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SHORT NOTE

June 19 2015 Rainfall Event Over Mumbai: Some Observational Analysis

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Abstract Some of the major metropolitan centers in the world are highly susceptible to flash floods and major disruptions, owing to sudden and excessive rainfall events. The city of Mumbai, India's financial capital, suffered one such event on 19 June, 2015. This was a second event of such nature, following the landmark event of 26 July, 2005. Such extreme rainfall events are often brought about by certain rapidly developing, local disturbances, which if actively monitored, may be provide important information that can be of great use for early warning to civic authorities and emergency planners. In this paper, we have analyzed a number of different meteorological and remotely sensed parameters, a few days before the actual event, to track the development and eventual culmination of a "perfect storm" that affected Mumbai and left the city tattered. We show how regional upper layer disturbance patterns are developed, induced by warming of sea-surface temperature (SST) and sustained by instability in the atmospheric boundary layers to quickly develop into massive cyclonic storms.

Keywords India · Rainfall · Mumbai · Local-disturbance · Sea-surface temperature · Geopotential height · Wind shear

Introduction

On 19 June 2015, the city of Mumbai experienced an extreme rainfall event within 24 hours. The rainfall measured at Mumbai, in Santa Cruz and Colaba was respectively, around 283 mm and 209 mm (source: Indian Meteorological Department Automated Weather Stations – AWS). This rainfall within 24 hours was one of the highest recorded in Mumbai after the extreme rainfall event of 26 July 2005. At Chhatrapati Shivaji International airport (Fig. 1a) (WMO station) total rainfall of ~283 mm was recorded on 19 June 2015 (Fig. 1b), the third highest total rainfall on a day since 2000. This was followed by another extreme rainfall event on 23 June when several weather stations in the city recorded rainfall in the range 220–273 mm (Skymet AWS: http://www.skymetweather.com/content/weather-news-and-analysis/monsoon-rains-recorded-by-skymet-in-mumbai/). Over the entire month of June, Mumbai received the second highest total rainfall in a decade, after June of 2013.

Extreme rainfall events (>50 mm) in a day are common along the western coast of India, during the summer monsoon period (Gadgil et al. 2004). But such extreme rainfall events cause frequent flash floods, especially in low lying urban cities, throughout the world due to growing built up areas and lack of a good drainage system (Carter 1961; Hollis 1975; Beecham and Chowdhury 2012). Mumbai city, with population of more than 19 million (as of 2013), has grown in all respect, built up areas and new infrastructure. During summer monsoon, water logging/flash flood is a common problem affecting daily lives of people. During the last such event on 26 July 2005, Mumbai received more than 450 mm of rainfall, severely affecting the daily life of people and causing financial loss of well beyond $2 billion (Prasad and Singh 2005; Bohra et al. 2006).

Even given the history of such rainfall events, the heavy rainfall in the month of June 2015 was unexpected especially with the progress of a strong El-Nino that was expected to

