

# Observational/forecasting aspects of the meteorological event that caused a record highest rainfall in Mumbai

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**The Santacruz observatory at Mumbai airport experienced unprecedented rainfall of 94.4 cm on 26 and 27 July 2005, an all-time highest record over the city. The country's commercial capital came to a complete standstill due to severe flooding/deluge. It also caused severe damage to life and property. In the present article, we have brought out the characteristics of this unique rainfall event, compared it with past intense rainfall events in India and other places in the world, and also analysed various data to find possible causes of occurrence of this event. Technology available for prediction of such events is also briefly touched upon.**

**Keywords:** Isohyet analysis, synoptic scale feature, scale interaction, thunderstorm.

Mumbai (lat. 18.50°N, long. 72.52°E), formerly called Bombay, situated on the west coast of India, is the commercial and financial capital of the country. It generates about 5% of India's GDP and contributes over one-third of the country's tax revenues. It is among the few port cities of the world having major industrial and economic activities. The influx of labour and other work force over the last two decades has resulted in the total population of the metropolitan and the surrounding suburbs to increase from 9.9 million in 1981 to 13.0 million in 1991 and 17.7 million in 2001. Mumbai is not only the most populated city in India, but also the fourth most populated city in the world after Tokyo (36.0 million), New York (22.0 million), and Seoul (21.7 million). If only the population of the metropolitan city, excluding its surrounding suburbs is considered, Mumbai is the second most populated city in the world, after Shanghai. Such densely populated cities with highly developed infrastructure are always vulnerable to natural disasters. The economic losses are also expected to increase over time, as people move into more vulnerable areas because of shortage of free space.

Parts of Mumbai experienced an unprecedented rainstorm on 26 and 27 July 2005. The 24 h rainfall ending at 0830 h IST of 27 July was 94.4 cm as per the meteorological observatory at Santacruz airport, Mumbai. Colaba, the other meteorological observatory, which is roughly 27 km

away, recorded only 7.4 cm rain during the same period. Very heavy rains also lashed other parts of Maharashtra on subsequent days and completely disrupted normal life across the state, with Mumbai being the most severely hit. On the subsequent two days, though rainfall over Mumbai reduced to 1.9 cm per day, it again increased to 20 cm on 1 August 2005; further worsening the situation over the already deluged city. Mumbai was totally cut-off from the remaining parts of the world almost for a week. Mumbai airport was closed for two days on 26 and 27 July as the runway was waterlogged, the terminal building flooded and crucial navigation and landing aids damaged, thus forcing all international and domestic flights to be diverted or cancelled. Normal operations could resume only on 4 August 2005. Train services to and from Mumbai were also cancelled for more than a week. Local trains which are Mumbai's life line – running every 3 min and ferrying 4.5 million passengers daily – were totally thrown off gear as railway tracks were not only submerged, but also damaged. Following were the initial damage assessments due to this severe rainfall spell and flooding in the state, as reported by *Financial Times* and *Economic Times* on 4 August 2005.

- The number of dead in the Maharashtra floods could well be above 1000, with Mumbai alone accounting for over 409.
- Around Rs 5000 crores estimated loss in the state, with Mumbai accounting for half the amount.
- No electricity in certain areas of Mumbai city for up to five days.
- One million people rendered homeless.
- About 1100 flights cancelled and airport closed for two days.
- Five million mobile and land lines crashed.

In addition to the two observatories at Colaba and Santacruz, Mumbai of India Meteorological Department (IMD), the Maharashtra government and the Mumbai Municipal Corporation have a separate network of rain gauges, which also captured this intense rainfall event. The gauge at Vihar Lake, located around 15 km northeast of Santacruz, recorded 104.9 cm of rain on 27 July 2005. The measurement of rainfall at Santacruz is of importance, particularly in the field of national and international aviation.

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In the present article, we have brought out the characteristics of this unique rainfall event that resulted in 94.4 cm rainfall over Santacruz on 27 July. An attempt is made to examine spatial and temporal extent of this rainstorm by pooling together all the rainfall reports on 27 July from other recording stations in the city and its suburbs, and making an isohyetal analysis. We have also compared this rainfall event with rainfall records available for other places in India and elsewhere in the world. By analysing data from various sources, possible causes for such exceptional rainfall have been investigated by examining whether the event was purely a mesoscale system attributed to thunderstorms having life period of a few hours or a synoptic scale event with intense atmospheric vortex/offshore trough remaining with highly supporting, large-scale circulation pattern already prevailing over the west coast of India or an interaction between both the scales. We have also referred to satellite and radar pictures to identify cloud-development characteristics and discussed the possible role of orography because of the presence of the Western Ghats in the east in producing such heavy rainfall. Finally, latest technological capabilities available in India and abroad are discussed for predicting such important events.

### Characteristics of the rainfall event

Normally, in July and August, many stations of Konkan and Goa, including Mumbai and coastal Karnataka, which are on the windward side of the Western Ghats of India, receive high rainfall due to orographic effect. The strong westerly moist wind from the Arabian Sea that strikes perpendicularly to the hills extending roughly in a north-south direction, is lifted up vertically during active monsoon and causes very heavy rainfall on the windward side<sup>1,2</sup>. Because of this orography, during many days in the monsoon season, strong westerly/southwesterly flow over the Arabian Sea also results in the formation of offshore trough/mesoscale vortices over the sea off the west coast, causing very heavy rainfall activity along the west coast of India, including Mumbai<sup>3</sup>. Strengthening of such westerly/southwesterly flow over the Arabian Sea is observed when the Arabian Sea branch of the monsoon is active or when a depression/low pressure area forms over North Bay of Bengal and moves to Central India<sup>1</sup>. Gujarat–Konkan coast also experiences very heavy rainfall, up to 40 cm, during active monsoon conditions due to the presence of mid-tropospheric cyclone (MTC) over the region<sup>4</sup>.

Table 1 shows climatological frequency of heavy rainfall distribution over the two main stations in Mumbai (Colaba and Santacruz) in different categories based upon data of 1901–2004. It shows that there is a probability of nearly 35–48% and 11–13% during each monsoon season for Mumbai to have at least one day with rainfall of more than 20 cm and more than 30 cm respectively. Hence Mumbai is vulnerable to intense rainstorms during the monsoon season.

