Understanding Large Scale Characteristics Corresponding to Heavy Rainfall Events over Indian Subcontinent

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ABSTRACT

There is an intensive need to study the dynamics of the heavy rainfall events as the intensity and frequency of such events have increased over Indian subcontinent in a warming scenario. Large scale synoptic signatures of such local events help in differentiating between heavy rain and normal rain events and hence it is beneficial to look upon these events from a large scale flow perspective. In this study, three case studies have been taken into consideration i.e. Gujarat (29th June-2nd July 2005), Maharashtra (26th -27th July, 29th July-2nd August 2005) and Ratnagiri (30th May-1st June 2006).

Key Words: *Heavy rainfall, Large scale circulation, Teleconnections, Anomalous flow.*

1. Introduction

Heavy rainfall and flash floods create havoc and disaster all over the world. Whether it is Asia, Europe, East or West, this form of severe weather has caused heavy loss of lives and property. Every time the one who suffers the most through any natural calamity is the common man. Moreover the state also has to bear a potentially high economic loss and every time after such a calamity, there is a high risk of an epidemic as well adding more to the woes of people.

It is indeed highly dichotomous that we are still unable to understand the principal mechanisms responsible for such events giving rise to errors in predictions and projections of our models. The major reason behind this inability is that these events are in general local or regional in scale which makes them highly difficult to predict well in advance. In Indian context, the major heavy rainfall events like Mumbai in 2005, Ratnagiri in 2006 or the more recent ones like Uttarakhand in 2013 and Kashmir in 2014 have created havoc all over resulting in widespread damage over the area. These events were of mesoscale in nature but still their synoptic signature is way different from normal rainfall events and hence this study revolves around understanding the large scale flow corresponding to these heavy rainfall events.

In earlier studies like Lima et al. (2009), the authors have brought out the fact that heavy rainfall events over Southeast Brazil are mostly concurrent with two major synoptic perturbations which are Cold front and the South Atlantic Convergence zone and hence by distinguishing various past events with either of these two perturbations, they were able to give an edge in predicting the heavy rain episodes over their region with a sustained lead in time.

In yet another study by Chen and Li (1995), they have deciphered the large scale conditions which were dominantly responsible for the genesis of heavy rainfall during 20-23 May 1987 along the Southeastern China coast. This made them able to understand the dynamics behind the two peaks observed on 0000 UTC 20 May and 0000 UTC 22 May. Furthermore, they were able to explain less rain observed over Taiwan due to weakening of both the upper-level and low-level troughs.

Prediction of heavy rainfall with high accuracy over Indian region has always been a tough task because of its position in the tropics and moreover due to the presence of Arabian Sea and Bay of Bengal which are of different characteristics and influence the Indian land mass differently in every way. Hence if we can understand the mechanism and dynamics of synoptic features associated with heavy rainfall events which can be easily differentiated with normal rain events then predictability aspect can be improved significantly.

2. Data and Method

South west monsoon over Indian subcontinent shows active and break spells and inter-seasonal and intra seasonal oscillations as well. To distinguish between normal and heavy rainfall events, following criterion of IMD (Rajeevan et al, 2008) has been used in this study.

- 5-100 mm/day as Moderately Heavy rainfall
- 100-150 mm/day as Heavy rainfall
- >150 mm/day as Very Heavy rainfall

For extracting these events, IMD daily rainfall gridded data (Rajeevan et al, 2008) at 0.25°x0.25° resolution from 1901-2012 have been used. Following Very Heavy rainfall (>150 mm/day) events which occurred recently are chosen according to IMD criterion:

- Gujarat on 29th June and 1st July 2005 (Latitude 22.5°-23.5°, Longitude 72.3°-73.3°)
- Mumbai on 26th July 2005 (Latitude 18.7°-19.7°, Longitude 72.5°-73.5°) and re-intensifying on 29th July and then in between 1st and 2nd august 2005 (Latitude 17.4°-18.4°, Longitude 73.1°-74.1°)
- Ratnagiri on 31st May 2006 (Latitude 16.5°-17.5°, Longitude 72.9°-73.9°)

As indicated in earlier studies by Francis et al. (2005) and Lima et al. (2009) Outgoing Longwave Radiation (OLR) can be used as a proxy for rainfall. Hence 3-hourly daily gridded data for OLR from Kalpana-1 has been used to study and substantiate the presence of cloudiness and rain over the regions.