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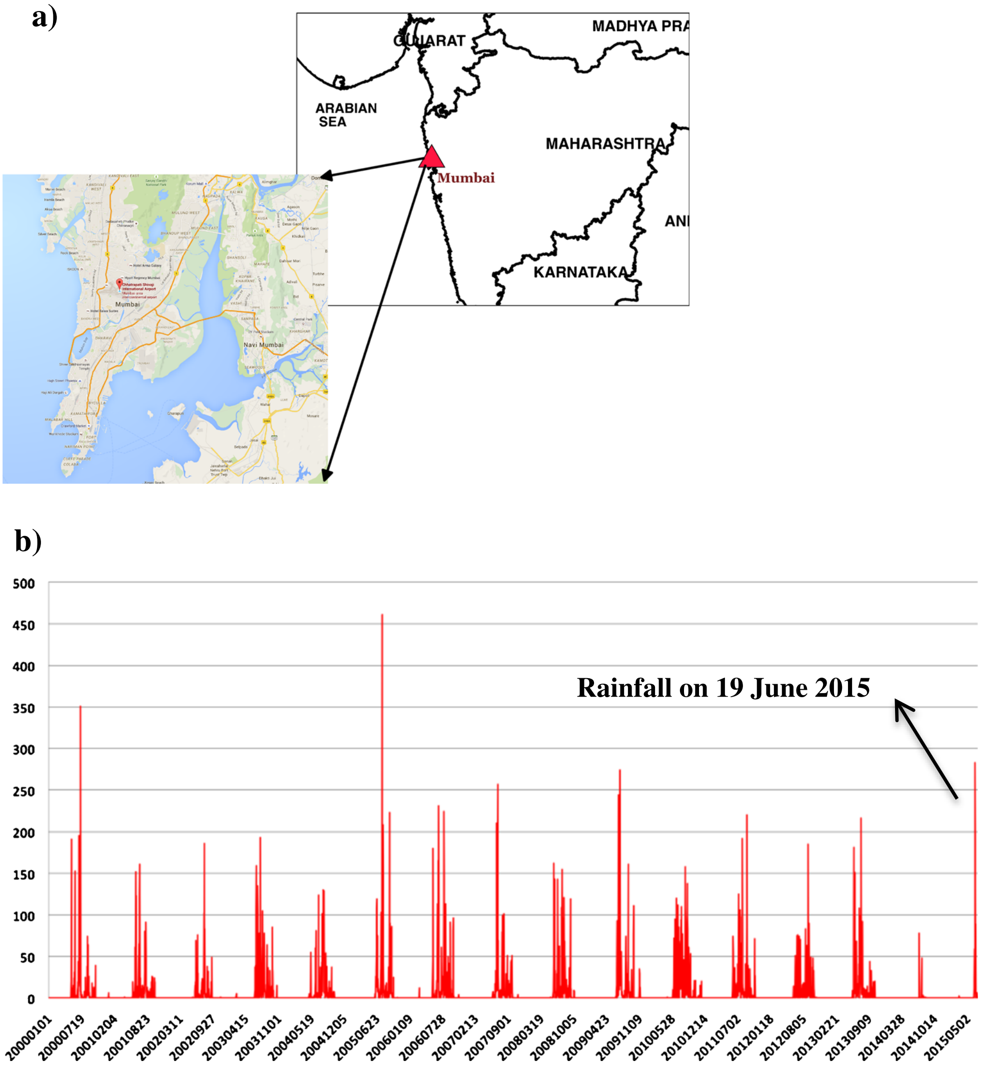


Fig. 1 **a**) The location of the WMO station located in Chhatrapati Shivaji airport in Mumbai. (*map courtesy: Google maps*). **b**) The daily-accumulated total rainfall (mm) during 1 January 2000 – 6 July 2015, obtained from the WMO station located in Chhatrapati Shivaji airport in Mumbai

cause poor monsoon and lower than average rainfall (Sikka 1980; Pant and Parthasarathy 1981; Rasmusson and Carpenter 1983). Although several discrepancies in the relationship between El-Nino and Indian monsoon has been discussed (Kumar et al. 1999; Sarkar et al. 2004; Kumar et al. 2006), still such an extreme rainfall (June 2015) was not expected in view of the ongoing El-Nino event. The city was totally unprepared for this event and there were heavy losses in terms of workdays lost, hindrance to mass transit systems, damage to properties and even loss of life.

In this paper, we have analyzed a number of satellite and meteorological parameters to study the development of parameters relating to extreme rainfall, off the western coast of India, close to Mumbai. Understanding of such rapidly developing local fluctuations provide an insight in developing forecasts of extreme rainfall events to alert civic bodies and emergency personnel, to face such an event. Similar efforts to explain the 2005 event based on observation data (Prasad and Singh 2005) as well as modeling (Bohra et al. 2006; Kumar et al. 2008; Sahany et al. 2010) provided valuable insights. Bohra et al. (2006), have pointed out deficiencies in the current weather prediction model being used by the Indian agencies and have suggested several improvements to fix the model. Kumar et al. (2008) and Sahany et al. (2010), have discussed in detail the factors that may have triggered such events. Another study, using the WRF model, to understand the catastrophic rainfall over Uttarakhand in June 2013 (Kumar et al. 2015) has also highlighted the importance of timely prediction and warning for better disaster mitigation.

