalous anti-cyclonic circulation over north Konkan and adjoining regions, weak monsoon flow and southward movement of the TCZ. (2) Light rainfall days composite anomalies illustrate weak monsoon flow, low cyclonic vorticity of the order of $1\text{--}4$ (10^{-6} S^{-1}) and absence of E–W wind shear. (3) Moderate rainfall days composite anomalies demonstrate the weak E–W shear, absence of cyclonic vortices embedded in it (while it is strong in intense heavy rainfall composite anomalies) and lower magnitudes of vorticity, i.e. $4\text{--}6$ (10^{-6} S^{-1}) over the region as compared to composite anomalies of intense heavy rainfall events.

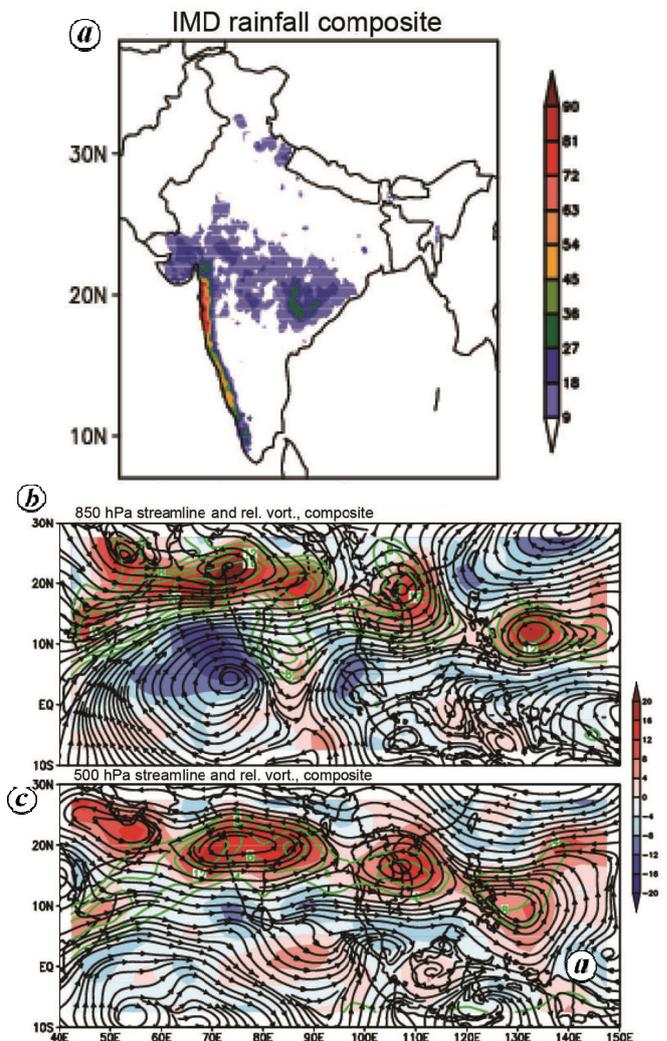


Figure 6. *a*, Composite anomalies of intense heavy rainfall (>150 mm/day) events for Dahanu station for the period 1965–2016. *b*, Composite anomalies of 850 hPa relative vorticity (10^{-6} S^{-1} , shaded) and streamline (vectors) associated with intense heavy rainfall (>150 mm/day) events for Dahanu station for the period 1965–2016. *c*, same as (*b*), but for 500 hPa level. Green contours show the actual relative vorticity (10^{-6} S^{-1}).

It is clear from the analysis that there exists no similarity between the synoptic pattern observed for the intense heavy rainfall composite and rainfall category of moderate and below. Thus the synoptic pattern observed for intense heavy rainfall composite is found to be a favourable condition for its occurrence.