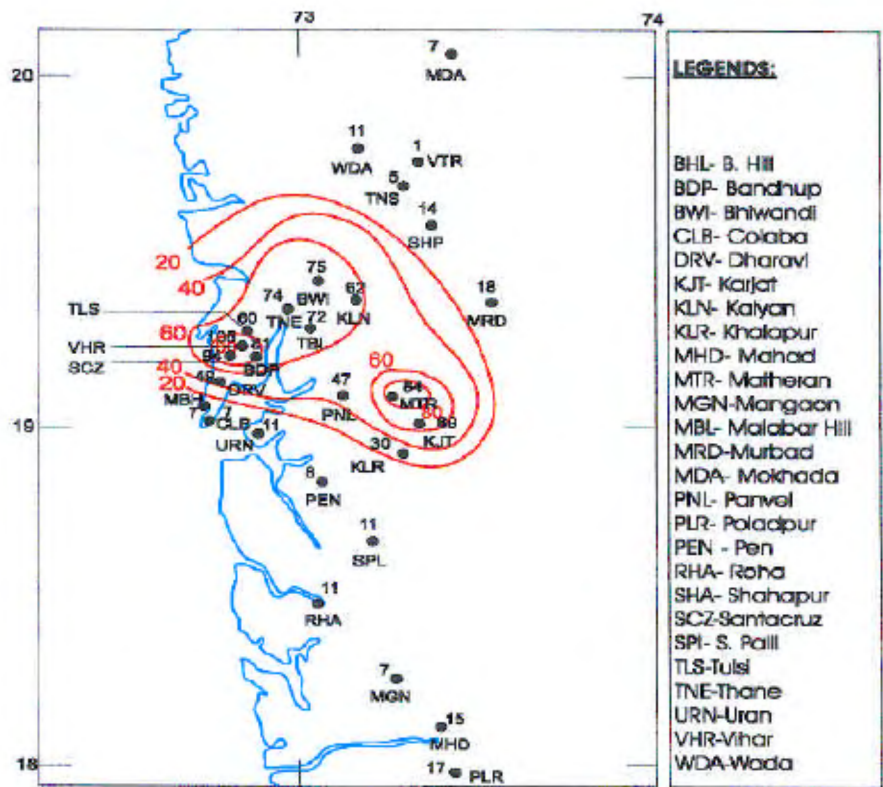
The 24-h rainfall up to 0830 h IST on 27 July 2005 over Mumbai and its neighborhood is given in Figure 1. On this day, not only did Santacruz record 94.4 cm, but also Vihar Lake, which lies nearly 15 km northeast of Santacruz, recorded higher amount of rainfall, i.e. 104.9 cm. However, the amount decreased thereafter in the northeast sector of Santacruz, with Bandhup and Tulsi reporting rainfall of 81.5 and 60.1 cm respectively. Even stations which are farthest northeast of Santacruz, e.g. Bhiwandi, Thane and Kalyan, reported 75, 74 and 62 cm of rainfall respectively. However, rainfall reduced significantly to a few centimetres beyond 50 km to the northeast of Santacruz at lake stations, e.g. Tansa and Vaiterna reported 5 and 1 cm of rainfall respectively. South of Santacruz, Colaba recorded only 7.4 cm of rainfall. Isohytal contour analysis in Figure 1 shows that the rainfall contour of 60 cm covered an area of nearly  $35 \times 20 \text{ km}^2$  lying close but to the northeast of Santacruz, while the highest contour of 80 cm covered an area of nearly  $10 \times 10 \text{ km}^2$ , lying to the northeast, close to Santacruz.

From Figure 1, it is also interesting to note the occurrence of another very high rainfall area lying nearly 45–50 km away to the southeast of Santacruz. In this area, Matheran and Karjat recorded 84 and 69 cm of rainfall respectively. Isohytal analysis also shows the location of another rainfall maximum ( $> 60 \text{ cm}$ ) over the area covering these stations having small spatial extent of  $15 \times 15 \text{ km}^2$ .

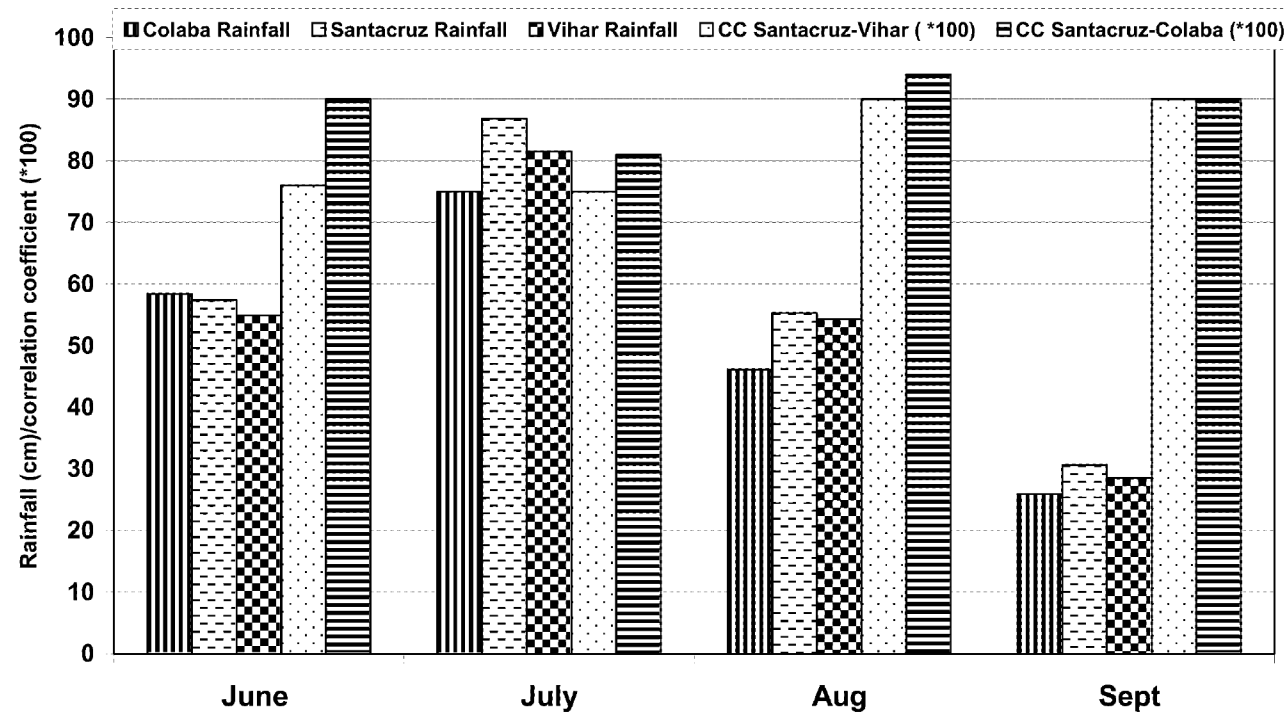
Normally in the monsoon season from June to September, Colaba receives 205 cm, while Santacruz receives 230 cm of rainfall; 12% higher than the former though both are within 27 km distance. To understand the microclimatological characteristic of rainfall distribution over different parts of Mumbai, monthly rainfall totals over Vihar Lake, Santacruz and Colaba with their correlation coefficients (CC) are shown in Figure 2, using long period dataset from IMD. The analysis shows that the June rainfall is a little higher over Colaba than over Santacruz and Vihar Lake, and vice versa in September. This is because Colaba in south Mumbai receives more rainfall during the

**Table 1.** Occurrence of very heavy rainfall events over Mumbai

Observatory	No. of occasions with rainfall more than 20 cm/day	No. of occasions with rainfall more than 20 cm/day consecutively for two days	No. of occasions with rainfall more than 30 cm/day	No. of occasions with rainfall more than 30 cm/day consecutively for two days
Colaba	50	5	13	2
Santacruz	37	3	11	1



**Figure 1.** Rainfall observations (in cm) reported from different parts of Mumbai and its suburbs on 27 July and isohyetal analysis over a 24 h period.



**Figure 2.** Monthly rainfall climatology over different stations in Mumbai and their correlation coefficients.

onset phase in June. However, in July and August, stations in the north, including Santacruz and Vihar Lake receive higher rainfall than Colaba and rainfall difference during both the months is higher than during the other months. The CC between monthly rainfalls show a higher value between rainfall of Santacruz and Colaba than that between the rainfall of Santacruz and Vihar in June, while their CC are more or less the same for other monsoon months. Actual values of their CC are 0.75 and 0.8 in July, 0.9 and 0.92 in August, and 0.9 and 0.9 in September respectively. Because of the existence of such high CC between these stations, any event responsible for high rainfall over any of these stations is always favourable for occurrence of similar high rainfall over the other two stations. However, the present extreme rainstorm event which was responsible for the occurrence of the highest rainfall of 94.4 and 104.9 cm over Santacruz and Vihar Lake respectively, has given rise to very less rainfall of 7.4 cm over Colaba. Hence, the rainfall characteristics associated with the present event have broken the climatic relationship that normally occurs during monsoon.