Materials

Extreme rainfall events are associated with the land-ocean–atmosphere coupling. Understanding of such coupling is complex and requires various types of data related to land, ocean, atmosphere and meteorological parameters.

The global merged Infrared (IR) brightness temperature data (BT) are considered for the cloud-top temperature, during and around the period of anomalous rainfall event of 19 June 2015. This data is obtained from the Climate Prediction Center (CPC) archive of US National Weather Service. We have used the full resolution (4 km) IR (~11 micron) brightness temperature that covers 60 N-60S and is derived from all available geostationary satellites (GOES-8/10, METEOSAT-7/5 and GMS) (Janowiak et al. 2001), we will refer this data as CPC IR BT.

We have also considered BT data from the thermal infrared band (10.5–12.5 micron) (TIR) of Very High Resolution Radiometer (VHRR) onboard the Kalpana-1 (METSAT) satellite, launched by Indian Space Research Organization (ISRO). The half-hourly data have been analyzed at ~12 PM local time, daily, we have obtained this data from the MOSDAC (http://www.mosdac.gov.in/) meteorological data archive of India.

SST anomalies have been taken from the NOAA 0.25^0 x 0.25^0 optimum interpolated dataset. This dataset has been derived by blending in different observations (Reynolds et al. 2007) from multiple platforms (satellites, ships, buoys).

We have also used the Global Forecast System (GFS) model data on a $0.25^0 \times 0.25^0$ lat-long grid, from the National Centers for Environment Prediction (NCEP), USA. GFS is a coupled weather forecast model that is run by NCEP globally at a base horizontal resolution of ~13 kms for the first 10 days which drops to ~27 km thereafter. Vertically, the model is