Role of moisture convergence and wind confluence

It is interesting to note from the anomaly map of streamline and relative vorticity that confluence of lower-level south westerlies associated with anti-cyclonic circulation over the Arabian Sea, westerlies associated with the upper air cyclonic circulation from Oman region and easterlies/north-easterlies associated with the northwestward movement of LOPAR resulted in extremely heavy rainfall over North Konkan and adjoining areas (Figures 4–6). Vorticity anomalies at 850 and 500 hPa during the Dahanu case study, Mumbai floods and composite of intense heavy rainfall events were found to be in the range 16–20 (10^{-6} S^{-1}). Figure 8 shows the vertically integrated moisture convergence (VIMC) (from 1000 to 300 hPa) and streamline for the Dahanu case study, Mumbai floods and composite of intense heavy rainfall events. High positive anomalies of VIMC ($\sim 100 \text{ (} 10^{-6} \text{ g kg}^{-1} \text{ S}^{-1}\text{)}$) were found to be prominent during these events over

North Konkan and adjoining areas. The Global Precipitation Mission (GPM) satellite-derived (Figures 4 a and 5 a) and IMD-observed (Figure 6 a) rainfall dataset concurrently show heavy rainfall values over regions of high moisture convergence/confluence along the E–W-oriented vortices. This implies that moisture convergence of the order of 100 ($10^{-6} \text{ g kg}^{-1} \text{ S}^{-1}$), vorticity of the order of 16–20 (10^{-6} S^{-1}) and wind confluence over the region from these systems are favourable for the intense heavy rainfall occurrence.

Summary and discussions

In the present study, we examined the mechanism on the occurrence of intense heavy rainfall events over north Konkan and adjoining regions during SW monsoon season. At first, we considered the Dahanu station extremely heavy rainfall event which occurred on 21 September 2016 and recorded 528 mm rainfall in 24 h. Synoptic conditions associated with this event were studied. It was observed from the analysis that four major synoptic systems existed during the events: (i) LOPAR over west-central BoB and associated cyclonic circulation extending up to mid-tropospheric level. (ii) Cyclonic circulation extending up to 500 hPa near Oman coast and adjoining

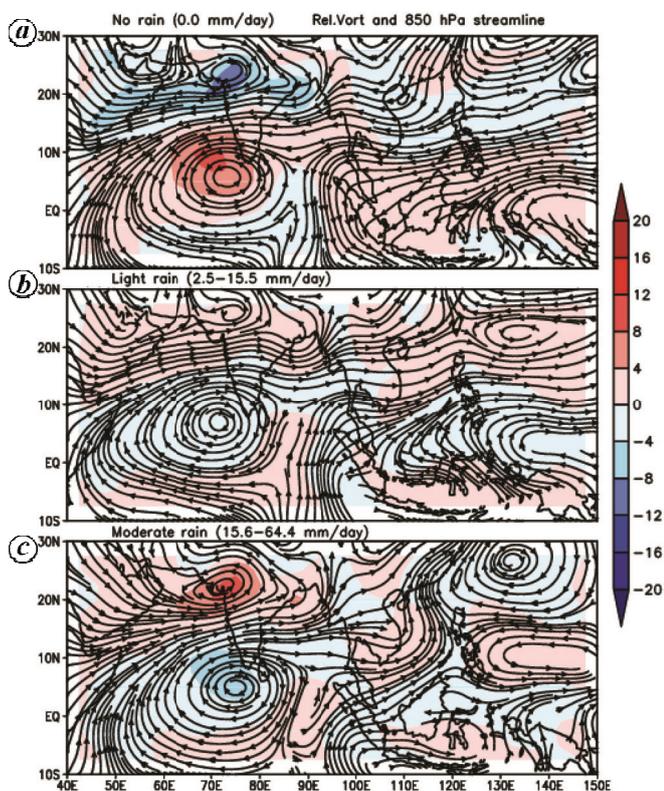


Figure 7. Composite anomalies of 850 hPa streamlines and relative vorticity (shaded, 10^{-6} S^{-1}) for (a) no rain, (b) light rain and (c) moderate rain categories.