Examination of past records of daily rainfall for more than 100 years for Mumbai shows that the rainfall of 94.4 cm is the highest ever recorded in Mumbai. Earlier, the highest was 57.8 cm on 5 July 1974, recorded over Colaba. The other two very heavy rainfall events in decreasing order were also recorded over Colaba. These are 54.8 cm on 10 September 1930 and 47.8 cm on 10 June 1991. However, Santacruz had never recorded such a high rainfall before. Its records show that the earlier highest rainfall was 39.9 cm on 10 June 1991 followed by 37.5 cm on 5 July 1975, 34.6 cm on 23 August 1997 and 31.8 cm on 23 September 1981.

Figure 3a and b shows 3-hourly rainfall and cumulative rainfall distribution respectively over 24 h during 26–27 July in Santacruz and Colaba. For Santacruz, it shows 0.09 cm from 0830 to 1130 h IST and 1.8 cm from 1130 to 1430 h IST for 26 July. Hence in the first 6 h, the rainfall was less at Santacruz. Then there was a sudden increase in the intensity of rainfall in following 3 h in Santacruz, when the 3-hourly highest realized rainfall of 38.2 cm was recorded from 1430 to 1730 h IST on 26 July. This was again followed by another intense spell of 26.8 cm from 1730 to 2030 h IST, making a total of 65 cm (70% of the 24 h rainfall) in 6 h in Santacruz between 1430 and 2030 h IST in the afternoon of 26 July. Rainfall intensity decreased to almost one-third in Santacruz during the next 6 h, with rainfall accumulation of 21.6 cm. It further decreased drastically in Santacruz to about 6 cm in the last 6 h ending at 0830 h IST of 27 July. In contrast, the 3-hourly rainfall data of Colaba for the same time period plotted in Figure 3a shows no rain or very less rain. The highest was only of 2.4 cm observed between 0230 and 0530 h IST on 26 July. Similarly, it is interesting to note the contrast characteristics of rainfall occurrences over both stations from their 3-hourly cumulative observations

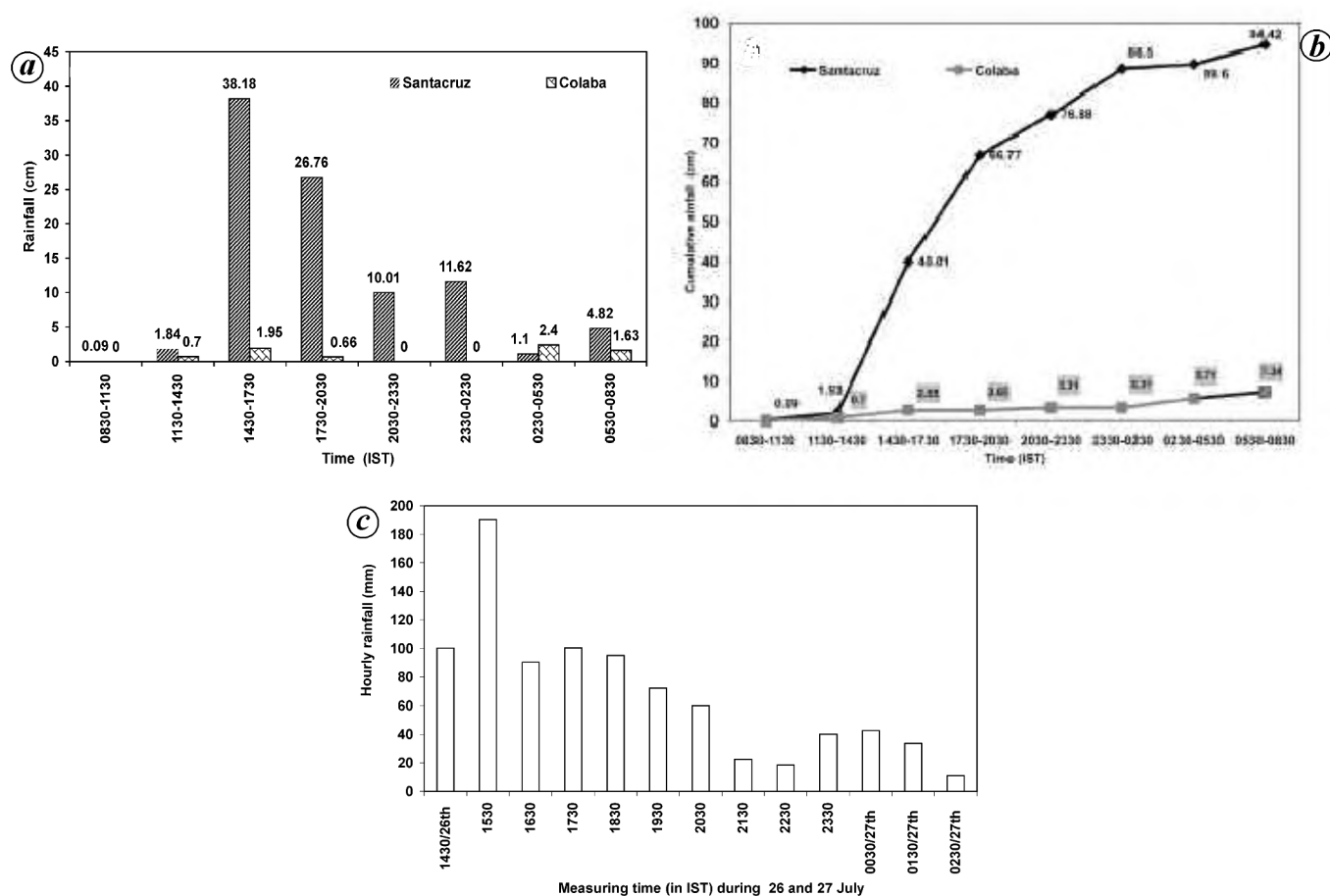
plotted in Figure 3b. A continuous sharp raise in cumulative rainfall value from 1.9 to 88.5 cm was observed over Santacruz during the 3-hour period 1130–1430 till the three hour period 2330–0230 h IST, in contrast to very small increase in cumulative rainfall values from 0.7 to 3.3 cm over Colaba for the same period.

Hourly rainfall from IMD autographic rainfall recorder could not be retrieved as the instrument was submerged in rainwater after 1430 h IST. However, an IMD observer working at Mumbai during the rainstorm period had taken a lot of pains to preserve such important hourly observations from 1430 h IST onwards, by continuing manual observations when the intense rainfall occurred. The observer had to swim across the flood of water which accumulated in the observatory compound as a result of ensuing severe rainstorm, to rescue the rain gauge from the groundwater and re-install it at the nearest roof top of the office building, from where he finally succeeded to carry out the observations. Hence, the special effort and courage showed by him need much appreciation. These hourly observations taken manually by him are shown in Figure 3c. It shows that the highest hourly rainfall was 19 cm (190 mm) between 1430 to 1530 h IST. It was preceded by 10 cm of rainfall between 1330 and 1430 h IST, followed by 9 and 10 cm in the subsequent 2 h.

