

L E T T E R S

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UNPRECEDENTED EXTREMELY HEAVY RAINFALL OVER GUJARAT DURING 20- 26 JUNE, 2015

1. Gujarat state experienced unprecedented extremely heavy spells of rain during the onset phase of southwest monsoon 2015. The high intensity rainfall event was experienced during 20-25 June, 2015. Some stations recorded extremely heavy rainfall over Gujarat on 25 June. Daily accumulation of this high intensity rainfall events caused high number loss to life and huge loss to property in Gujarat during the period 20 to 26 June. Extremely heavy rainfall events are frequently occurred during the active phase of southwest monsoon over various parts of the country, but occasionally occurred on the onset phase over the monsoon covered area. Many a times, these events disrupt life and loss to properties, breach dams and bridges and causes flood conditions and severely affect population and economy. The major portion of rainfall activity over Gujarat state occurs mainly during the month of July and August due to active synoptic and sub-synoptic scale systems associated with monsoon. The state of Gujarat lies between 20°60' N and 24°42' N and 68°10' E to 74°28' E on the western coast of India having four physiographic four regions, namely, (i) coastal plain (ii) northern upland (iii) northwest desert-type region and (iv) north-south oriented northern parts of Western Ghat Hill ranges. The Girnar is the highest hill in the state (1,145 M). South Gujarat particularly Saurashtra has a unique topographical feature; it is surrounded by Arabian Sea in the south, Gulf of Kutch in the northwest and the eastern parts by Gulf of Khambhat.

The climatological records reveal that the highest one-day rainfall ever recorded in Gujarat was 990 mm at Dharampur (990 mm) on 2 July, 1941 followed by Navsari (780 mm) on 2 July 1991 respectively. During 20-26 June, 2015, the state of Gujarat experienced an unprecedented heavy rainfall episode. The highest rainfall during this period was recorded at Bagasra (636 mm) followed at Dhari (511 mm) and some other stations were recorded extremely heavy rainfall on 25 June, 2015. According to Dhar and Nandargi (1993), all the severe rainstorms that occurred over Gujarat during 1880 to 1990 happened only during monsoon season. The study carried out by Mohanty *et al.*, 2014 concludes that the frequency of heavy rainfall activity over Gujarat has increased significantly during the 2004-2013 due to increase in

cyclonic activity over Arabian Sea at the beginning and end of the monsoon season.

In the past, several studies (Desai *et al.*, 1998; Shyamla and Shinde, 1999; Francis and Gadgil, 2006; Kumar *et al.*, 2009; Litta *et al.*, 2007; Taraphdar *et al.*, 2009 and Rao and Ratna, 2010) reveal that the atmospheric conditions for extremely heavy rainfall (*i.e.*, 204.4 mm and more rainfall in past 24 hours) events over western and northwestern parts of India are not always similar; rather they vary from event to event and from place to place and depends on local topography and orographical features. Litta *et al.* (2007) suggested that the localized heavy rainfall which occurred over Santacruz (Mumbai) on 5 July, 2005 was possibly due to the subsidence of the mid-tropospheric meso-scale vortex super-imposed on the active monsoon conditions over the region. Shyamla and Shinde (1999) concluded that the cyclonic circulation over Saurashtra, south Gujarat region and adjoining northeast Arabian Sea at 925 and 850 hPa gives rise to widespread rainfall activity in north Konkan, south Gujarat and Saurashtra. Desai *et al.* (1998) found that very heavy to exceptionally heavy rainfall (*i.e.*, 204.4 mm and more in 24 hours and ever recorded rainfall) in northwest India particularly in the months of August and September occurred when the upper level westerly trough lay over the low-level easterly trough.

The cumulative rainfall of a spell during 24-25 June, 2015 is one of the ever recorded rainfall in a single spell over Gujarat state during the month of June, however, the occurrence of extremely heavy rainfall over the state is not very common during the month of June. The authors have chosen this event to investigate the synoptic and dynamical conditions of the atmosphere responsible the occurrence of the event. The relationship between the heavy rainfall process and large-scale circulations pattern and water vapor transport are investigated to further understand the mechanism of this event.

The synoptic situations and dynamic conditions that contributed to extremely heavy rainfall event are discussed based on surface and upper air synoptic data. The interplay of synoptic scale and meso-scale disturbances are analyzed by taking into consideration the remote sensing satellite and radar data and Numerical Weather Prediction (NWP) model outputs.