Table 1
Large scale parameters from ERA-Interim data used for the analysis

LevelsParameters	Surface	850 hPa	500 hPa	200 hPa
Mean sea level pressure(hPa)	•			
Zonal(u) wind velocity(ms^{-1})	•	•	•	•
Meridional(v) wind velocity(ms^{-1})	•	•	•	•
Geopotential (m^2s^{-2})		•	•	•
Relative Vorticity ($1x10^{-5}$ s^{-1})		•	•	•
Vertical Velocity (Pa s^{-1})			•	

Since the major focus of this study is on large scale synoptic flow corresponding to the heavy rainfall events, European Center for Medium Range Weather Forecasting (ECMWF) product Reanalysis-Interim (Jan 1979-Present) data have been used for surface and upper level parameters. This data set is a 0.25°x0.25° 3-hourly gridded data at the surface and 0.25°x0.25° 6-hourly gridded data at pressure levels. Table 1 lists the parameters used at the surface and the upper levels. Using these parameters, the position of monsoonal trough, position of a depression or of a cyclonic circulation was obtained using the surface analysis of these events.

3. Discussion

3.1 Case Study I: Gujarat 2005

Moderately heavy rainfall was observed over Gujarat state on 29th June and Heavy rainfall on 1st July 2005 with stations recorded more than 40 cm rainfall in 24 hours as shown in Table 2. From the spatial plot in Fig. 1 one can see the heavy rainfall system over Maharashtra, Konkan and Goa and Gujarat. The system has started developing on 27th June 2005 over Coastal Maharashtra and started intensifying from 28th June 2005 and has reached Southern Gujarat on 29th June 2005 and persisted till 30th June and then a decrease in intensity was observed over the region on 30th June 2005. It again started intensifying on 1st July 2005 and a record rainfall of 150 cm at Navsari has been observed henceforth as depicted in table 2.

Table 2
Station rainfall accumulated in 24 hours over the region under consideration for Gujarat event (Case Study I).

29th June 2005	1st July 2005
Songadh – 55 cm	Navsari – 150 cm
Dohad – 40 cm	Limbdi – 50 cm
	Nadiad – 60 cm

From the OLR analysis following deductions can be made:

- Approximate normal values of OLR i.e. 235 Wm^{-2} can be seen on 27th June 2005.
- As the time progresses, a decrease in OLR

can be seen over Coastal Maharashtra and southern Gujarat from 28th June 2005.

- On 29th and 30th June the value of OLR reached to a minimum of approx 120 Wm^{-2}.

3.1.1 Large scale features : Case I

Surface

The spatial plot of mean sea level pressure in Fig 2 shows depression over eastern Indian region and lay centered over Jharkhand. It is also showing the axis of monsoon trough passing through western Rajasthan, Northern Gujarat, Central Madhya Pradesh meeting the center of depression and then southeastwards to east central Bay. The trough is also visible over coastal Gujarat extending to Kerala. Lower MSLP values (around 990 hPa) show the presence of storm on the surface. The winds overlayed on mean sea level pressure show a cyclonic circulation over Gujarat and the adjoining areas.

Lower Troposphere (850 hPa)

The winds at 850 hPa show the extension of cyclonic circulation from surface to 850 hPa which signifies convergence at lower level. Furthermore, positive vorticity values at 850 hpa (approx 15×10^{-5} s^{-1} on 29 June 2005 intensifying to 25×10^{-5} s^{-1} on 1st July 2005) in fig indicates an anticlockwise circulation and a lateral shear with stronger flow to the right of the direction of the flow. It just substantiates the presence of cyclonic circulation over the region and further indicating about the presence of trough shown in the Geopotential field.

