MAUSAM, **71**, 3 (July 2020), 513-522

L E T T E R S

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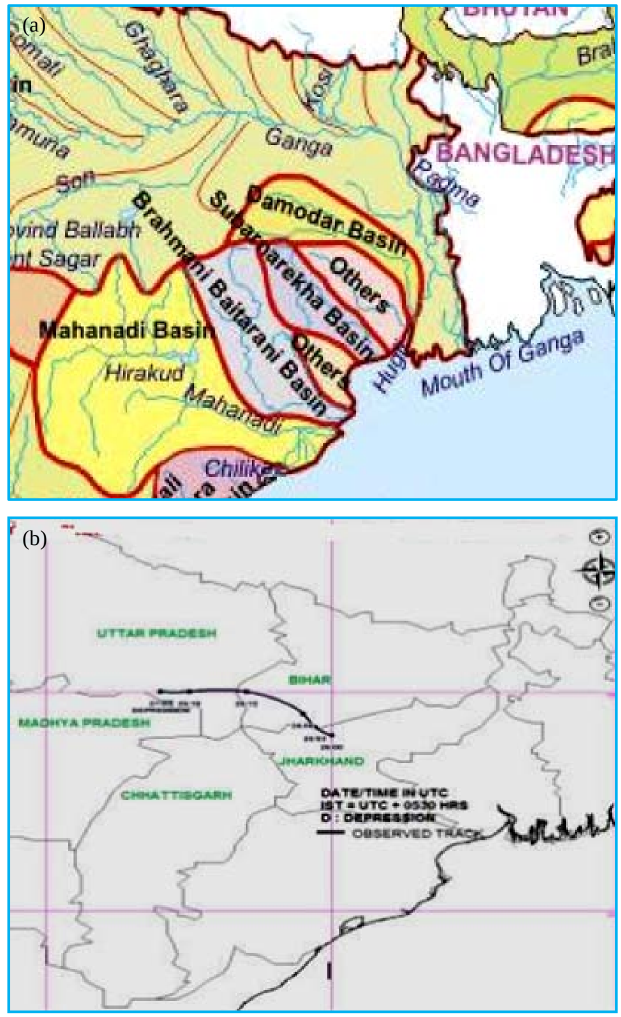
DIAGNOSTIC ANALYSIS OF CATASTROPHIC FLOOD OVER EASTERN INDIA IN JULY 2017 - A CASE STUDY

1. Floods are very common in eastern India during southwest monsoon season. It brings a lot of misery to the people of this region. Every year eastern Indian states namely West Bengal, Odisha and Bihar witness such types of flood during monsoon period. Major river basins in eastern India are Ganga river basin in Bihar and West Bengal area, Odisha has three river basins namely Mahanadi, Subarnarekha, Brahmani and Baitarani [Fig. 1(a)]. As majority of tributary rivers of Ganga passing through Bihar and West Bengal; these two states are more prone to massive flood during monsoon season. The abnormal occurrence of rainfall generally causes floods. It occurs when surface runoff exceeds the capacity of natural drainage. The heavy rainfall is frequently occurring event over the area during South-West Monsoon (SWM) every year. The geographical location of the area, orography and its interaction with the basic monsoon flow is considered as one of prime factors of these heavy rainfall activities. Synoptically, the latitudinal oscillation of eastern end of the Monsoon Trough and the synoptic disturbances formed or passing over the eastern India region and / or its neighbourhood that brings moisture laden Easterly or South-Easterly winds over the area are the main causes responsible for heavy rainfall in this area.

The Eastern Parts of India receives 84% of its annual rainfall (more than 1000 mm) during South-West Monsoon (SWM), which is its principal rainy season. The variability of the monsoon makes the region highly vulnerable by the impacts of natural disasters such as droughts and floods. Singh *et al.* (2014) found that the monsoon variability has amplified in the recent decades with a gradual decline in the monsoon circulation and rainfall and at the same time, a phenomenal rise in extreme rainfall events over South Asian Sub continent. The extreme events are on the rise at a rate of about 13 events per decade (more than one per year). Roxy *et al*., 2017 found the frequency of extreme rain events not only increasing, but the extremes themselves are intensifying over time. Guhathakurta *et al*. (2011) have studied about impact of climate change on extreme rainfall events and flood risk in India. They found in their study that frequency of heavy rainfall events are decreasing in major parts of central and north India while they are increasing in peninsular, east and north east India.



Figs. 1(a&b). (a) River basins in Eastern India and (b) Track of land Depression

Wang *et al.* (2006) suggested an overall weakening of the global land monsoon precipitation in the last 56 years, primarily due to weakening of the summer monsoon rainfall in the Northern Hemisphere. Mohan *et al.* (2017) found statistically significant (95% level) increase in hydroclimatic intensity index during the period of 1951-2010, which is mainly caused due to significant increase in precipitation intensity. Akinsanola *et al*. (2016) studied atmospheric conditions for heavy rainfall event during September, 2012 over Nigeria and found that strong moisture convergence (divergence) in the lower (middle) and well organized African Easterly Jet (AEJ) in 700 hPa responsible for occurrence of extremely heavy rainfall over study area.