2. Synoptic features associated with the extremely heavy rainfall have been taken from weekly weather report published by India Meteorological Department.

TABLE 1

24-hour rainfall (mm) recorded at 0830 hours IST at various rain gauge stations over Saurashtra (Gujarat) during 21-26 June, 2015

District and name of rain gauge stations in Saurashtra (Gujarat)	Daily rainfall during 21-26 June, 2015					
	21	22	23	24	25	26
Sabarkantha (Khedbrahma)	14.0	92.0	0.0	0.0	189.0	0.0
Surat (Choryasi)	0.0	5.0	172.0	24.0	103.0	0.0
Surat (Kamrej)	0.0	3.0	141.0	36.0	106.0	0.0
Surat (Surat City)	0.0	31.3	103.2	51.5	177.0	0.0
Amreli (Bagasra)	0.0	13.0	4.0	24.0	636.0	0.0
Amreli (Dhari)	0.0	20.0	8.0	55.0	511.0	0.0
Amreli (Jafraabad)	7.0	6.0	98.0	132.0	112.0	0.0
Amreli (Khambha)	16.0	16.0	31.0	119.0	97.0	0.0
Amreli (Rajula)	28.0	60.0	65.0	192.0	81.0	0.0
Amreli (Savarkundla)	0.0	7.0	15.0	113.0	180.0	0.0
Amreli(Vadiya)	0.0	5.0	0.0	40.0	393.0	0.0
Bhavnagar (Bhavnagar)	0.0	27.4	38.8	61.6	137.4	0.0
Bhavnagar (Palitana)	0.0	5.0	41.0	94.0	251.0	0.0

Daily rainfall records during 20-26 June, 2015 at various stations of Gujarat have been collected from Meteorological Centre Ahmadabad. Station wise daily rainfall was collected and depicted on the map of Gujarat while cumulative rainfall for consecutive 6 days between 21 to 26 June and the same is represented in histogram. The synoptic scale and meso-scale disturbances are analyzed from the synoptic charts, Meteosat 7 Satellite wind and other derived parameters viz., vorticity, convergence and divergence etc. are obtained from (<http://tropic.ssec.wisc.edu/archive>). Infra-red (IR) and Cloud Top Brightness Temperature (CTBT) of INSAT-3D satellite have also been analysed for the detection of convection and its coverage area. National Centre for Environment Prediction (NCEP) re-analysis data (www.esrl.noaa.gov/psd/data/composites) have been utilized to find out various dynamical and thermodynamical parameters like convergence, divergence and vorticity etc. Numerical weather prediction models namely Global Forecasting System (GFS) and Weather Research and Forecasting (WRF) forecast output of pressure, wind, vorticity fields and rainfall etc have been also considered to diagnose the causes of extremely heavy rainfall event. Various graphs of rainfall versus weather parameters have been prepared for better understanding the causes of the high intensity rainfall.

3. *Synoptic situations and realized rainfall:* The advancement phase of southwest monsoon 2015 was marked by the formation of the cyclonic storm 'Ashobaa' over northeast Arabian Sea on 8 June, 2015. It moved

west-northwestwards towards Oman coast and weakened on 12 June over the Sea and a fresh low-pressure area developed over northeast Arabian Sea off Gujarat coast on 21 June. Later, it concentrated into a well marked low pressure area on 22 June and intensified into a depression over northeast and adjoining eastcentral Arabian Sea on 23 June and on the same day, it further intensified and moved over Saurashtra and neighborhood as a deep depression.

During the same period, an off-shore trough ran from Gujarat coast to north Kerala coast. Both systems contributed to enhance the pressure gradient and strong surface winds along west coast. Ultimately, it strengthened the monsoon current and moisture supply over to Gujarat. In conjunction to these synoptic features, a trough in mid-latitude westerlies ran roughly along Long. 65.0° E and Lat. to the north of 30.0° N on 22 June and along Long. 68.0° E with southern tip of trough extends upto Lat. 25.0° N at 500 hPa on 23 and 24 June, 2015. The ridge line at 200 hPa passed along Lat. 22.0° N on 23 and 24 June, enhanced divergence over the Gujarat area. The persistence and regular moisture incursion over in the Gujarat region also contribute in enhancement of rainfall intensity.