Middle Troposphere (500 hPa)

The winds at 500 hPa in Fig 3 show an anticyclonic circulation over Gujarat, Saurashtra, Kutch and Coastal Maharashtra. Relatively low Geopotential over this region indicate the presence of storm at mid-troposphere levels. High positive relative vorticity values at 500 hPa (approx 15×10^{-5} s^{-1} on 29 June 2005 to 30×10^{-5} s^{-1} on 1st July 2005) supports the presence of storm at 500 hPa. Negative values of vertical velocity (approx -0.9 hPa s^{-1}) indicate the ascending motion of the parcel which signifies cloudiness and rain. A very high negative value of ù on 12 UTC of 29 June 2005 i.e. -2.1 hPa s^{-1} was observed which signifies heavy rainfall over that period on that region.

Upper Troposphere (200 hPa)

A western disturbance can be observed above Jammu and Kashmir at 200 hPa which is moving eastnortheastwards. A very strong anticyclonic circulation and a very high Geopotential confirm the presence of ridge over Gujarat which is extending to Eastern India. The vorticity pattern over Indian subcontinent and jet stream can be sharply seen in this picture as a upper air flow pattern.

Table 3
Station rainfall accumulated in 24 hours over the region under consideration for Maharashtra event (Case Study III).

	Mumbai (Santa Cruz)	Ratnagiri District
25th July 2005	**8.0 mm**	86.0 mm
26th July 2005	**0.8 mm**	91.1 mm
27th July 2005	**944.4 mm**	17.0 mm
28th July 2005	**31.3 mm**	17.6 mm
29th July 2005	**17.4 mm**	58.0 mm
30th July 2005	**45.3 mm**	75.7 mm
31st July 2005	**60.0 mm**	18.8 mm
1st August 2005	**161 mm**	102.7 mm
2nd August 2005	**153.5 mm**	86.8 mm
3rd August 2005	90.9 mm	8.4 mm

3.2 Case study-II: Maharashtra 2005

During monsoon period of the year 2005, Maharashtra experienced two extremely heavy rainfall events within a single week. First one was over Mumbai starting on 00UTC 26 July 2005 which is quite an infamous date in history as the economic capital of India experienced a record rainfall of 94.4 cm over a 24 hour period starting from 03 UTC of 26 July 2005 over a highly localized region of Santa Cruz. The second one was over Ratnagiri district starting on 00 UTC 31 July 2005. It can be seen in fig. 4(a) and (b).

Very low OLR over Mumbai region suggests a presence of dense clouds and rain over the region on 00 UTC 27th July 2005. A very low OLR can be seen on 00 UTC 31st July 2005 which is substantiating the presence of second system over coastal Maharashtra.

3.2.1 Large scale features: Case II

Surface

The axis of monsoonal trough lies over Rajasthan, Madhya Pradesh and then passing through the low pressure area over the bay and finally going into Andaman Sea. It can be seen in Fig 5(a) that a relatively low SLP on 12 UTC 25th July 2005 of around 995 hPa lies over coastal Maharashtra suggests the formation of a cyclonic circulation at the surface level over the region. This low is intensifying on 12 UTC 26th July 2005 and persisting over the region till 12 UTC 27th July 2005 indicating the intensification of cyclonic circulation over the region. A cyclonic circulation has been present over Rajasthan and Gujarat state as can be seen in fig. 5(b) which has merged to the above low pressure area on 12 UTC 1st August 2005. The axis of the monsoon trough lies over Rajasthan, Gujarat and then passing through the center of the low and finally moving into Bay of Bengal. The presence of severely low sea level pressure of around 993 hPa indicates the presence of a very strong cyclonic circulation over Maharashtra, Gujarat, Madhya Pradesh and Rajasthan.