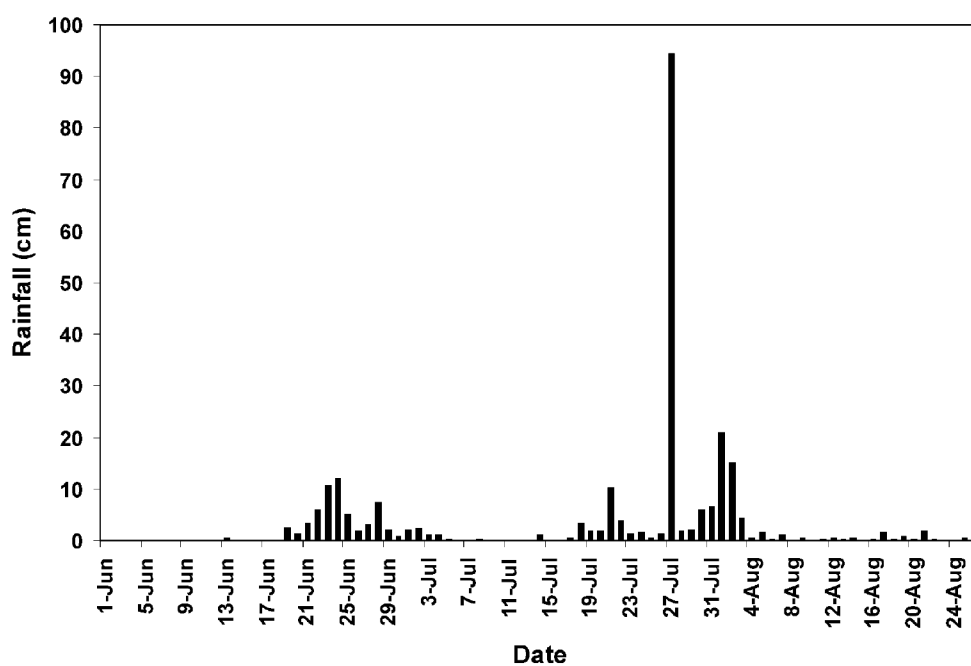
Rainfall rates from rain gauges tend to have a serious sampling problem, area wise, in association with this type of convective rain events. The spacing between rain gauges, even in relatively dense networks as in the Oklahoma Mesonet, USA<sup>5</sup>, is not capable of resolving the details of precipitation distribution. Though a digital radar could have provided high-resolution precipitation observations, in the absence of the same, an effort is made to use available data resources to analyse the present intense rainfall event.

To compare the hourly rainfall variation or diurnal variation of the present event with climatological ones, hourly rainfall normal was prepared using hourly rainfall data available daily for 10 years. It shows the occurrence of highest rainfall in the early morning between 0100 to 1000 h IST with lowest in the afternoon/evening between 1400 and 1900 h IST, having intensity 1.0–1.5 and 0.3–0.5 cm/h respectively, in contrast to occurrence of highest rainfall between 1430 and 2030 h IST, as noted in Figure 3c in the present extreme rainfall event.

The analysis of large-scale rainfall distribution data over the west coast from 24 onwards till the occurrence of this severe rainstorm, shows the occurrence and movement of very high rainfall zone of the order of 15–40 cm from south to north in the Maharashtra region. However, rainfall on 27 July was higher compared to those on earlier days over the Ghat section – Dhirpuri, 48 cm; Lona-vala, 35 cm and Mahabaleshwar, 26 cm. Fairly widespread rainfall with very heavy showers at a few places was also reported from the rest of Maharashtra on 27 July – with Parbhani, 27 cm, and Aurangabad, 11 cm.



**Figure 3.** *a*, Rainfall observations at 3-hourly intervals over Santacruz and Colaba on 26 and 27 July 2005. *b*, Same as (*a*) but cumulative totals. *c*, Same as (*a*) but at 1-hourly intervals from 1430 to 0230 h IST of next day.



**Figure 4.** Daily rainfall over Santacruz during June to August 2005.

**Table 2.** Highest 24 h rainfall records in India and the world

Rainfall (cm)	Station (State/UT)	Date
<b>India</b>		
116.8	Amini Devi (Lakshadweep)	5–6 May 2004
103.6	Cherrapunji (Meghalaya)	13–14 June 1876
99.8	Cherrapunji (Meghalaya)	11–12 July 1910
99.6	Kasauli (Himachal Pradesh)	17–18 June 1899
98.9	Mawsynram (Meghalaya)	9–10 July 1952
98.7	Dharampur (Gujarat)	1–2 July 1941
98.9	Cherrapunji (Meghalaya)	12–13 September 1974
94.4	Santacruz (Maharashtra)	26–27 July 2005
Rainfall (cm)	Station and country	Date
<b>World</b>		
184.1	Cilaos, Reunion Island	15–16 March 1952
179.6	Foc Foc, Reunion Island	7–8 January 1966
166.2	Belouvc, Reunion Island	27–28 February 1964
155.2	Aurere, Reunion Island	7–8 April 1958
137.8	Muuocaicang, Nei Mougol China	1–2 August 1977
122.8	Paishih, Taiwan	10–11 September 1963
117.5	Halaho, Taiwan	9–10 September 1963
116.8	Amini Devi, India	5–6 May 2004
115.0	Bagerio, the Philippines	14–15 July 1911
112.3	Belledenker QLD, Australia	3–4 January 1979

Daily rainfall of Santacruz plotted in Figure 4 shows reduction of rainfall from 11 cm on 21 July to 3.9 cm on 22 July. It further reduced to 0.4 and 1.2 cm on 25 and 26 July. Rainfall observations for other stations from India show that mostly dry weather conditions prevailed over North India and northern Maharashtra during 22–25 July, though parts of southern and eastern India, including south Madhya Maharashtra and South Konkan and Goa had reported scattered to fairly widespread rainfall activity during the same period. Occurrence of such contrasting spatial rainfall pattern is normally associated with revival of break/weak monsoon conditions over India<sup>6</sup>. Analysis of circulation and rainfall pattern over India before and during the occurrence of the present rainstorm also confirms that the break/weak monsoon prevailed over India during 19–22 July, which was subsequently revived over southern and eastern parts of India during 23–25 July. After the occurrence of the devastating rainfall event of 94.4 cm during 26–27 July over Mumbai, Figure 4 shows the occurrence of subdued rainfall thereafter till 31 July, followed by very heavy rainfall of 20.8 and 14.9 cm respectively, on 1 and 2 August. Then, rainfall was again subdued over Mumbai till the end of the August (Figure 4).

### Comparison with other one-day rainstorms

Though the rainfall of 94.4 cm is an all-time record for Mumbai, there have been records of heavier rainfall at other places in the country before. Even during 26–27

July, as stated above, Vihar Lake near Santacruz, Mumbai and a non-IMD observatory reported rainfall of 104.9 cm. The other highest 24 h rainfall records in India (collected from National Data Centre of IMD at Pune) and the world<sup>7</sup> are given in Table 2.

Table 2 shows that the most extraordinary rainstorms ever recorded on earth have occurred on the small and mountainous Indian Ocean Island of Reunion. This is located 21° south of the equator, some 500 miles east of the island of Madagascar. It is located directly on the normal path of the tropical cyclones in the southwest Indian Ocean. The island is only about 50 miles in diameter at its widest and has several tall volcanic mountain peaks, the height of which reaches an elevation of 3069 m. When the tropical storm strikes, the mountains provide phenomenal orographic lift for the storm moisture, enhancing the rainfall intensity.