A wide area along the track of deep depression experienced heavy to very heavy rainfall at many places with extremely heavy falls at isolated places particularly in southwest sector of the system, indicating typical characteristics of a monsoon depression with rainfall

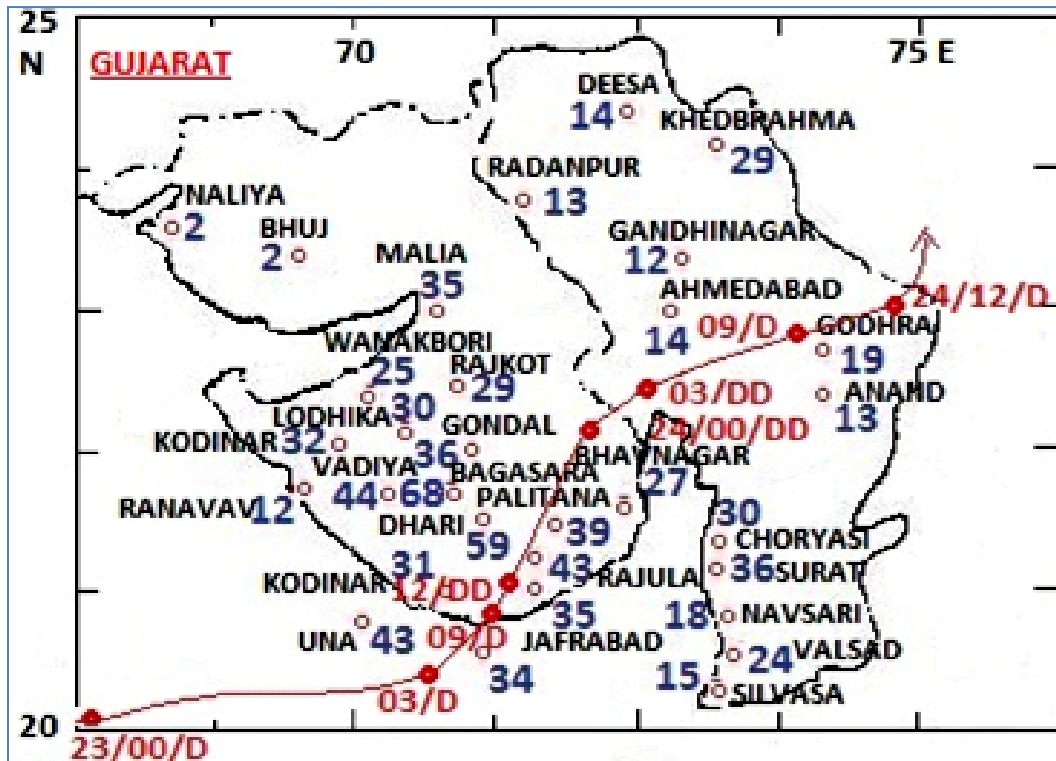


Fig. 1. Rain gauges station wise cumulative rainfall (cm) and track of the deep depression during 23-25 June, 2015

concentrating in the southwest quadrant where the maximum cloudiness, convergence and vorticity generally occurs. As a result of high wind confluence over northeast Arabian Sea and also there was the maximum low-level convergence and high vertical motion of moist air in the right forward quadrant of this low-pressure system. During this period, the low-pressure area shift from northeast Arabian Sea to Gujarat keeping most parts of Gujarat in the right forward quadrant of it. The system took about 15 hours to pass Amreli district from evening of 23 June to morning of 24 June, 2015. It moved northeastwards from the evening of 24 June and weakened into a depression over north Gujarat Region and it further weakened into a well-marked low-pressure area over West Madhya Pradesh and adjoining south Rajasthan.

The rainfall recorded at various stations during 21-26 June, 2015 over Saurashtra Gujarat is given in Table 1. The spatial distribution of rainfall over Gujarat recorded at 0830 hours IST on 21 June was light rain at isolated places and subsequently a gradual increase in rainfall intensity and spatial coverage were observed. On 23 June, moderate to heavy rainfall occurred at many places with very heavy at isolated places; moderate to heavy at many places with very heavy at isolated places on 24 June; peak rainfall activity was observed on 25 June. Heavy to very heavy rainfall at many places with extremely heavy falls at a few places were recorded with exceptionally heavy

rainfall at Bagasra (646 mm), Dhari (511 mm) and Vadiya (393 mm) in Amreli district. No rain was recorded on 26 June.