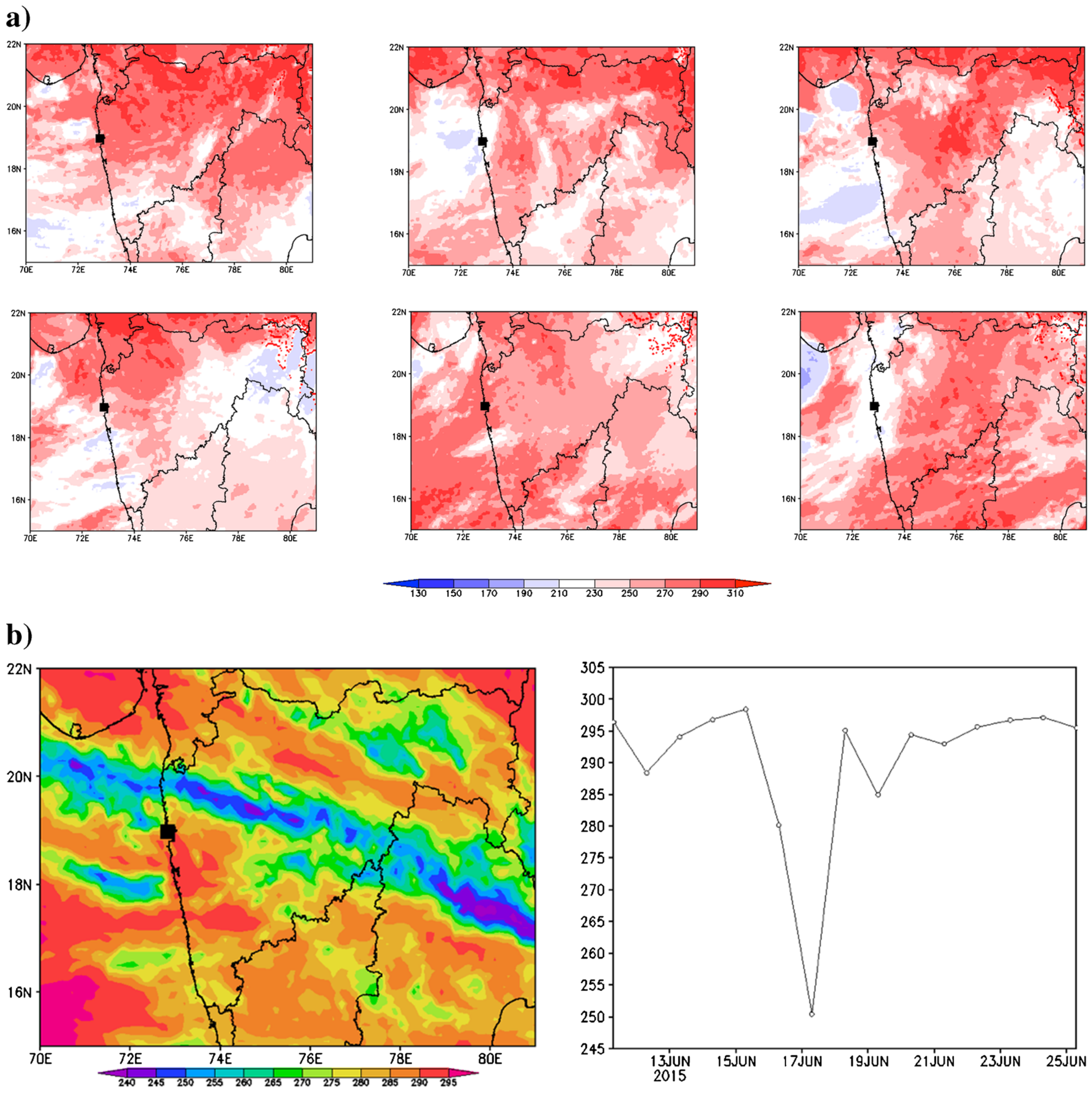


Fig. 2 **a**) The CPC IR BT (Kelvins), collected at 12:30 local time, from 18–23 June 2015 (going from left to right, from top panel to lowest panel). **b**) Brightness temperature on 19 June (*left*) and time series of Brightness temperature (in Kelvins, right) from 13– 25 June of 2015, derived from Kalpana-1 TIR, showing changes in BT over Mumbai. The city of Mumbai is marked with a *black square*

divided into 64 layers and temporally, model forecast is given out every hour for the first 12 hours, three hourly thereafter till day 10 and every 12 hours after that. The GFS forecasts are made at four time steps every day (00z, 06z, 12z and 18z) and forecasts are made up to 16 days in the future. GFS analyses, that describe the state of atmosphere at the time of model initialization, are given out at 00z and 12z every day.

The daily rainfall data over the Santa Cruz (Chhatrapati Shivaji airport) have been taken from WMO station data archive, through their global web interface (http://gis.ncdc.noaa.gov/map/viewer/#app=clim&cfg=cdo&theme=daily&layers=0001&node=gis).

Results

Figure 2a shows the daily CPC IR BT in and around Mumbai. The city of Mumbai is shown with a black square in this and all subsequent figures. Figure 2b shows the BT for 19 June, from the Kalpana-1 TIR channel. The sudden drop in the IR brightness temperature/cloud top temperature (around 250 K from an average of ~290 K) is clearly seen on 19 June (Fig. 2b), from the Kalpana-1 TIR BT time series. This sudden drop in BT on 19 June 2015 reflects rapid vertical uplift and advective cooling associated with build up of an intensive storm and lifting.

This strong advective cooling is also seen from Fig. 3 that shows the lifted index on 18 June. Lifted index is a measure of the difference between 500 mb ambient temperature and that of a rising parcel of air. A negative lifted index is thus an indication of developing instability in the atmosphere. A strong negative lifted index (−3 K and lower) is seen to hover over Mumbai and surrounding areas from Fig. 3. The development of a storm system and intensifying cyclone pattern is further seen from Fig. 4. The 500 mb geopotential height (Fig. 4a) variation from 18–23 June 2015, shows the development of a strong depression, just off the west coast of India, near the southern tip of Gujarat. The positioning of this depression is seen to change from 19 June 2015 (Fig. 4a upper panel center) to 23 June 2015 (Fig. 4a lower panel right). The 500 mb depression is observed very close to the city of Mumbai, on 19 June causing heavy rainfall.