It is interesting to note from Table 2 that the most extraordinary rainstorm ever recorded in India has also occurred in Amini Devi, a small Island in Lakshadweep. The rainstorm occurred during 5–6 May 2004, due to the formation of a depression near the island on 5 May, which intensified to a cyclonic storm on 6 May by remaining nearly quasistationary there for almost 24 h. The other record-holding stations, e.g. Cherrapunji, Kasauli and Mawsynram are in the hilly regions of Himalaya. In fact, Cherrapunji and Mawsynram are two well-known stations in the world climatology for the occurrence of the highest annual rainfall. Hence, Table 2 shows that the heaviest 24 h rainfall has been experienced in case of either a tropical storm or in the hilly regions or due to a combination of both. The other heaviest rainfall in India has also been recorded at Dharampur in the vicinity of Mumbai. Dharampur in south Gujarat is about 250 km north of Mumbai. This indicates that the region around Mumbai is prone to this type of extreme weather events, which have occurred in association with active monsoon conditions over the area, the favourable conditions for which have been discussed elsewhere in this article.

### Possible causes

#### *Mesoscale system embedded in favourable synoptic scale flow pattern*

Before the occurrence of the present severe rainstorm over Mumbai, break/weak monsoon conditions were observed over India during 19–22 July. The monsoon revived due to the formation of a low-pressure area over north Bay of Bengal off Gangetic West Bengal–Orissa coast on 23 July. The system persisted over the same area for two subsequent days and became well marked on 25 July. It moved slowly inland and lay over Orissa on 26 morning. By then, the monsoon had revived over peninsular India and parts of east coast of India, while most parts of

northwest India, including Gujarat and northern Maharashtra experienced dry conditions. It may be noted that the low-pressure area moved fast on the day when Mumbai received very heavy rainfall, and lay over central parts of Madhya Pradesh on 27 morning. It became less marked on 29 July over southeast Rajasthan. By then, the monsoon had also revived over most parts of India.

Another low-pressure area formed over northwest Bay of Bengal off Orissa coast on 28 July, which intensified into a depression on 29 July and to a deep depression on 30 and lay close to Chandbali, Orissa. Then, it lay near Jharsugura, Orissa on 31. It weakened to a well-marked low and moved fast to Sagar in central Madhya Pradesh on 1 August. It weakened into a low near Guna, northwest Madhya Pradesh on 3 August and further weakened on 4 August over east Rajasthan.

Observations also show strengthening of the Arabian Sea branch of the monsoon in association with formations of both the systems in the Bay of Bengal. Both the systems were responsible for overall strengthening of rainfall activity over the west coast of India. As discussed earlier, the occurrence of rainfall from 24 to 27 July over the west coast, including the record highest rainfall of 26–27 July in Mumbai (Figure 4) was partly due to strengthening of winds over the west coast, which in turn was because of the formation of the first monsoon disturbance over north Bay and its westward movement during 24–27 July, as discussed before. The offshore trough was present in the sea level chart from Konkan coast to Karnataka coast during this period, but it was shallow. There was temporary reduction in rainfall over the west coast, including Mumbai for two days after 27 July, when this system moved far westwards and weakened. With this movement, the rainfall zone also moved northwards to Gujarat after 27. There was a second spell of very heavy rainfall with significant increase over the state, including Mumbai from 31 July to 2 August, with the value reaching 20.8 cm on 1 August at Santacruz (Figure 4). This is again because of the response of Mumbai to the formation and movement of the second monsoon disturbance from the Bay of Bengal to Central India as described before and an offshore trough off the west coast. It may be noted that both the monsoon disturbances had moved fast to Central India during occurrences of both the heavy rainfall events over Mumbai.

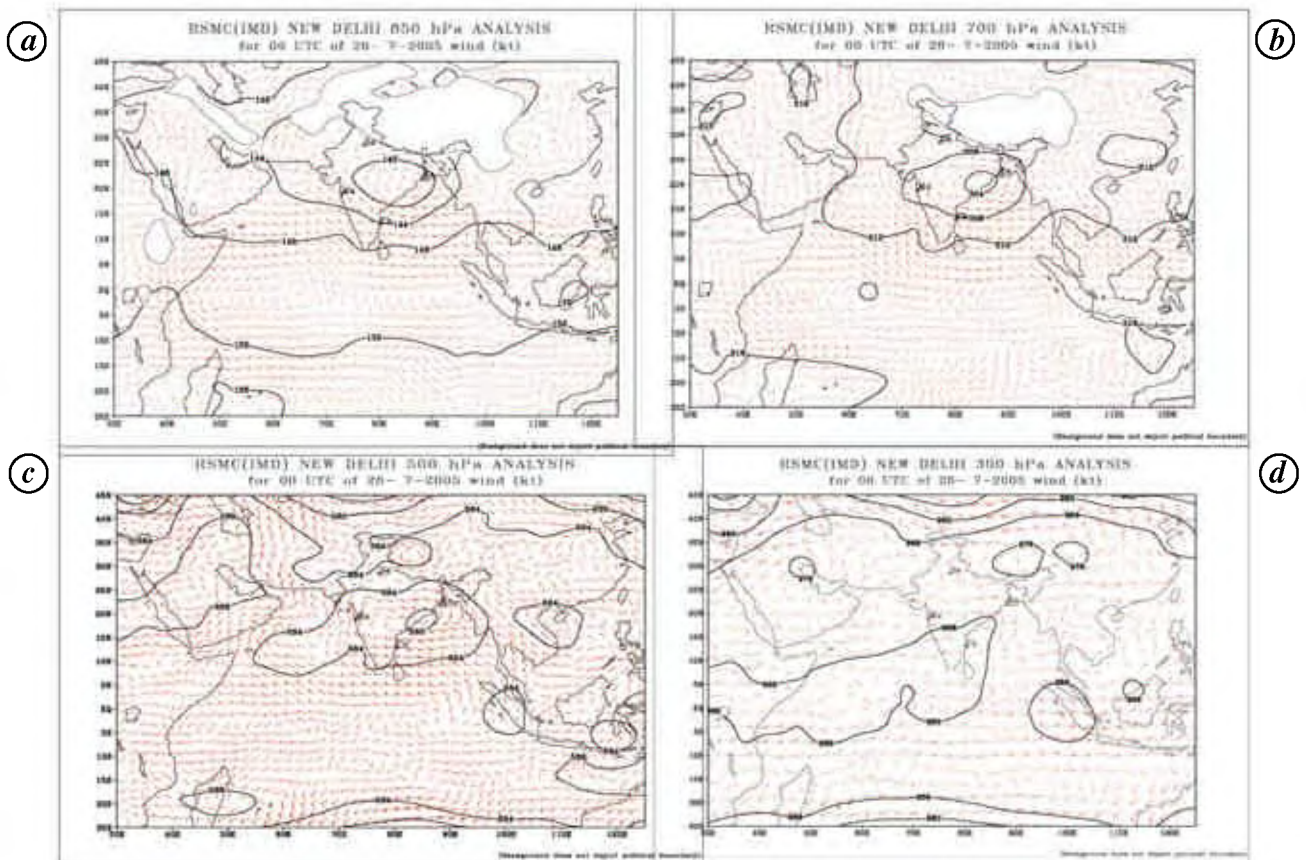
An earlier study<sup>8</sup> showed that a pressure gradient of about 4–8 hPa along the west coast of India between 15 and 20°N is necessary for the occurrence of a heavy rainfall event in the Mumbai belt. This combined with a trough off Konkan coast or a low near Saurashtra or a depression forming in the Bay or moving across west Madhya Pradesh, is more effective than the pressure gradient alone<sup>8</sup>. In the present case, it is also noted from 3-hourly synoptic surface chart that pressure gradient remained nearly 4–6 hPa from 0530 to 1730 h IST of 26 July, along the west coast between 15 and 20°N, when this exceptional heavy rainfall occurred. Sarma<sup>9</sup> studied the variation of heavy rain-

fall >5 cm at Mumbai between Santacruz and Colaba during July–September. The study also shows that on days of large variation in rainfall, westerly winds are of the order of 30–40 knots and the depth 3 km or more, while on days of little variation of rainfall, the speed is less than 20 knots and depth 1.5 km. In the present rainfall event of 26–27 July, when there was a record highest difference of rainfall received in both the stations, observed westerly winds were also of the order of 30–55 knots, with depth up to 5.8 km or more.