The daily cumulative rainfall during 21-26 June, 2015 at various stations along with the track of the deep depression presented in Fig. 1. Both Table 1 and Fig. 1 depicts that the higher values of daily and cumulative rainfall that was recorded during 21-26 June on the western side of the track of the deep depression. The cumulative rainfall during 21-26 June, 2015 and 24-hours rainfall (mm) recorded at 0830 hours IST on 24 June at various stations over Gujarat reveals that the higher values of both cumulative and 24-hour rain were recorded at Bagasra, Dhari and Vadiya. Cumulative rainfall (in mm) during 21-26 June and 24 hours rainfall recorded at 0830 hours on 24 June, 2015 at various station over Gujarat depict the intensity of rain on a day Fig. 2.

3.1. *Observed wind patterns:* The observed winds were in the order of 20-40 kts between 400 and 599 hPa on 21 and 22 June and 30-50 kts on 23 June. These winds weakened to 25-30 kts on 24 June and 20-25 kts on 25 June over south of the system centre. A western disturbance as a trough in mid-tropospheric westerlies was ran roughly along Long. 68.0° E and north southern tip extends upto Lat. 25.0° N at 500 hPa on 23 and 24 June, 2015. The highest wind speed at 700 hPa was 40 kts

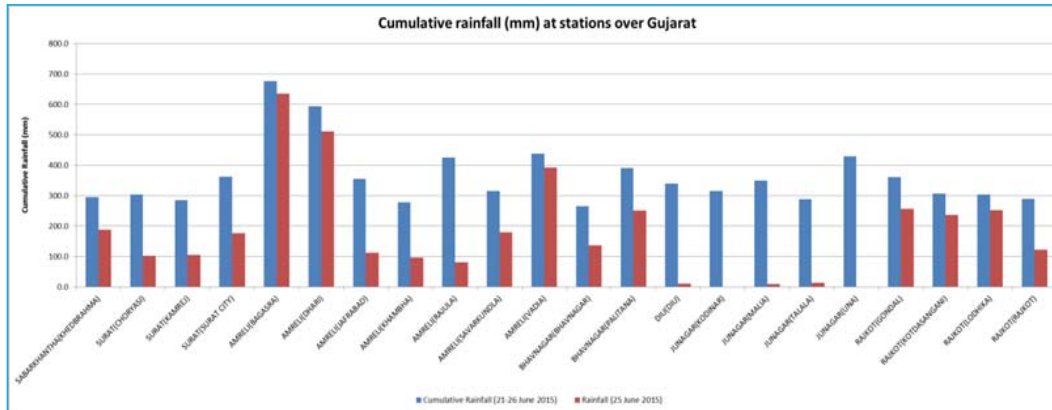


Fig. 2. Cumulative rainfall (mm) during 21-26 June, 2015 and 24 hours rainfall (mm) recorded at 0830 hours IST on 24 June at various stations over Gujarat