Jadhav *et al*. (2009) studied about the frequency and duration of Low pressure systems (LPS) during the monsoon season and found that the total frequency of LPS has neither increased nor decreased significantly but the duration of LPS has significantly increased. They suggested that the (LPS) can trigger intense rainfall events in the vicinity of the path of the low, or they may cover a large region and persist for a long time period, which results in the release of a large amount of precipitation over a greater area. Generally, during active phase of SWM, the main factors that cause heavy rainfall over the region are (*i*) Formation of Low pressure/ Depression/ Deep Depression (*ii*) Upper air cyclonic circulation over land/Bay of Bengal and adjoining areas, (*iii*) Active monsoon trough over the region may cause heavy rainfall. Generally, these synoptic systems move west north-westward towards monsoon axis during SWM season. Most of the flood in Odisha & West Bengal are associated with passage of monsoon depression over this area. The structure, track and movement of monsoon depressions and associated rainfall patterns have been studied and reviewed in detail (Sikka, 1977 and Pant and Kolli, 1997)

July 2017 witness heavy to very heavy rainfall with extremely heavy rainfall over Gangetic West Bengal (GWB) and Jharkhand (23-26 July, 2017) leading to massive flood in GWB and parts of Jharkhand. This massive flood caused immense loss to life and property over the area of Gangetic West Bengal, South Orissa, Jharkhand and SE Chhattisgarh during July 2017. This study diagnostically evaluate the atmospheric conditions that led to the extremely heavy to very heavy rainfall spell over Eastern parts of India during 21-27 July, 2017 in SW Monsoon season leading to massive flood. Mainly synoptic scale situation, moisture flux convergence (MFC), wind pattern and absolute vorticity has been analysed and discussed.

2. There was a flood report over parts of West Bengal and Jharkhand during 23-31 July 2018. Ten districts of GWB namely Howrah, Hooghly, South 24 Parganas, East & West Midnapore, Bankura, Burdwan, Birbhum, Murshidabad and Nadia has been severely affected. As per media report 96 people lost their life in these districts. As many as 22 lakh people affected 60 thousand hauses damaged completely and more than 2 lakh hectare of agriculture farm affected. Whereas 12 districts of Jharkhand (Ranchi, East Singhbhum, West Singhbhum, Sarikela Kharsawan, Khunti, Ramgarh, Bokaro, Dhanbad, Hazaribagh, Chatra, Latehar, Lohardaga) were affected adversely. There was a report of loss of life (16 Nos.) along with 10 lakh people directly affected and 1.5 lakh hectare agriculture land damage. Eight teams from India's National Disaster Response Force (NDRF) were deployed on 27 July to provide assistance to the state authority in rehabilitation and evacuation of flood affected people. Five further teams from NDRF were later deployed to flood-hit areas, including three teams to Kolkata.

3. The spatial and temporal pattern of precipitation has been investigated using daily rainfall data of India Meteorological Department. Daily station wise rainfall data has been collected from Meteorological Centre Ranchi, Bhubaneswar, Bhopal, Lucknow, Patna and Regional Meteorological Centre Kolkata for the study period. Synoptic analysis of the system is carried out by the surface and upper air chart generated through Synergie workstation of India Meteorological Department, Kolkata.

NCEP reanalysis data of wind, surface pressure and specific humidity has been used for the computation of dynamical parameter vertical integrated moisture flux convergence. The pressure level data obtained at six-hour intervals : 0000, 0600, 1200 and 2400 UTC. The spatial resolution for this study was 2.5 × 2.5 degrees latitude and longitude, on a global scale with eight pressure levels corresponding to 1000, 925, 850, 700, 600, 500, 400 and 300 hPa in the vertical. Vertical Integrated Moisture Flux convergence from surface to 300 hPa was calculated with the help of GrADS for the study area on daily basis.

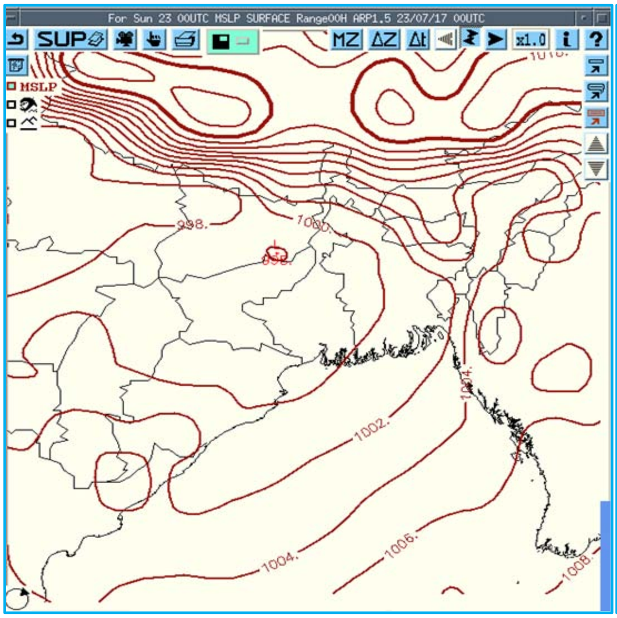
The expression for Moisture Flux Convergence (MFC) arises from the conservation of water vapor in pressure (*p*) coordinates:

$$\frac{dq}{dt} = S \qquad (1)$$

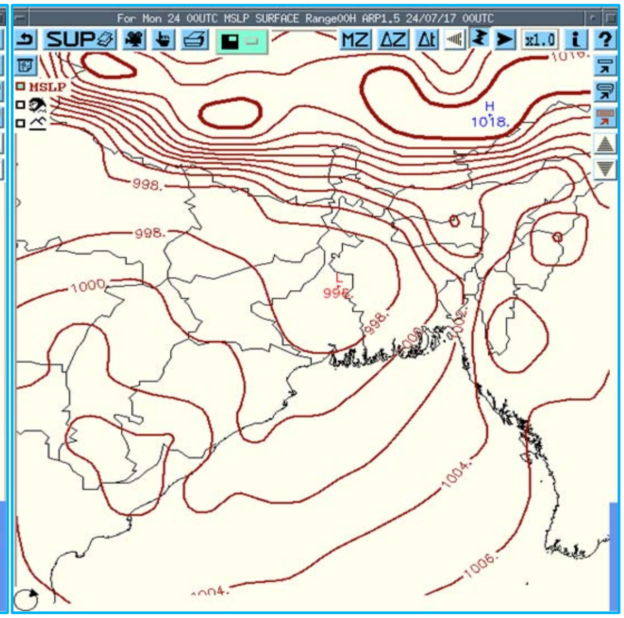
where,

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial p'}$$

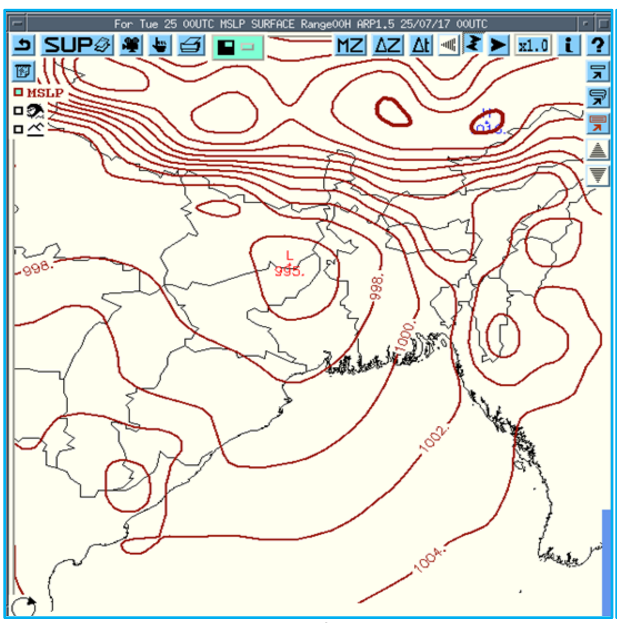
u, *v* and *w* represents the standard three-dimensional wind components in pressure coordinates and *q* is the specific humidity : *S* represents the storage of water vapor, which is the difference between the sources and sinks of water vapor following an air parcel. *S* typically takes the form *E* – *C*, where *E* is the evaporation rate into the air parcel and *C* is the condensation rate into the air parcel. Many studies that employ (1) make the assumption that all the condensed water immediately precipitates out (*P*), so that *S* = *E* – *P* (Palmén and Holopainen, 1962). Using the continuity equation, $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial p} = 0$, Equation (1)