Lower Troposphere

Geopotential at 850 hPa shows clearly the position of monsoon trough over Indian peninsula. The low pressure area over Northern Bay at the surface is also visible at 850 hPa which shows the extension of cyclonic circulation from the surface to lower troposphere as well. 850 hPa winds also indicates an anticlockwise turning of winds over the region showing the presence of cyclonic circulation and hence a storm over the region. Relatively low Geopotential (13200 m^2s^{-2}) also substantiates the storm over the region. Relative vorticity shows the well marked low pressure area over Northern Bay prominently with very high vorticity values and it is marking the evolution of that low over in land region as well. The winds are indicating the presence of anti clockwise turning of winds giving rise to a cyclonic circulation over Maharashtra and Gujarat. Very high positive vorticity values of around $15x10^{-5}$ s^{-1} suggest a deep cyclonic circulation extending up to lower troposphere.

Table 4

Station rainfall accumulated in 24 hours over the region under consideration for Ratnagiri event (Case Study III).

	Ratnagiri District	Panjim
31st May 2006	637.0 mm	67.8 mm
1st June 2006	205.0 mm	69.4 mm

Middle Troposphere

Geopotential at 500 hPa level in fig. 6(a) shows the well marked low over Northern Bay extended up to Middle troposphere moving inland with time and reaching Coastal Maharashtra giving rise to anti clockwise turning of winds over the region and hence a presence of vortex with lower level convergence and upper level divergence over the region. The winds at 500 hPa are also defining the clockwise turning of winds over the small region where a low is formed. Relatively low Geopotential over 500 hPa again indicates a highly convective storm over the region. A positive vorticity of around $15x10^{-5}$ s^{-1} over the region indicates the presence of a localized Mesoscale vortex over Mumbai. It also shows the movement of the low over Bay of Bengal inland providing conditions for the formation of vortex over Mumbai. For the subsequent event on 31st July, Geopotential field at 500 hPa in fig. 6(b) shows the depression at mid troposphere as well. A cyclonic circulation at mid troposphere as indicated by wind barbs suggests the presence of heavy convective activity at the region. The western disturbance can be seen over northern Indian region prominently over Jammu and Kashmir. Very high positive vorticity values varying from $6x10^{-5}$ $s^{-1}$to $15x10^{-5}$ s^{-1} shows the presence of strong deep cyclonic winds over the region. Strong negative vertical velocities (-1.5 Pa s^{-1}) shows strong ascending of parcel over the region giving rise to strong convergence over the region.

Upper Troposphere

A very high Geopotential over Pakistan and Uttar Pradesh shows the well marked ridge over the region. . The tropical easterly jet (TEJ) can be seen marking the evidence of strong south west monsoon over Indian peninsula. The ridge can be seen from Pakistan to Indo Gangetic plains meeting over the strong Geopotential gradient over West Bengal. Positive vorticity values over Maharashtra region indicate the cyclonic circulation over upper troposphere as well. The negative vorticity over the ridge substantiates its location and the jet stream flow can be visualized as well extending a bit southwards into Indian subcontinent.

3.3 Case Study III : Ratnagiri 2006

This event is a bit different from the previous two cases as this happened during pre monsoon season of 2006. As evident from the spatial plot of rainfall anomalies in fig.7, anomalous rainfall started developing on 00 UTC 29 May 2006 over Konkan belt and started intensifying on 00 UTC 30 May 2006 over Ratnagiri and finally reached a maxima on 00 UTC 31 May 2006 which starts dissipating on 12 UTC 31 May 2006. The 24-hour accumulated station rainfall can be seen in Table 4.

A low intensity OLR of around 100 Wm^{-2} can be seen over the region on 00 UTC 31st May 2006. Previous to this day, a system with low OLR can be seen approaching the Konkan coast from Arabian Sea on 00 UTC 29th May 2006.