Hence synoptic-scale features were highly favourable for the occurrence of heavy to very heavy rainfall over Konkan and Goa and other parts of Maharashtra. This insight seems to have helped forecasters to predict the same 48–72 h in advance, in their daily weather forecasts. These forecasts were issued mainly based on synoptic analysis of large-scale features and certainly failed to capture day-to-day variation of intense rainfall activity which occurred in mesoscale, as is the case with Mumbai.

It is apparent that large-scale features alone cannot explain a phenomenal rainfall event of this kind. We have tried to analyse both synoptic and mesoscale features further to figure out scale interaction that might have led to the occurrence of such a severe rainstorm over Mumbai. Figure 5 shows large-scale flow pattern over the Indian region observed at 0000 UTC of 26 July at different standard levels of the atmosphere. It shows the presence of strong cyclonic circulation extending up to mid-tropospheric levels tilting southwards with height near Orissa and east Madhya Pradesh, associated with the well-marked low-pressure area on the surface. But over the western part of India, it does not show the presence of any MTC over northeast Arabian Sea off Gujarat–Maharashtra coast. One can clearly note the prevalence of strong westerly/northwesterly winds with speed of 30–50 knots in the lower level at 850 hPa over Mumbai (Figure 5a), which becomes northerly at 700 hPa (Figure 5b), northeasterly at 500 hPa (Figure 5c) and easterly at 300 hPa (Figure 5d). Nearly similar conditions prevailed over Mumbai on 24 and 25 July, two days before.

To support this, we have also plotted wind speed and wind direction from radio sounding data of Santacruz in Figure 6a and b at different levels, for 24–27 July up to 300 hPa. It may be noted that the upper air radio sounding data of Mumbai is available for all days for all levels up to 150 hPa or above, except at 0000 and 1200 UTC of 26, for which these data are only available up to 250 and 550 hPa respectively. Figure 6a and b shows that wind speed between 925 and 850 hPa reached up to 48–52 knots on 25 and 26 July in a westerly direction. However, wind speeds near the surface during these days were of the order of 5–10 knots. Figure 6b shows angle of wind direction towards the station. It shows that wind direction in the lower levels remained between 270 and 310° from 1000 hPa up to 600 hPa during 24–26 July. Hence angle of wind direction at the lower levels over the station was

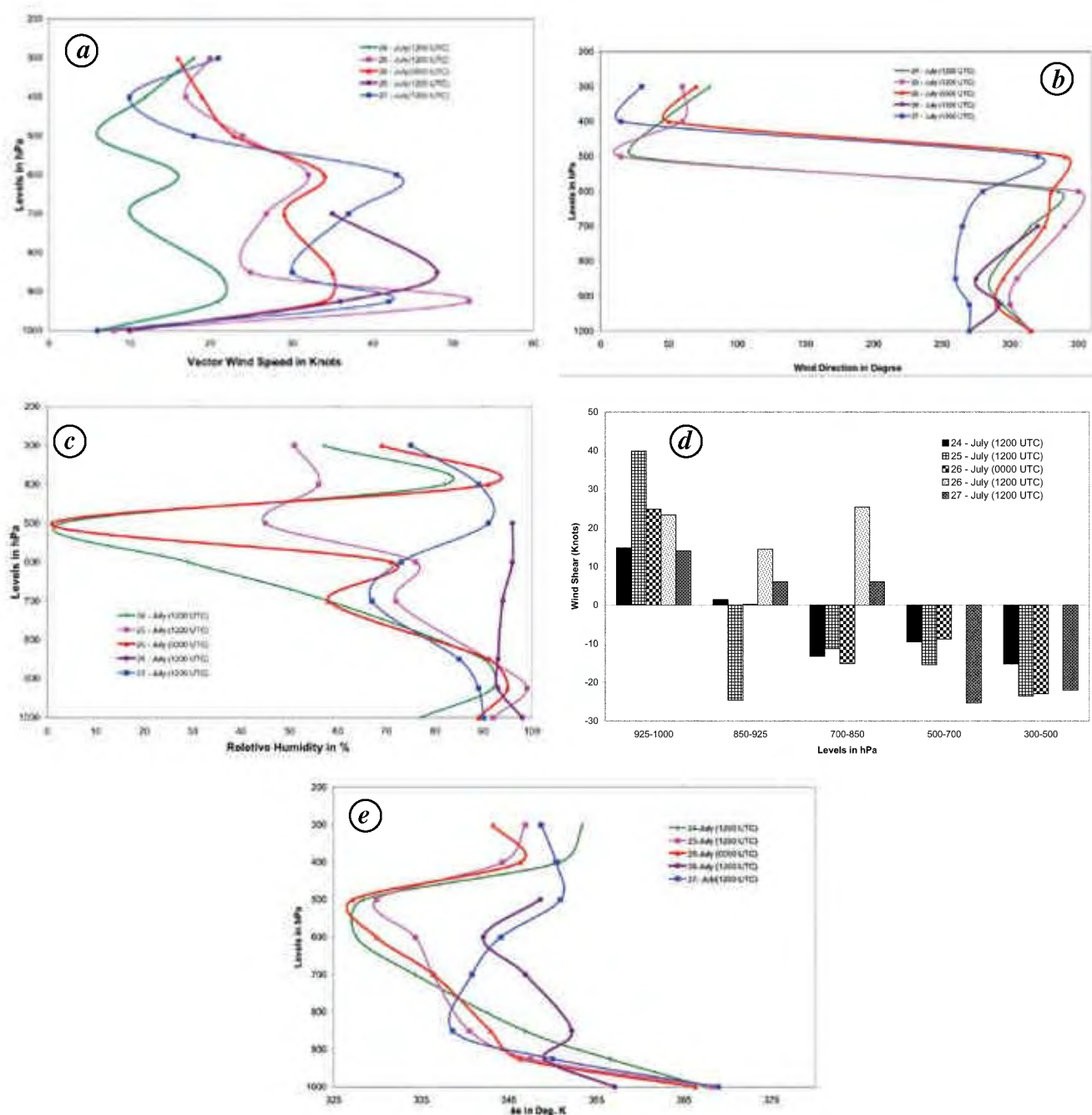


**Figure 5.** Circulation pattern at 0000 UTC on 26 July 2005 at (a) 850 (b) 700 (c) 500 and (d) 300 hPa (Wind barb indicates wind direction and wind speed. It points in the direction 'from' which the wind is blowing, with each short barb representing 5 knots and each long barb 10 knots). Contours are geopotential heights in metres.

mainly westerly, with least variation before and during the occurrence of the present severe rainstorm. Thus, wind conditions were highly favourable at the lower troposphere for continuous moisture incursion from the adjoining Arabian Sea on both a few days before and during the occurrence of the present severe rainstorm. Analysis of the data for further higher levels in Figure 6a and b shows decrease in the wind speed to below 30 knots and change in wind direction, with pressure height from 315–355° (i.e. northwesterly or northerly) at 700 hPa to 5–60° (i.e. northerly or northeasterly) at 300 hPa, indicating that winds were veering with height before and during the occurrence of the present rainstorm in Mumbai. One may further note from these figures about the least changes of both wind speed and direction with height from near the surface till 500 hPa at 1200 UTC of 27 July over Mumbai. But during 25–26 July (1200 UTC), i.e. before and during the occurrence of the present severe rainstorm, there was abrupt strengthening of wind speed between 925 and 850 hPa followed by abrupt weakening at subsequent levels, with direction changing from westerly to northeasterly with height. Veering is defined as a clockwise turning of wind direction as we move up through the atmosphere. It is

always accompanied by warm air advection<sup>10</sup>, which also happened over Mumbai region before and during the occurrence of the present severe rainstorm.