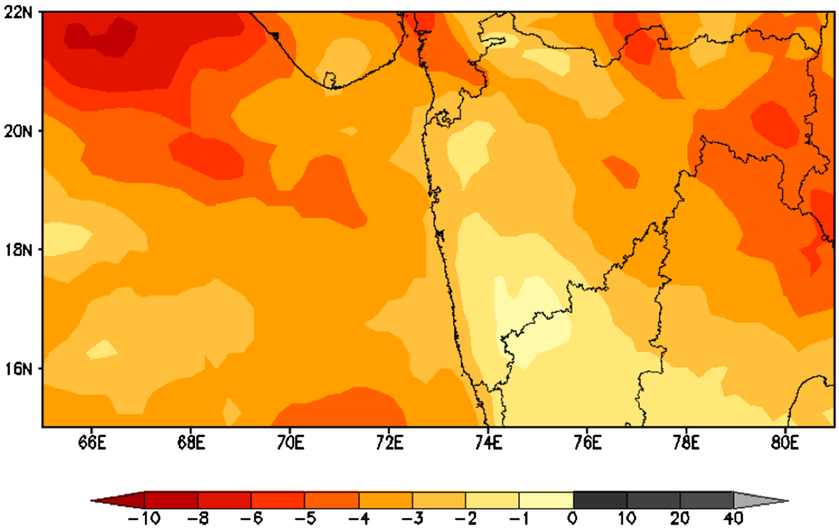
Fig. 4 Plots of different meteorological parameters as derived from the GFS 12z analysis. Each set of figures represents days during 18 – 23 of June 2015, from left to right and from top to bottom. **a**) 500 mb geopotential height (shaded, in gpm) with wind stream contours at 925 mb. **b**) The vertical shear, calculated between 200 and 850 mb. **c)** Absolute vorticity at 500 mb (x10^5) hertz. The city of Mumbai is marked with a *black square* in all the figures ▶

A strong positive vorticity is also seen to develop at 500 mb at the same time, indicating strong counter-clock wise wind pattern and storms at the upper level (Fig. 4c). Again the positioning of the positive vorticity pattern and its adjacency to the city of Mumbai is noteworthy. What further aids in the build up of this strong cyclonic storm system is the low tropospheric wind shear of 15 knots or less on 19 and 20 June 2015 (Fig. 4b). The vertical wind shear increases between 21 and 22 June 2015 and is likely responsible for the break up of the single cell storm pattern to two cells as clearly seen from the geopotential height on 23 June 2015 (Fig. 4a).

Furthermore, the position of the depression at 500 mb and location of the maximum positive vorticity shows Mumbai and its adjoining areas on the eastern or right hand side of this developing and strong counter clock wise wind pattern, indicating strong upper level uplift over this area, corroborating similar observation seen from the analysis of CPC and Kalpana-1 BT (Fig. 2).

The SST anomaly plot from 16 to 19 June 2015 (Fig. 5a) shows a strong positive anomaly all along the western coast

Fig. 3 The best of 4-lifted index from GFS on 18 June 12z analysis (Kelvin)