3.3.1 Large Scale Features : Case III

Surface

The surface mean sea level pressure plot in fig. 8 shows a cyclonic circulation over coastal Karnataka with surface winds turning inwards on 00 UTC 30th May 2006. With time the cyclonic circulation lies over coastal Maharashtra and Konkan belt and getting intensified on 00 UTC 31st May 2006. This cyclonic circulation persists over the region till 12 UTC 1st June 2006.

Lower Troposphere (850 hPa)

Winds at 850 hPa indicate the extension of cyclonic circulation at the surface to lower troposphere. Intensification of cyclonic turning of winds can be observed from 00 UTC 30th May 2006. Relatively low Geopotential (13600 m^2s^{-2}) over coastal Maharashtra and adjoining areas on 31st May supports the presence of strong cyclonic circulation at 850 hPa. An extremely high value of positive vorticity (35x10-5 s-1) indicates a strong cyclonic shear at 850 hPa.

Middle Troposphere (500 hPa)

At mid troposphere, relatively low Geopotential values (approx 57000 m^2s^{-2}) in fig. 9 indicates the presence of a trough or a storm over coastal Maharashtra over Ratnagiri district which can be seen as a part of the storm formed over Arabian sea region as can be seen in the region of low Geopotential field in the Arabian Sea. Ascending motion of parcel over the region with very high negative values of w over the region (approx. -2.1 Pa s^{-1}) shows a strong vertical updraft in the region creating lower level convergence and upper level divergence which is releasing latent heat required for the intensification of the convective storm through CISK(Convective instability of second kind).

Upper Troposphere (200 hPa)

The winds flowing from east to west and turning clockwise over Ratnagiri district and the adjoining areas giving rise to cyclonic circulation at 200 hPa. The high vorticity region can be seen extending from the Arabian Sea which shows the presence of storm over Arabian sea which has moved inland on 12 UTC 30th May 2006 resulting in convection over the region.

4. Conclusion

After analyzing the large scale synoptic signatures relating to the three case studies of Gujarat-2005, Maharashtra-2005 and Ratnagiri-2006, the results can be summarized as follows:

- After performing synoptic analysis for case study-I over Gujarat (lat 22.5°-23.5°, lon 72.3°-73.3°), the most prominent factor which may have caused this event is the persistence of trough over the region with lower level convergence and upper level divergence thus initiating the storm over the region giving rise to such heavy amount of rainfall over the studied regions. Being a monsoonal event, the large scale monsoonal flow fed the intense local system and thus making it an extreme weather event.

- In case study-II over Maharashtra where two very heavy rainfall events occurred at two different regions within a week of time, among which one was over Mumbai(lat 18.7°-19.7°, lon 72.5°-73.5°) from 26th July 2005 to 27th July 2005 and other over Ratnagiri region(lat 17.4°-18.4°, lon 73.1°-74.1°) on 29th July and then on 2nd August 2005. The major reasons behind the first event can be the presence of a local meso-scale vortex over the region formed due to the position of monsoon trough and a low pressure over northern bay which has moved to central India with time.

The second event could have been due to a mid tropospheric cyclone over Ratnagiri which has started forming on 28th July due to intense moisture feeding from Bay of Bengal and Arabian Sea. Both of these cases were taken in accordance as they happened within a week in two different regions out of which the one over Mumbai was totally a meso-scale system getting energy from the latent heat release of the monsoonal system while other one occurred due to formation of low in mid tropospheric levels giving rise to a cyclonic system showing maximum intensity between 700 and 500 hPa.

- For the case study III over Ratnagiri district (lat 16.5°-17.5°, lon 72.9°-73.9°), the possible synoptic factor could have been the presence of a storm over Arabian Sea which could have provided the necessary conditions for the development of cyclonic circulation over Ratnagiri region. Furthermore strong winds from east at 200 hPa denote strong circulation in upper troposphere resulting in heavy rainfall over the region. As seen in the Figs corresponding to this event, it was observed that the storm gradually moved in land and gave extensively heavy rain over Ratnagiri coast and moreover the off shore trough provided the necessary flow to the system giving rise to such an extremely heavy rainfall over the region.

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