Figure 5 also shows the interaction of two kinds of air masses near north of Mumbai. The air mass prevailing at the lower level up to 700 hPa and having strong westerly/northwesterly direction, was moist in characteristic with completely maritime origin, as it originated from the sea area and was part of the low-level Somali jet which became westerly over the Arabian Sea then westnorthwesterly near Mumbai. Vertical relative humidity profile plotted for Mumbai in Figure 6c also confirms this, as their values are higher during 25–26 at the lower levels compared to 24 and 27 July. The flow prevailing at the mid-level was mostly dry northnorthwesterly winds and colder in characteristic as it had continental origin. As discussed before, very heavy rainfall over the west coast of India was confined to south of Mumbai from 24 to 26 July, which was associated with the revival of break/weak monsoon that prevailed before over India during 19–22 July, while north of Mumbai, Gujarat and West Rajasthan experienced mostly dry weather from 23 to 26 July. Thus, it supports the fact that the winds which came through the latter re-



**Figure 6.** (a) Wind speed, (b) direction, (c) relative humidity, (d) vertical wind shear and (e)  $\theta_e$  (all parameters are for 24–27 July).

gion from the north at upper levels towards Mumbai until the morning of 26 were relatively dry northerly.

Daily NCEP temperature and moisture data ([www.cdc.noaa.gov](http://www.cdc.noaa.gov)) are also critically analysed for the period 24–27 July to find whether these two air masses have such distinct characteristics or not. Daily spatial composites of air temperature, relative humidity and precipitable water content at different standard levels from 1000 to 200 hPa for 24–27 July, showed that the winds in the lower levels

up to 700 hPa coming from the west were more moist and warmer, while those at mid-tropospheric level from the north were relatively drier and colder.

It may be noted that this interaction of air masses had happened during 24–26 July over Mumbai just when break monsoon which prevailed during 19–22 July, had started reviving due to the formation of a low pressure over the Bay of Bengal on 23 July. Hence, except the warm isotherm west of Mumbai in the Arabian Sea at lower

levels with colder isotherms at its north, isolated warmer isotherms at lower levels are also observed north of Mumbai. However, advection was from west at these levels due to prevailing of strong westerlies up to 50 knots from the Arabian Sea, thus bringing warm and moist air from the west. Rao<sup>1</sup> has also shown that in break/weak monsoon conditions, in the west of Mumbai it is warmer and in the north up to the Himalayas, temperature decreases at mid levels. It is perhaps the warmer air spreading across northern India from the west and the cooling associated with rainfall along the Himalayas that may cause the temperature to increase towards south from the Himalayas in break monsoon situation.

Sawyer<sup>11</sup> studied the boundary between the monsoon air mass and the continental air mass over northwest India during advance phase of the monsoon, which is similar to the revival of break monsoon as it is in the present case. He demonstrated that continental air warmer than the monsoon air up to 700 hPa, lies above the latter at these levels. Above 700 hPa, the monsoon air being warmer will overlie the continental air. It has been observed in association with severe thunderstorms that a lid of warm, dry air at the top of the moisture boundary layers also appears to be favourable for the development of severe thunderstorms. Such a lid inhibits early release of convective instability which finally helped in establishing intense convective instability in the atmosphere with time. Interaction of these two peculiar types of air masses and their veering are very much favourable for severe thunderstorms<sup>12,13</sup>. We have also shown from observations that this rainfall event was partly associated with the occurrence of severe thunderstorms.

Study of relative humidity at different levels for 24–27 July in Figure 6c, shows that the relative humidity reached its highest values at 1200 UTC of 26 July compared to all other days. It was nearly 90–95% at various levels for which observations are available. An updraft in the low levels (0–3 km) along with relatively strong ambient vertical wind shear might have triggered the development of additional lifting forces needed for the occurrence of severe localized rainstorm like the present one. Hence, we have computed vertical wind shear of zonal component of wind over Mumbai between different standard levels from 1000 to 300 hPa and plotted in Figure 6d, rather than computing only one value between 850 and 200 hPa. It shows the presence of strong vertical wind shear over Mumbai at lower level between 925 and 1000 hPa with the order of magnitude as 23–40 knots from 1200 UTC of 25 till 1200 UTC of 26 July, i.e. just before and during the event. In fact, the highest ever positive wind shear for the data period irrespective of different pressure levels was observed at 1200 UTC of 25 with the order of 40 knots between 925 and 1000 hPa, which was just one day before the occurrence of the event. It was followed by another high value of 30 knots at 1200 UTC of 26 observed at further higher level between 700 and 850 hPa, which was

just during the time of occurrence of the most severe part of the present rainstorm when the rainfall intensity reached its peak. However, it was of low value on 24 and 27 July between respective levels.

In Figure 6d, vertical wind shear between the subsequent higher levels shows the presence of negative wind shear, i.e. subsidence, most of the time with large variation in their values. In Figure 6d, the highest negative wind shear values were observed at 1200 UTC of 25 and at 0000 UTC of 26 between 850 and 925 hPa as also 500 and 700 hPa respectively. In other words, at 1200 UTC of 25, warm and moist westerly air which lay at a very lower level was strongly lifted up to 925 hPa from the lower level with simultaneously strong subsidence of dry and cool winds over the region in the aloft. On the next day, at 0000 UTC of 26, i.e. just before the rainfall event, though vertical uplifting continued up to 925 hPa, the strong subsidence of dry and cool air which was there between 850 and 925 hPa in the previous day's observation at 1200 UTC, weakened to nearly 0 (see Figure 6d) at 0000 UTC of 26. Finally on 1200 UTC of 26, such vertical wind shear was observed to be positive and very high between 700 and 850 hPa (no observation is available at 500 hPa for 1200 UTC of 26). Hence, vertically uplifting of moist air mass was highest at 1200 UTC of 26 among all observations between 24 and 27 July, when rainfall intensity reached its peak.

As discussed before in the present study, the large-scale/synoptic atmospheric flow over Mumbai city was highly favourable from 24 July onwards. It was followed by a local environmental setting, which provided a conducive environment for the occurrence of intense thunderstorm on 26 July. We have supported with observations in the next section, that a mesoscale severe thunderstorm developed in the highly favourable large-scale/synoptic flow pattern that existed before, which subsequently resulted in exceptional heavy rainfall in the city. Hence the rainfall event that resulted in exceptional heavy rainfall of 94.4 cm in a 24 h time period can be defined as the combination of an intense mesoscale event (called as intense thunderstorm) with time period of 6 h and scale of the system as  $35 \times 20 \text{ km}^2$  that occurred in the afternoon due to interaction of two air masses embedded on already occurring very heavy rainfall due to highly favourable synoptic-scale/large-scale monsoon features prevailing over the region before the event, having timescale of 3–4 days and scale of the system in terms of 1000 km. Thus, we conclude that in the tropics, the interaction of two distinct air masses giving intense thunderstorm towards the afternoon/evening, as it happened in Mumbai with abundant moisture available from the Arabian Sea, when 70% of the total rainfall was realized in 6 h, might not be unusual. What is unusual is that the occurrence of the 24 h event that resulted in 94.4 cm of rainfall was a scale interaction with simultaneous occurrence of an intense thunderstorm embedded on already prevailing highly favourable synop-

tic-scale/large-scale monsoon feature over the Maharashtra region before and after.