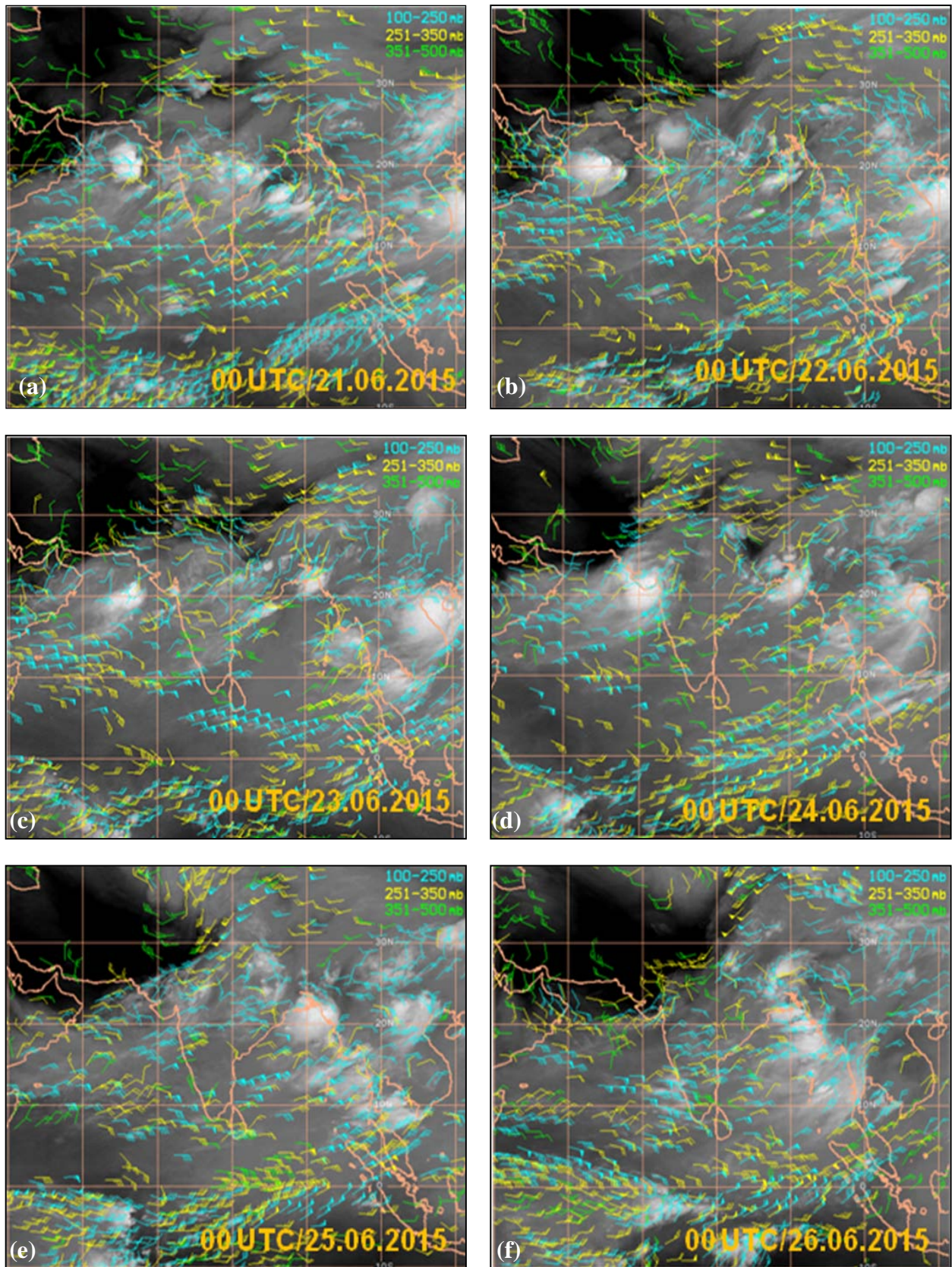
on 22 June and it decreased thereafter. It was 25 kts at 850 hPa and 23 kts at 700 hPa on 24 June and decreased thereafter in both levels. The wind speed between 400-599 hPa to the south of the system was in the order of 40-60 kts and north of the system (over north Pakistan and adjoining northwest Rajasthan) 60-80 kts on 25 June. It was 60-80 kts between 100-250 hPa during 21-23 June and 70-85 kts on 24 June over northeast Arabian sea [Fig. 3(a-f)]. Westerly/southwesterly winds with speed of the order of 30-40 kts at lower levels prevailed over northeast Arabian Sea in association with the deep depression over Gujarat and there was a strong anticyclonic wind over the same area at higher levels. Wind speed at 850 hPa was observed more than 15 kts and at 700 hPa more than 35 kts during 22-24 June at many stations over the region. Wind speed at 850 and 700 hPa was observed more than 15 and 35 kts respectively during 22-24 June, 2015 at many stations over the region.

3.2. Analysis of Satellite images and data: Satellite images from 0000 UTC to 1500 UTC of 24 June showed dense cloud mass with intense convection over south Gujarat. This intense cloud-mass persisted over Gujarat for about 15-18 hours on 24 June and this persistence of very intense convective clouds for a longer duration is one of the factors that contributed to realization of good amounts of rainfall over Gujarat. Observation of Satellite imageries of 0600 UTC during 23-26 June, 2015 Intense convective clouds spread in circular area over northeast Arabian Sea off Gujarat coast on 23 June and shifted towards northwest direction. INSAT 3 D satellite image indicates very intense convective clouds over Saurashtra particularly of Amreli district area of Gujarat [Figs. 4(a-f)]. The INSAT 3D TIR2 images at 0600 UTC indicate cloud top temperatures was from -53 to -83 °C over the same area of Gujarat state. On 25 June, the CTT of cloud mass increased indicating decrease in convection and cloud pattern also dis-organised over