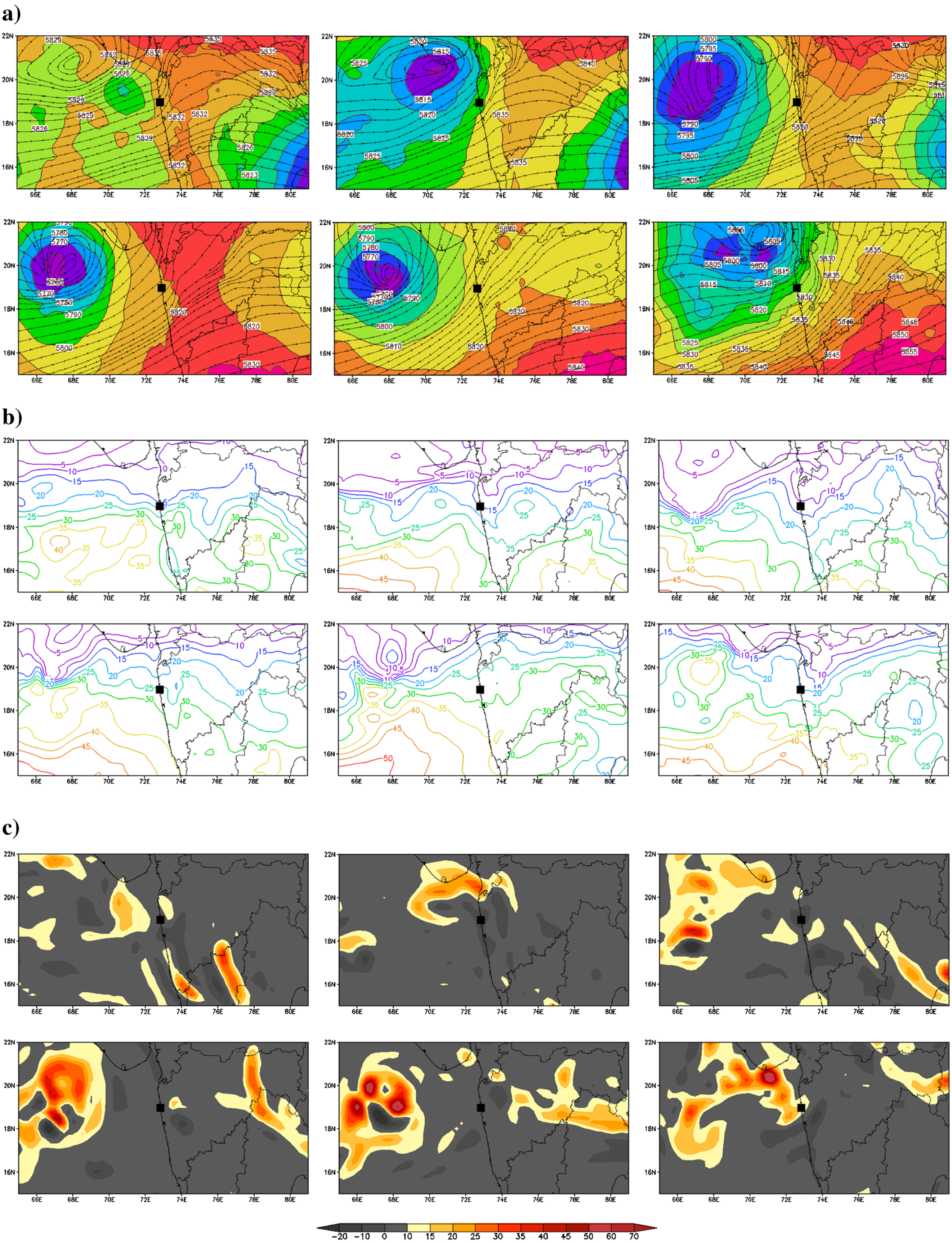