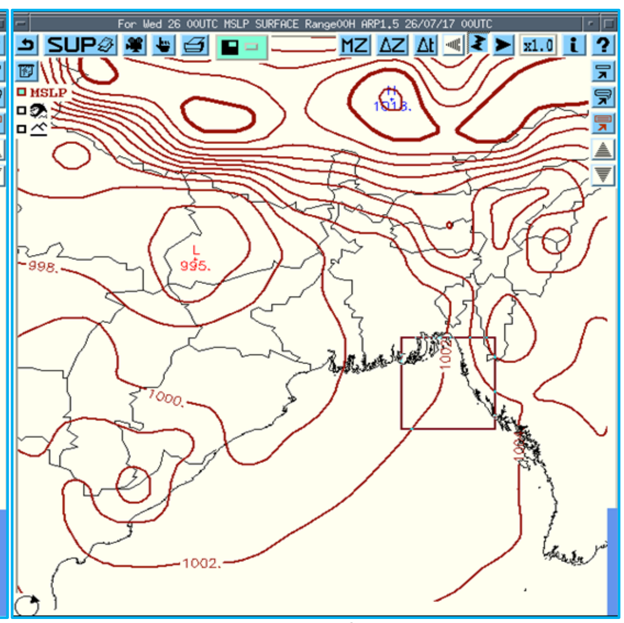
(a) MSLP on 23rd July, 2017



(b) MSLP on 24th July, 2017



(c) MSLP on 25th July, 2017



(d) MSLP on 26th July, 2017

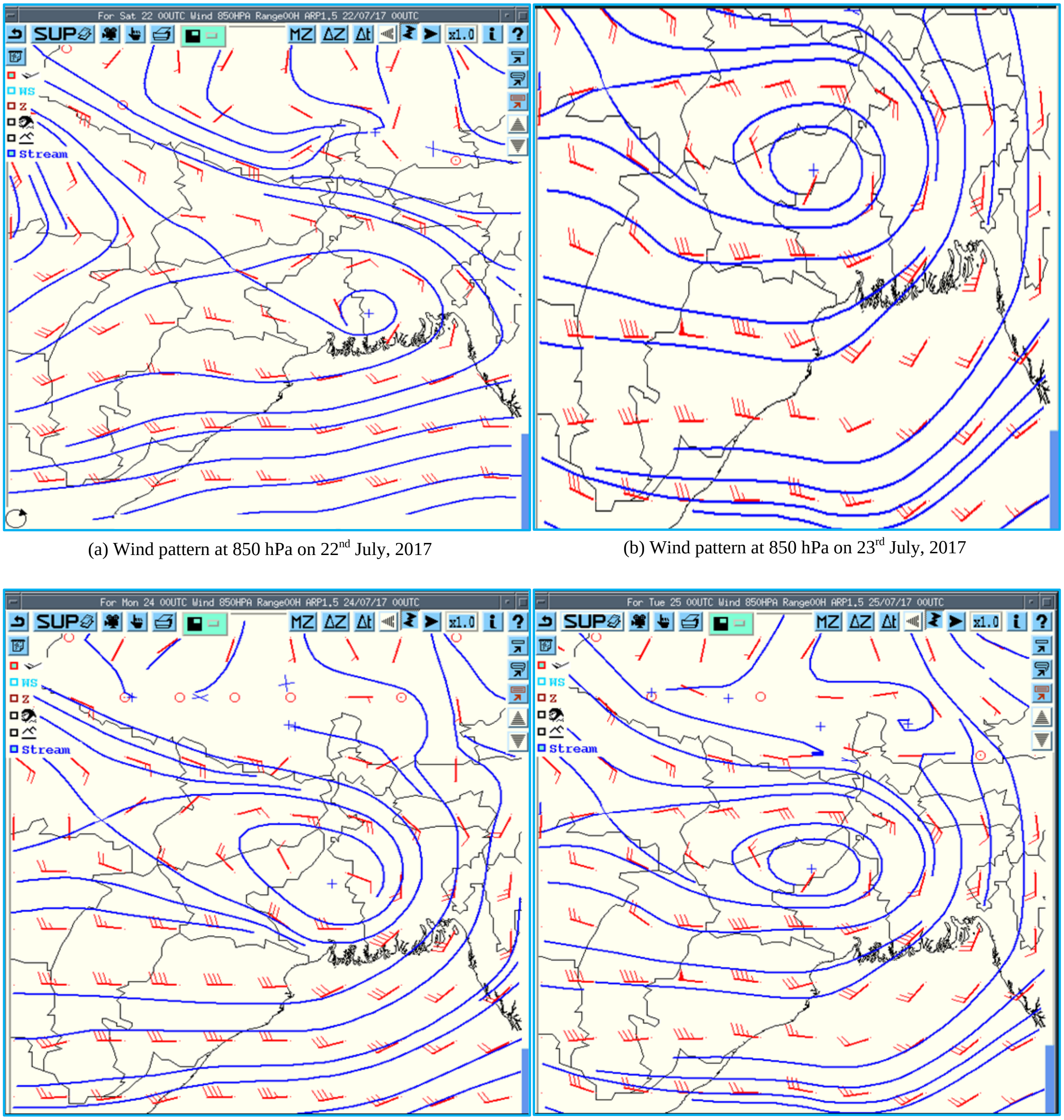
Figs. 2 (a-d). Mean Sea Level Pressure at 0300 UTC during 23-26 July, 2017

can be extended and rewritten in flux form, which conserves the total mass of moisture:

$$\frac{\partial q}{\partial t}+u\frac{\partial q}{\partial x}+v\frac{\partial q}{\partial y}+w\frac{\partial q}{\partial p}+q\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial p}\right)=E-P \qquad (2)$$

$$\frac{\partial q}{\partial t}+\nabla.(qV_h)+\frac{\partial}{\partial p}(qw)=E-P \qquad (3)$$

$\nabla = \hat{\imath}\frac{\partial}{\partial x}+\hat{\jmath}\frac{\partial}{\partial y}$ and $V_h = (u, v)$. Specifically equation (3) expresses the moisture budget for an air parcel,