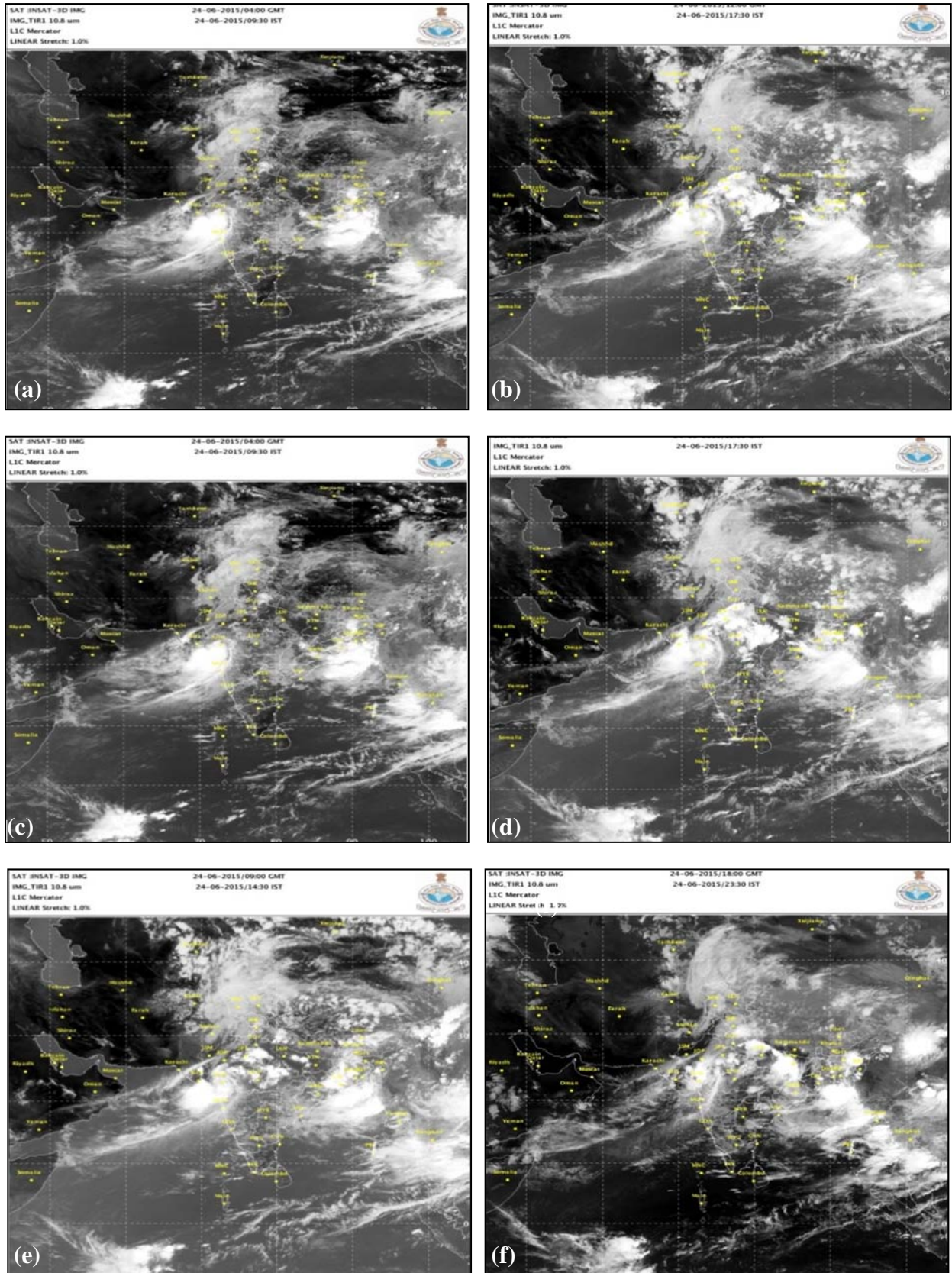
Gujarat region. The INSAT-3D (TIR1) imageries of 0400, 0600, 0900, 1200, 1500, 1800 UTC on 24 June showed that the large cloud mass observed over Amreli district area. Cloud imageris indicate that the cloud mass increased both horizontally and vertically and tilted slightly northeastwards.