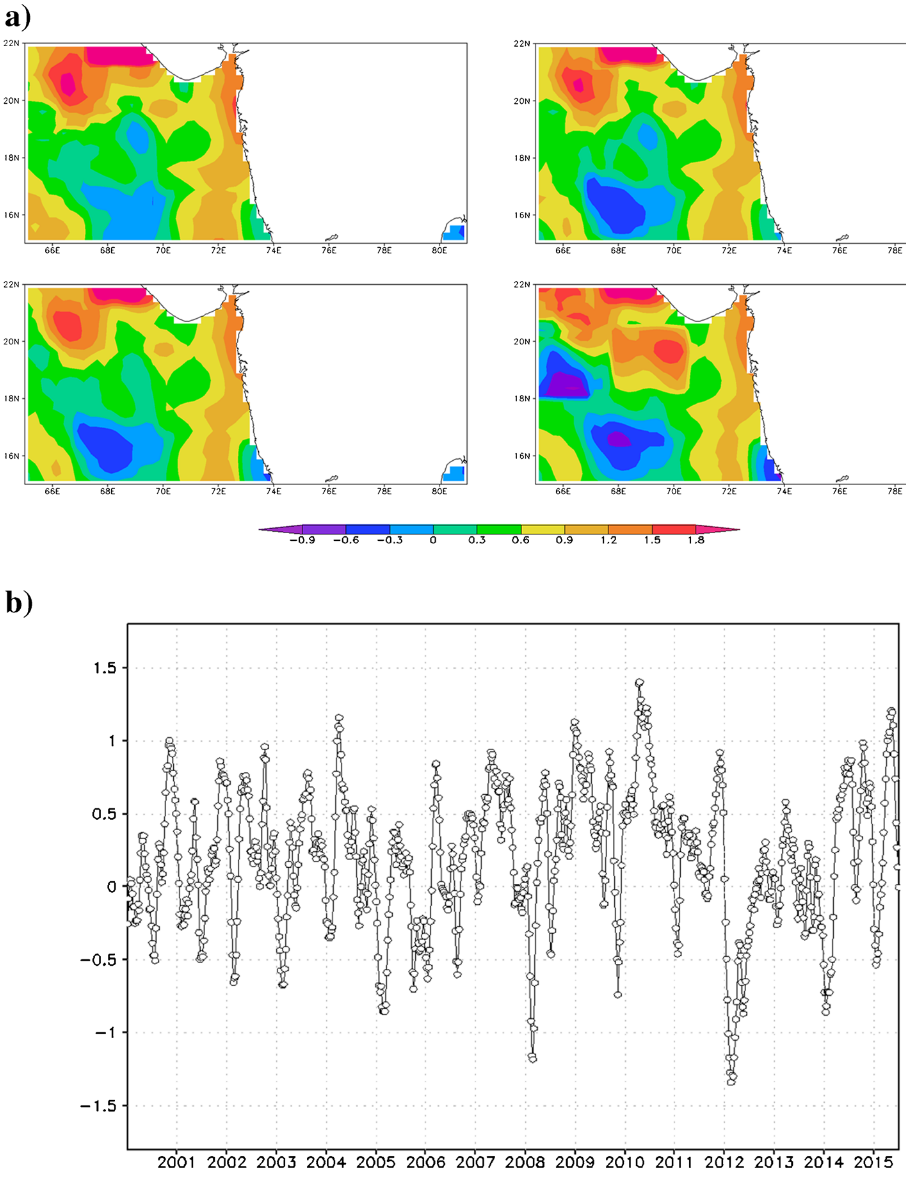