(a) Wind pattern at 850 hPa on 22nd July, 2017

(b) Wind pattern at 850 hPa on 23rd July, 2017

(c) Wind pattern at 850 hPa on 24th July, 2017

(d) Wind pattern at 850 hPa on 25th July, 2017

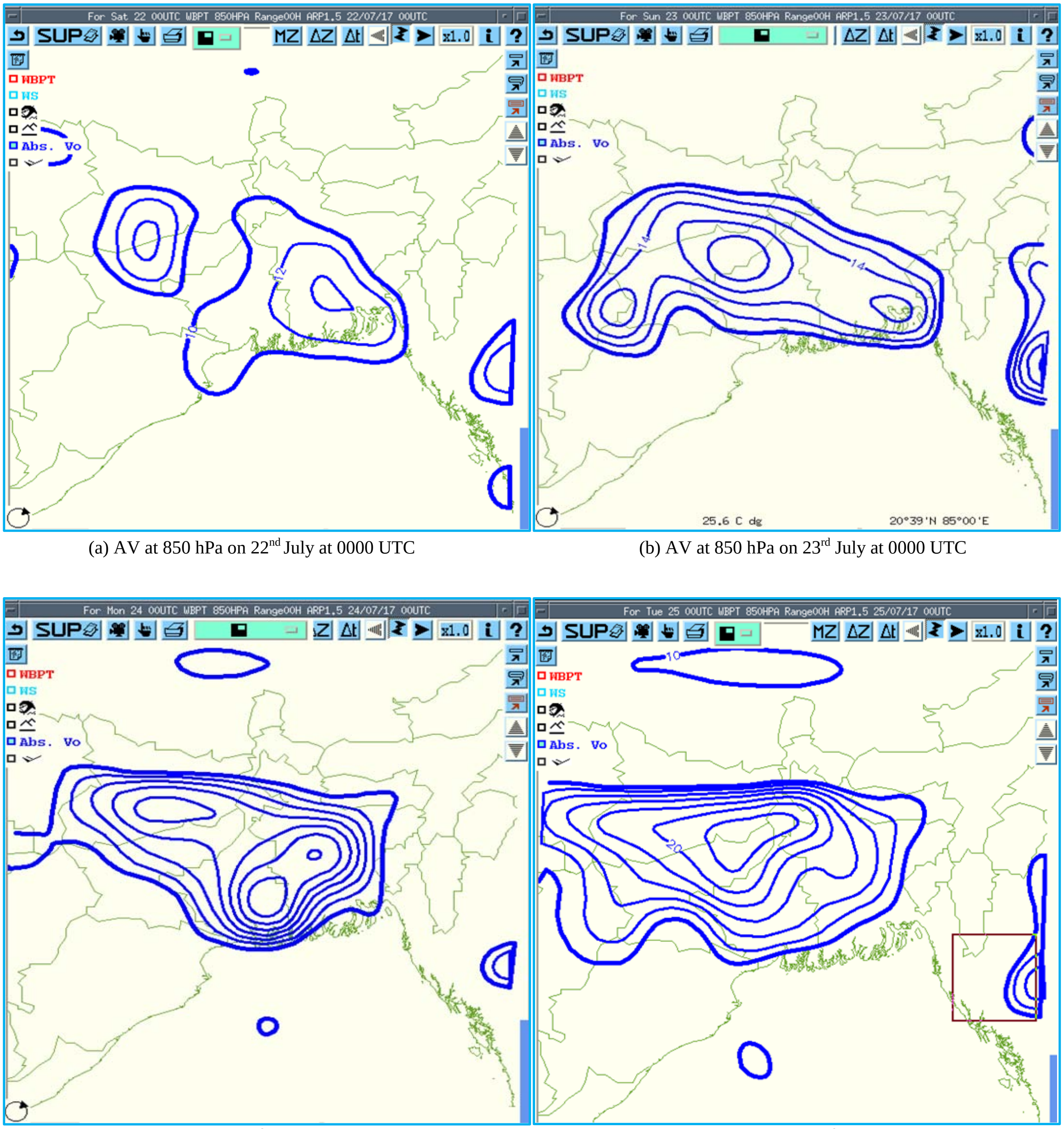
Figs. 3 (a-d). Cyclonic Circulation at 850 hPa level during 22-25, July, 2017

where the terms consist of the local rate of change of q, horizontal moisture flux divergence (the negative of horizontal lMFC), the negative of vertical moisture flux convergence and source and sink terms of moisture (specifically, evaporation and precipitation rates). By vector identity, horizontal MFC can be written as :

$$\mathrm{MFC} = -\nabla.(qV_h) = -V_h.\nabla q - q\nabla.V_h \qquad (4)$$

$$\mathrm{MFC} = -\left(u\frac{\partial q}{\partial x} + v\frac{\partial q}{\partial y}\right) - q\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \qquad (5)$$

In (5), first term is advection term represents the horizontal advection of specific humidity. The second term represents the convergence term denotes the product of the specific humidity and horizontal mass convergence (Banacos *et al*., 2005).



(a) AV at 850 hPa on 22nd July at 0000 UTC

(b) AV at 850 hPa on 23rd July at 0000 UTC

(c) AV at 850 hPa on 24th July at 0000 UTC

(d) AV at 850 hPa on 25th July at 0000 UTC

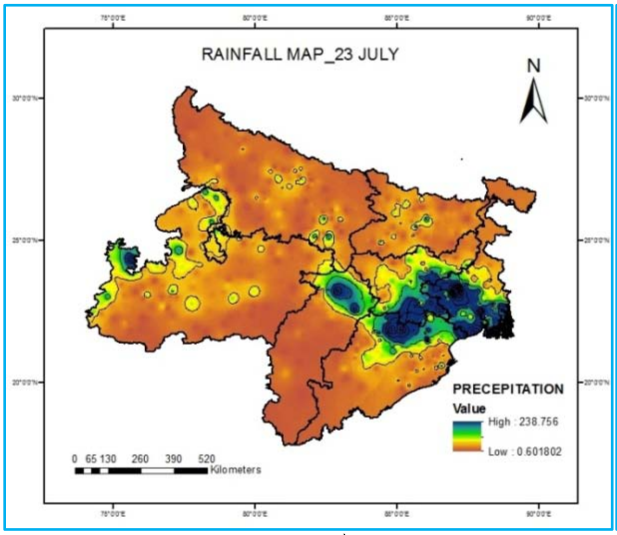
Figs. 4 (a-d). Absolute Vorticity (AV) at 850 hPa during 22-25 July, 2017

The microscopic measure of rotation in a fluid is a vector field and the curl of velocity is known as vorticity. The relative vorticity ζ is the curl of the relative velocity. In large-scale dynamic meteorology, the vertical component of the relative vorticity is:

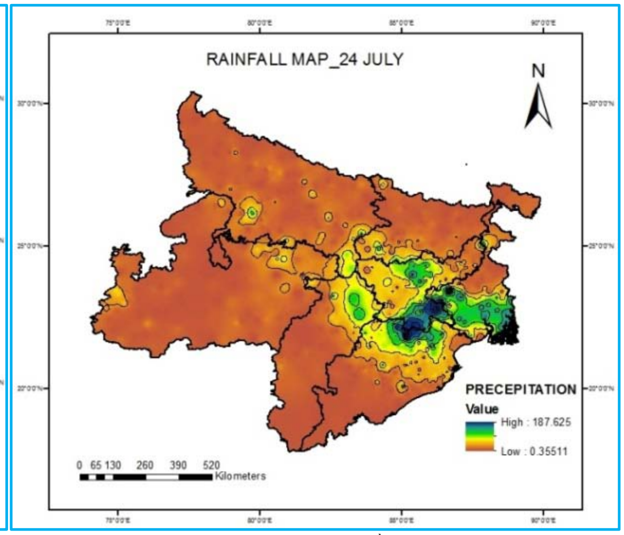
$$\zeta = k.(\nabla \times U) \quad (6)$$

Regions of positive vorticity are associated with cyclonic circulation and regions of negative vorticity are associated with anticyclone in the Northern Hemisphere. The sum of relative vorticity and Coriolis parameter is known as absolute vorticity (J. Holton, Dynamic Meteorology).

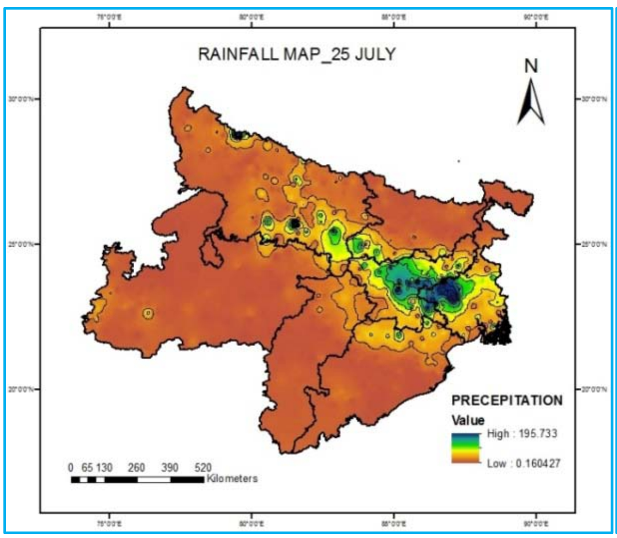
4. Major synoptic situation associated with massive flood over area of GWB and Jharkhand during



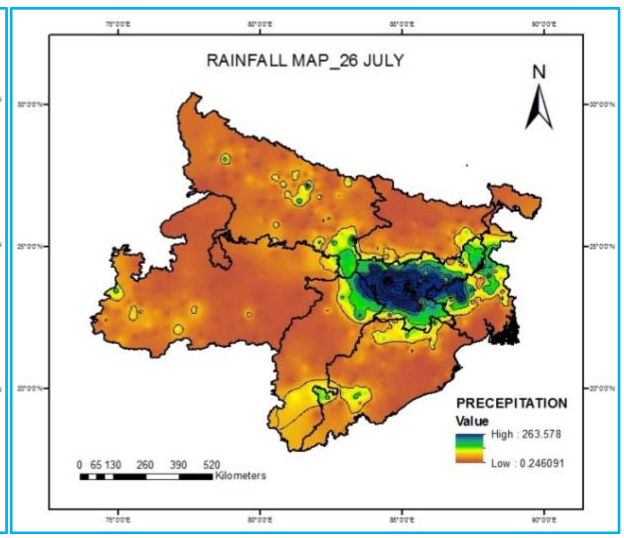
(a) Rainfall distribution on 23rd July at 0000 UTC