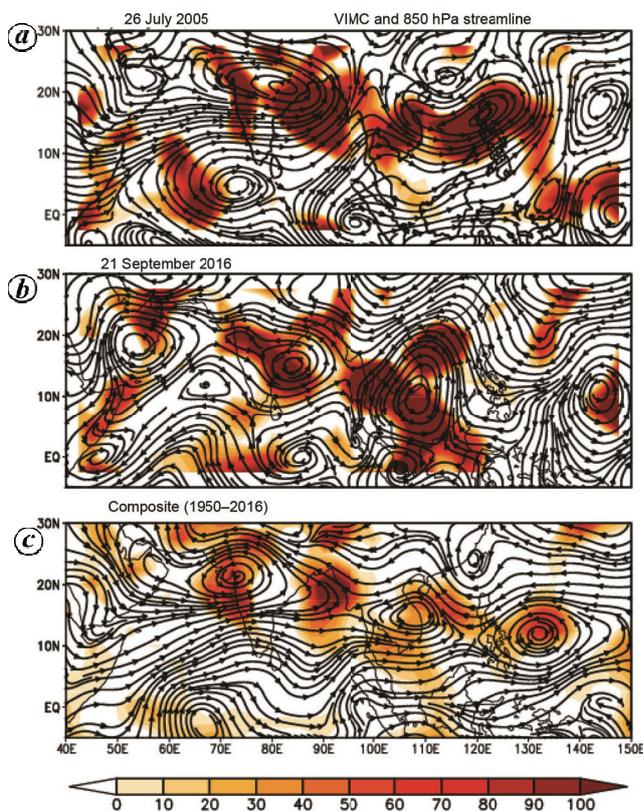


Figure 8. The 850 hPa streamlines and vertically integrated (1000–300 hPa) moisture convergence (shaded, $10^{-6} \text{ g kg}^{-1} \text{ S}^{-1}$) for (a) 26 July 2005, (b) 21 September 2016 and (c) composite of all intense heavy rainfall events mentioned in Table 1.

west Arabian Sea. (iii) Anti-cyclonic circulation over east-central Arabian Sea. (iv) A pattern of upper air cyclonic vortices embedded in E–W wind shear extending from 850 to 500 hPa vertically and from Oman coast to south China Sea horizontally.

It has been observed that confluence of westerlies from west Arabian Sea cyclonic circulation, southwesterlies from anti-cyclonic circulation of east-central Arabian Sea and easterlies to northeasterlies from cyclonic circulation of west-central BoB lead to moisture-laden wind convergence/confluence in north Konkan and adjoining regions. Similar analysis was performed for Mumbai floods case of 2005 for comparison. The TRMM satellite-observed rainfall, streamline and relative vorticity analysis for 850 and 500 hPa revealed that similar synoptic conditions were occurred during the Mumbai floods as well. One important observation from the present analysis is that the E–W orientation of the cyclonic vortices embedded in E–W wind shear, and position of the synoptic systems mentioned above decides the confluence zone and associated heavy rainfall events over the region.

After identifying similarities in the above-mentioned major extremely heavy rainfall events over the northwest coast of India, we now pose a question: Are heavy rainfall events over the region associated with similar synoptic conditions? In order to comprehend the mechanism of such events, we identified the intense heavy rainfall records (≥ 150 mm) over Dahanu station for the period 1965–2016 and carried out composite analysis for the same. It is worth mentioning that the composite anomaly inferred from the analysis corroborates well with the Dahanu and Mumbai extremely heavy rainfall event synoptic conditions. Therefore, it may be concluded that the synoptic conditions mentioned above are essential ingredients for the occurrence of heavy rainfall events over North Konkan and adjoining regions. However, the role of other monsoonal components (e.g. offshore trough, MTCs, etc.) in the occurrence of such events cannot be overlooked. Composite pattern using rainfall category of moderate (15.6–64.4 mm/day) and below (2.5–15.5 mm/day) shows a different picture than what we obtained using intense heavy rainfall composite. This strengthens the mechanism proposed in this study for the occurrence of intense heavy rainfall events over North Konkan and adjoining areas.

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