a)
b)
c)
22N
20N
18N
16N
66E
68E
70E
72E
74E
76E
78E
80E
−20
−10
0
10
15
20
25
30
35
40
45
50
60
70

Fig. 5 **a**) SST anomaly pattern (in deg. C) during 16–19 June (left to right and from top to bottom panel). **b**) Time series of weekly SST anomaly since first week of 2000 until the week of 5 July 2015



and especially off the southern tip off Gujarat. This pattern is seen to develop from 16 June 2015 onwards; a peak is seen on 19 June 2015 and slowly dissipates thereafter (not shown in Figure). The weekly SST anomaly from the first week of 2000, over a point close to the Mumbai coast (19 N, 72E) (Fig. 5b), shows the SST to be the second highest in the last one decade.

Such anomalous SST of almost 1.5 degree or more led to the development of a convective cell off the southern coast of Gujarat, in the Arabian Sea. A strong upward draft developed on 18 June, as seen from the strong low-level wind patterns (Fig. 4a). This convective cell intensified on 19 June and moved close to Mumbai and intense rainfall occurred over Mumbai on 19 June. Strong temperature contrast between 500mb ambience and the convective parcel (Fig. 3), weak tropospheric shear and strong surface winds enhanced the heat transfer from the ocean.

Strong negative vertical velocity (Omega) values with high levels of atmospheric moisture content in the air and strong upward moisture advection is also seen from Fig. 6a and b. This pattern is found during 18 to 23 June, showing the persistence of the vertical cell through continued moisture advection and moist adiabatic lapse rate. After 19 June this convective cell shifted westward towards deeper Arabian Sea and became even stronger. At this point the cell split into two, aided partly by the increasing tropospheric wind shear on 21 and 22 June. Since the main center of the storm shifted further off the coast of Mumbai, even though rainfall occurred until 23 June but the heaviest rain occurred on 19 June when all the meteorological parameters were ideal for the perfect storm.

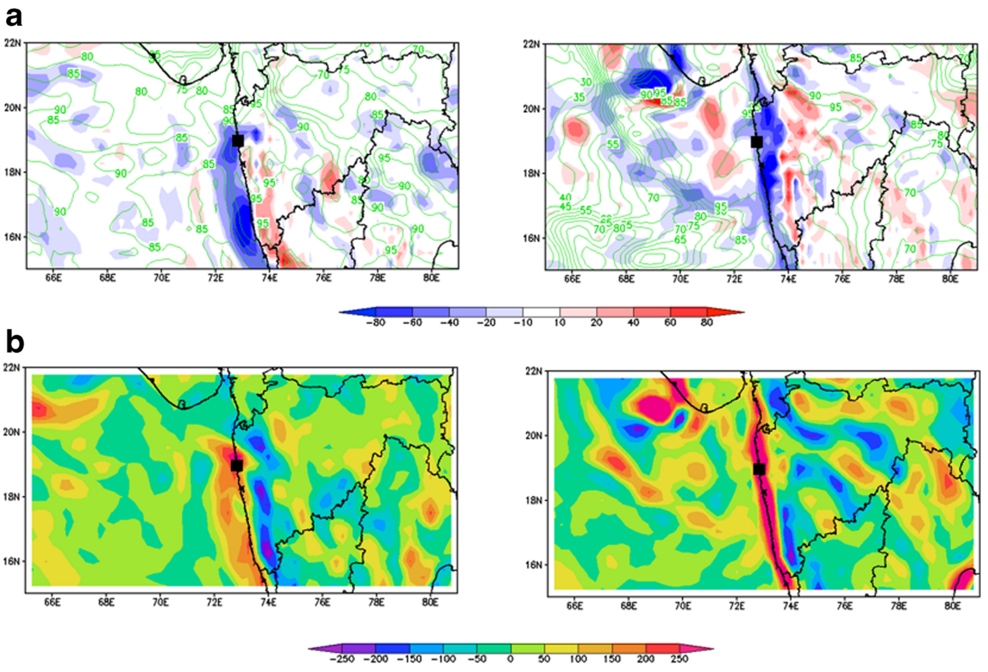


Fig. 6 **a**) Vertical velocity or Omega (mb/hr) at 700 mb (shaded) with contours of relative humidity (%) at 850 mb, derived from GFS 12z analysis on 18 of June and 23 June. **b**) Vertically integrated moisture convergence calculated between surface and 300 mb pressure level (kg/s) for the same time and days as in (**a**). Convergence is shown as positive

Conclusions

Though the general trends in Indian summer monsoon rainfall have been actively studied and a number of favorable parameters responsible for storm have been identified, but still the physical process and the key role of some of the parameters are not fully well understood. Moreover local fluctuations due to orography, local disturbances and short-term atmospheric oscillations can cause some local to regional anomalous rainfall pattern that can further hamper our ability to model and predict rainfall anomalies. Hence monitoring of real time weather information and meteorological variables is of crucial importance, especially for large cities like Mumbai where sudden rainfall and major water logging can completely throw the entire city off gear. Our study shows the necessity of an integrated approach to study of local and regional weather pattern that is still lacking in many parts of India and in many of the major metropolitan centers.

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