Cloud top brightness temperature (CTBT) imageries during 21-26 June, 2015 reveal that dense cloud mass with circular shape and CTBT, about 190 °K around the system center and extend to central Arabian Sea to the south and to the north/northeast over to Pakistan and West Rajasthan on 21 June. The shape of dense cloud mass was elliptic and reduced the area of CTBT to 190 °K on 22 June. The cloud mass with CTBT 190 °K or less split into 4 cloud clusters and a cloud cluster again organized with CTBT less than 190 °K and moisture feeder bands also became more significant on 23 June. It was also observed that small cloud-cluster with CTBT 180 °K or less over West Madhya Pradesh and Gujarat region on 24 June evening of June. Major portion of the cloud-mass drifted over to western Himalayan region on 25 June. As the system weakened and pass away from Gujarat area, the state was almost cloud-free on 26 June.

3.3. Analysis of dynamic and physical parameters: There was a huge variability in the values of dynamic parameters from day to day over northeast Arabian Sea and Gujarat during 20-26 June, 2015. The relative vorticity varied from 50 to $210 \times 10^{-5} \text{S}^{-1}$ between 850-925 hPa; upper air divergence from 5 to $40 \times 10^{-5} \text{S}^{-1}$ between 150-300 hPa and lower level convergence from 10 to $45 \times 10^{-5} \text{S}^{-1}$ between 850-925 hPa levels, wind speeds from 17-25 kts at 850 hPa and 20-40 knots at 700 hPa and relative humidity from 65-100% (Table 1). However, higher values of vorticity ($200-210 \times 10^{-5} \text{S}^{-1}$), divergence ($35-40 \times 10^{-5} \text{S}^{-1}$), convergence ($30-40 \times 10^{-5} \text{S}^{-1}$), relative humidity (85-100 %) at 700 hPa were observed during



Figs. 3(a-f). Meteosat 7 winds (higher levels) at 0000 UTC on (a) 21 June (b) 22 June (c) 23 June (d) 24 June (e) 25 June and (f) 26 June, 2015



Figs. 4(a-f), Kalpana-1 IR images at 0400, 0600, 0900, 1200, 1500 and 1800 UTC of 24 June, 2015

TABLE 2

Date-wise values of weather parameters over northeast Arabian Sea and adjoining Saurashtra (Gujarat) during 20-26 June, 2015

Meteorological Parameters	20 June	21 June	22 June	23 June	24 June	25 June	26 June
Vorticity 850-925 hPa ($10^{-5} \times s^{-1}$)	110	150	200	210	200	150	50
Divergence 150-300 hPa ($10^{-5} \times s^{-1}$)	30	30	40	35	35	10	5
Convergence 850-925 hPa ($10^{-5} \times s^{-1}$)	15	25	30	40	45	15	10
Wind (850 hPa) kts	15	15	25	25	25	22	17
Wind (700 hPa) kts	35	35	40	40	35	25	20
R.H. % at 700 hPa	65	70	85	90	100	80	65

22-24 June, 2015 Table 2. On 24 June, highest values of lower level convergence ($30-45 \times 10^{-5} s^{-1}$), upper level divergence ($30-40 \times 10^{-5} s^{-1}$), relative humidity (70-100 %), relative vorticity ($150-200 \times 10^{-5} s^{-1}$) and Vertical wind shear (10-20 kts) between 850 and 200 hPa levels. Strong value of vertical wind velocity helped to develop intense convective clouds. Higher values of divergence to convergence contributed in intensification of the weather system. High relative humidity helped develop clouds and vorticity of more than $150 \times 10^{-5} s^{-1}$ enhanced heavy rainfall in general. It is observed that high values of relative humidity, convergence at lower level and vertical wind velocity coincided at the time of formation dense cumulus clouds and very intense convective clouds seen in satellite images over Amreli district from 23 to 24 June, indicating that the system was more active over south Gujarat area during the same period.

Higher convergence area located over northeast Arabian Sea with value $25-35 \times 10^{-5} s^{-1}$ on 21, 22 and 23 June and $30-45 \times 10^{-5} s^{-1}$ over Gujarat and adjoining areas of northeast Arabian on 24 June between 850-925 hPa. Thereafter, it decreased rapidly to $10-15 \times 10^{-5} s^{-1}$ on 25 and 26 June. It is seen that on 24 June, there was highest convergence over Gujarat which resulted in copious amounts of rain. The higher divergence area was located over northeast Arabian Sea $20-30 \times 10^{-5} s^{-1}$ on 21 June; $30-40 \times 10^{-5} s^{-1}$ on 22 June; $15-20 \times 10^{-5} s^{-1}$ on 23 and 24 June respectively. It was seen between $20-35 \times 10^{-5} s^{-1}$ over Gujarat and adjoining areas of northeast Arabian on 25 June thereafter, it decreased rapidly to $5 \times 10^{-5} s^{-1}$ over a smaller area of Gujarat on 26 June, 2015.