(b) Rainfall distribution on 24th July at 0000 UTC



(c) Rainfall distribution on 25th July at 0000 UTC

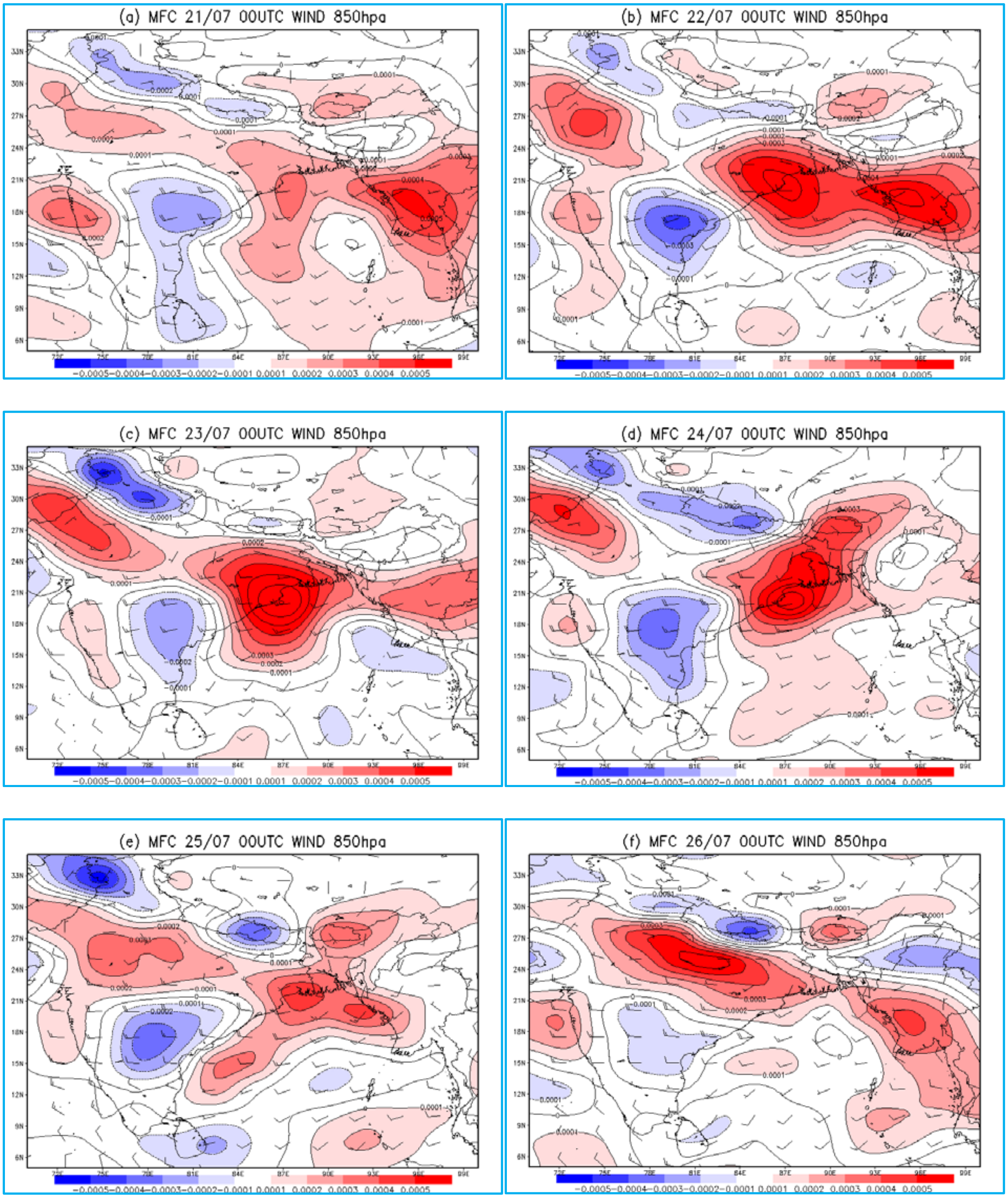


(d) Rainfall distribution on 26th July at 0000 UTC

Figs. 5(a-d). Daily Rainfall distributions (mm) during 23-26 July, 2017

21-31 July, 2017 is depicted in Fig. 1(b) and Figs. 2(a-d). Fig. 1(b) represent the track of depression over the region whereas Figs. 2(a-d) shows the Mean sea level pressure (MSLP) pattern during 23-26 July, 2017 and Figs. 3(a-d) represent lower level wind associated with depression. This flood was associated with the formation of a low pressure area (LOW) over GWB on 23rd July, 2017. This LOW was first observed as an upper air cyclonic circulation over South Bangladesh and adjoining areas of GWB & North Bay of Bengal with vertical extension upto 7.6 km above mean sea level (amsl) on 22nd July. Subsequently, the system moved over GWB and neighborhood on 23rd July. The system became well marked low pressure area (WML) and lay centered at same region with associated upper air circulation extended upto 9.5 km amsl on 24-25 July. It further intensified into a depression on 26th morning over northwest Jharkhand and neighborhood and weakens into WML on 27th & moved westward to eastern Uttar Pradesh [Fig. 1(b)]. The slow movement of the system and rapidly intensification over Jharkhand/GWB region leads to the heavy to very heavy rainfall along with extremely heavy rainfall over GWB and Jharkhand region caused massive flood in the districts of GWB and Jharkhand during 23-31 July, 2017.

4.1. Wind pattern at 850 hPa during 22-25 July, 2017 represented in Figs. 3(a-d). It revealed an upper air



Figs. 6(a-f). Vertical Integrated Moisture Flux Convergence (gmkg^{-1} sec^{-1}) from surface to 300 hPa during 21-26 July, 2017 and wind at 850 hPa at 0000 UTC

cyclonic circulation over south Bangladesh, adjoining Gangetic West Bengal and adjoining NW Bay of Bengal on 22nd July at 0000 UTC. The maximum wind speed upto 30 knots observed in the south west sector of circulation. Subsequently, the circulation moved slightly north westward over Gangetic West Bengal and adjoining NE Jharkhand on 23rd July. And maximum wind speed increased from 30 knots to 50 knots in the SW sector of

TABLE 1

Highest maximum rainfall observed in a day during 23-27 July, 2017

Date	State	Station	District	Rainfall (mm)	Lat.	Long.
23rd July	West Bengal	Bankura	Bankura	274	2313	8704
24th July	Jharkhand	Jamshedpur MO	Jamshedpur	227	2249	8611
25th July	West Bengal	Bankura	Bankura	226.3	2313	8704
26th July	Jharkhand	Latehar	Latehar	268.8	2345	8430
27th July	Jharkhand	Raidih	Gumla	154	2257	8426

the system. The cyclonic circulation intensified as well marked low pressure area on 24th July and laid centered at same region during 24-25 July. Due to the presence of strong South Westerly winds over NW Bay of Bengal, huge moisture incursion was taking place over the region. As the highest wind speed was observed in the SW sector of the system, so heaviest rainfall area was concentrated in this sector.

4.2. Inverse distance weighted interpolation (IDWI) method was applied for contour map plotting of rainfall over the region. Daily Rainfall distributions during the study period are shown in Figs. 5(a-d). Heavy to very heavy rainfall realized over South-Eastern parts of Jharkhand and adjoining areas of West Bengal and Odisha during 23-24 July. In association with intensification of the system, the heavy rainfall area extended west-north-westward over many parts of Jharkhand, Few parts of West Bengal and eastern parts of East Uttar Pradesh on 25th July and persisted over Jharkhand subsequently on 26th July. Highest rainfalls observed in 24 hours between 23 and 27 July are mentioned in Table 1.

Due to physiographic location and orientation of river basins, most of the rainfall over Jharkhand is ultimately run off to GWB. As a result massive flood observed over districts of Bankura, Birbhum, East and West Burdwan, Hooghly, Howrah, Murshidabad, Nadia, South-24 Paraganas and East & West Midnapore. Again, presence of Damodar Valley Corporation (DVC) over Jharkhand and GWB area and release of water from their dam during this period also contribute significantly to the massive flood over these districts of GWB leading to a lot of loss of life and property

4.3. The absolute vorticity at 850 hPa during the study period at 0000 UTC of each day are represented in Figs. 4 (a-d). In association with a cyclonic circulation, a positive vorticity upto 14×10^{-6} sec^{-1} was observed over South Bangladesh, adjoining Gangetic West Bengal and adjoining Jharkhand on 22nd July [Fig. 4(a)]. The positive vorticity further intensified and moved slightly moved West-North-Ward on 23rd July. The strong positive vorticity upto the range of 20×10^{-6} sec^{-1} persisted over the same region during 24-25 July.

4.4. The daily average vertically integrated moisture fluxes convergence of *u* and *v* components at 0000 UTC for the study period are shown in Figs. 6(a-f). The results show that moisture flux convergence starts appear from the east of the study area towards Eastern Bangladesh, one day prior to the occurrence of extreme rainfall event. The positive MFC up to the range of 40×10^{-5} $gmkg^{-1}$ sec^{-1} was developed on 21st July at 0000 UTC. Subsequently, the strong MIFC zone intensified from 40 to 50×10^{-5} $gmkg^{-1}$ sec^{-1} and moved westward laid over South Jharkhand, North Odisha and adjoining West Bengal on 22nd July. The strong IMFC zone persisted over the same region for three consecutive days from 22nd to 24th July with almost same intensity implying strong upward motion of convectively unstable moist air over majority of the study area. The slow movement and intensification of the system leads to the extremely heavy rainfall over study area. However, it moved further WNW ward towards the monsoon axis on 25th July.

5. The catastrophic Flood occurred over eastern parts of India in July, 2017 due to the formation of low/depression over GWB and adjoining area and its slow movement along monsoon trough. The low pressure system caused widespread rainfall with spells of heavy to very heavy rainfall along with extremely heavy rainfall over district of GWB and Jharkhand leading to massive flood over GWB**.** Moisture flux convergence starts appear from the east of the study area, one day prior to the occurrence of extreme rainfall event. Strong positive MFC up to the range of $40\text{-}50 \times 10^{-5}$ $gmkg^{-1}sec^{-1}$ was developed over South Jharkhand, North Odisha and adjoining West Bengal and persisted over the same region for about four consecutive days with almost same intensity implying strong upward motion of convectively unstable moist air over majority of the study area. Strong positive vorticity

upto the range of 20×10^{-6} sec^{-1} developed and persisted over the same region leads to the extremely heavy rainfall. Due to physiographic location and orientation of river basins, most of the rainfall over Jharkhand is ultimately run off to GWB leading to massive floods over Gangetic West Bengal.

The authors are grateful to Dr. K. J. Ramesh, Director General of Meteorology, India Meteorological Department for continuously encourage and his support. Authors express their sincere thanks to all staff members and officers of Meteorological Centre Ranchi & RMC Kolkata for their kind and sincere assistance in preparing this paper. The authors are also grateful to Dr. Sanjib Bandyopadhyay, DDGM, RMC Kolkata for valuable guidance and support.

The contents and views expressed in this research paper are the views of the authors and do not necessarily reflects the views of the organizations they belong to.

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Annexure1

Damage due to the Flood during 23 -31 July, 2017

State : West Bengal

As per media report disaster and causalities caused by flood in the state of West Bengal as follows :

Affected areas due to flood : Districts - 10 Nos. (Howrah, Hooghly, South 24 Parganas, East & West Midnapore, Bankura, Burdwan, Birbhum, Murshidabad and Nadia).

(a) Houses damaged: Completely/partially	:	60000 Nos.
(b) Affected Farm land	:	202957 Hectare
(c) No of people affected	:	22 Lakhs
(d) Human death toll	:	46 Nos.
(e) Death of animal	:	590 Nos.

State : Jharkhand

Affected areas due to flood : Districts - 18 Nos. (Ranchi, East Singhbhum, West Singhbhum, Sarikela Kharsawan, Khunti, Ramgarh, Bokaro, Dhanbad, Hazaribagh, Chatra, Latehar, Lohardaga…..)

(a) Houses damaged	:	Completely/partially
(b) Affected Farm land	:	150000 Hectare
(c) No. of people affected	:	10 Lakhs
(d) Human death toll	:	16 Nos.
(e) Death of animal	:	200 Nos.