3.4. Rainfall, divergence and convergence: The values of convergence between 850-925 hPa were $15 \times 10^{-5} s^{-1}$, $25 \times 10^{-5} s^{-1}$, $30 \times 10^{-5} s^{-1}$, $40 \times 10^{-5} s^{-1}$ and $45 \times 10^{-5} s^{-1}$ on 20, 21, 22, 23 and 24 June respectively (Table 2). Thereafter, these values suddenly decreased to $15 \times 10^{-5} s^{-1}$ and $10 \times 10^{-5} s^{-1}$ respectively on 25 and 26 June. Divergence between 300-150 hPa was $30 \times 10^{-5} s^{-1}$,

$30 \times 10^{-5} s^{-1}$, $40 \times 10^{-5} s^{-1}$, $35 \times 10^{-5} s^{-1}$ and $35 \times 10^{-5} s^{-1}$ on 20, 21, 22, 23 and 24 June respectively (Table 2). Thereafter, these values suddenly decreased to $10 \times 10^{-5} s^{-1}$ and $5 \times 10^{-5} s^{-1}$ respectively on 25 and 26 June. It indicates that increased convergence & divergence coincided with increased amount of rain and *vice versa*.

3.5. Rainfall and vorticity: Vorticity over northeast Arabian and Gujarat were observed $110-150 \times 10^{-5} s^{-1}$ on 20 and 21 June and $200-210 \times 10^{-5} s^{-1}$ on 23 and 24 June at 700 hPa, thereafter, rapidly decreased to $100 \times 10^{-5} s^{-1}$ during 25-26 June. It reveals that an increase in rainfall is associated with an increase in the vorticity during 22-24 June, 2015. Thereafter, a sharp decrease in rainfall is observed with fall in vorticity values.

3.6. Rainfall and relative humidity: The relative humidity was 62-82% at 700 hPa on 20 and 21 June and 62-100% on 22 and 24 June. Thereafter, it rapidly decreased to 62% during 24-26 June. It was observed that the higher relative humidity values on 23 and 24 June that contribute a large to good quantity of rainfall on 23 and 24 June, 2015. Thereafter, relative humidity decreased and the rain ceased. It indicates that the higher relative humidity, the higher possibility of intense rain.

4. The present study reveals the main causes of exceptionally heavy rainfall spell over Saurashtra (Gujarat) are as follows:

(i) The strong southwesterly flow in lower levels over northeast Arabian Sea, which was converging over Saurashtra, transport the large amount of moisture from Arabian Sea over to Saurashtra area.

(ii) Co-occurrence of high relative humidity, lower level convergence, upper level divergence, high vorticity in lower levels and high vertical wind velocity over Amreli district area persisted mainly between 23-25 June, 2015. Moisture flux was higher between 20-25 June with a peak value of 300 g/kg on 24 June, 2015.

(iii) The sluggish movement of the system from the Arabian Sea for a considerable period contributed in exceptionally heavy rainfall over the district of Amreli. The system moved almost north-northeasterly direction from 0000 to 0900 UTC of 24 June keeping the affected area to the west and the southwest of the system, resulting in the zone of heaviest rainfall in the southwest quadrant of the system. This is in conformity to the earlier studies which established that the zone of maximum rainfall in the southwest quadrant of a monsoon depression.

(iv) Specific topographical features of Bagasra and Dahri and their location *vis-a-vis* the moisture sources in its proximity *viz.*, Arabian Sea, Gulf of Kutch and Gulf of Khambhat contribute in exceptionally heavy rainfall.

(v) The higher negative CTT and CTBT indicated that the very intense cloud mass with high vertical extension lay over the region for a long duration also contributed to this heavy rainfall event.

5. The authors are thankful to Director General of Meteorology for his constant encouragements to carry out the present case study. Authors sincerely thanks to all divisions of India Meteorological Department and other agencies like NOAA and CIMSS for using their products to carry out this study. Authors also thanks to National Disaster Management Authority encouraging the such study of heavy rainfall events.

The contents and views expressed in this letter are the views of the authors and do not necessarily reflect the views of the organizations they belong to.

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(Received 24 March 2017, Accepted 8 March 2019)

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