### *The event was an intense thunderstorm*

Severe thunderstorms are normally of high frequency and most violent over India during summer from April to June, when the atmosphere is highly unstable because of high temperatures prevailing at lower levels. However, in the main monsoon months of July and August, their frequencies over India are less. For the occurrence of thunderstorms, three factors are essential, i.e. instability, an uplifting mechanism and moisture in the lower and mid levels of the atmosphere. An unstable air mass is warm and moist near the ground and relatively cold and dry in the upper atmosphere. If an air mass is unstable, air that is pushed upward will continue to rise. Lift is the mechanism that pushes the air upward. Sources of lift can be synoptic-scale low-level convergence, orography, or differential heating. These 'warm pockets' are less dense than the surrounding air and bound to rise once pushed up. In case sufficient moisture is available, moisture condenses into small water drops as air rises in a thunderstorm updraft which forms clouds. When the moisture condenses, heat is released into the air, making it warmer and less dense than its surroundings. This helps the updraft to continue.

Precipitation during the monsoon over India could be in the form of thundershowers, showers or rain<sup>1</sup>. Each type occurs according to the prevailing synoptic conditions, e.g. onset, active/break monsoon, withdrawal, etc. The most striking features of monsoon rain is the occurrence of lesser number of thunderstorms along the west coast of India to the south of 20°N, once the monsoon is established. This is because of the prevalence of a highly moist air mass in great depth in the lower levels with instantaneous availability of weak low convergence, which does not leave any chance for intense convection to develop that may lead to the occurrence of a thunderstorm. It has also been found that the growth of cumulus clouds above 6 km is inhibited by the wind shear due to the easterlies aloft<sup>14</sup>. However, during the onset/withdrawal phase or prevalence/revival of break monsoon conditions<sup>15</sup>, fairly widespread thunderstorm activities have been observed over many stations, especially from those located in northwestern and peninsular India, including Mumbai. This is mainly because of the factors discussed by Sawyer<sup>11</sup>.

As the rainfall over Mumbai after arrival of the monsoon is generally not associated with severe thunderstorm activity, the monsoon cloud tops are of relatively lower height along the west coast of India<sup>3</sup>. Climatological study of thunderstorm days over Mumbai<sup>16,17</sup> shows occurrence of highest in June with frequency of 5.5 days per month, during which the monsoon normally advanced over the region, followed by October with 4.0 when monsoon started withdrawing from the region, few thunder-

storm activities are observed in July and August. Their mean frequency is only three per month for July as against 24 rainy days in the month. Mostly, these thunderstorms might have occurred during weak monsoon/break monsoon conditions when there is incursion of dry air at mid-troposphere<sup>1</sup>. Climatological study of squall reports over Mumbai too shows highest occurrence in June and October, one per year for both months followed by few in July (0.3 per year) and August having no squall. However, autographic weather observations in Santacruz on 26–27 July 2005 showed the occurrence of 94.4 cm rainfall in 24 h, which reached the highest intensity in the afternoon/evening (Figure 3), was associated with severe thunderstorm activity. Autographic weather observations and synoptic observations at Santacruz reported thunderstorms and lightning with rain at 1400, 1700, 2202 h IST of 26 and at 0530 h IST of 27 July. Squall with wind speed reaching 42 knots was experienced at 1630 h IST of 26. Because of intense thunderstorm activity with the presence of deep clouds in the afternoon, the minimum temperature over Santacruz between 0830 h IST of 26 and 0830 h IST of 27 was recorded as 24.1°C at 1700 h IST, i.e. in the afternoon of 26 July. The period of lowest temperature occurred between 1430 and 1730 h IST, whereas this is the epoch of the maximum temperature over the station under normal circumstances.

We have compared the timing of occurrence of this thunderstorm and squalls with the climatological timing of occurrences. Climatological study of daily occurrence of thunderstorm and squall timings in July<sup>16,17</sup> showed commencement timing of thunderstorms distributed throughout the day, least in the early morning, while in case of squalls, the most favourable timing is from 1430 to 2330 h IST, when maximum squalls occurred. Hence there is nothing unusual with the occurrence timing of both squalls and thunderstorms, as had happened in the present case.

McNulty<sup>18</sup> argued that it is important for forecasters to be able to distinguish between severe and non-severe thunderstorms. It has been found that if the environment (uplifting, instability or moisture) of a thunderstorm changes, then the type and characteristics of the thunderstorm that formed before may also change. The amount of vertical wind shear in a storm's environment at lower levels, is critical in determining the type of storm that will form. If the vertical wind shear is weak, multicellular storms with short-lived updrafts will be favoured. Studies by McNulty<sup>18</sup>, and Johns and Doswell<sup>19</sup> have indicated that the three determining factors in such a decision are, extreme instability, strong vertical wind shear, and mid-level dry air or an intrusion of dry air at mid-level. If the vertical wind shear at very lower level is stronger as was the case for Mumbai, then storms with longer-lived updrafts will develop. Closely related to the concept of vertical wind shear is veering, which was also favourable over Mumbai on 26

July. Veering of low-level wind is instrumental in the production of thunderstorm rotation. Once this vertical rotation is established, a mesocyclone can develop which may produce a supercell or significant severe weather. The amount of moisture in the air has an effect on thunderstorm too. If the amount of moisture is low, then the storms tend to have high bases. If the amount of moisture is high, the storms tend to have low bases. Lower the cloud base, better is the chance for flash flood-producing rains. It may be noted that the existed environment over Mumbai on 26 July was characterized by high instability, strong vertical wind shears at the lower levels and veering of the wind with height with sufficient moisture supply from the Arabian Sea by the prevailing large-scale monsoon circulation. As a result, development of the severe thunderstorm in the form of supercell or mesocyclone towards afternoon/evening over Mumbai region, when the most intense spell of rainfall occurred, cannot be fully ruled out.

To find out whether atmospheric thermodynamic conditions prevailing over Santacruz have supported the occurrence of such localized severe thunderstorm embedded in large-scale favourable monsoon circulation due to interaction of two distinct air masses as discussed earlier, we have analysed daily atmospheric vertical sounding data from 22 July to 4 August when such an event occurred on 26 July and rainfall again increased on 31 July and 1 August. An attempt is also made to examine different instability indices.

Variation of convection in the atmosphere depends upon dynamics as well as thermodynamics instability indices.  $\theta_e$  or equivalent potential temperature is the prime parameter for measuring moist convective instability. Steeper the fall in the values of equivalent potential temperature, more is the presence of convective instability. A critical parameter for atmospheric convection is the convective available potential energy (CAPE), a measure of the vertical instability of the atmosphere under moist convection. CAPE is the work done by the buoyancy force on a parcel lifted through the atmosphere moist adiabatically and is given by<sup>20</sup>

$$\text{CAPE} = - \int_{\text{LFC}}^{\text{LNB}} (T_{vp} - T_{ve}) R_D d(\ln p),$$

where  $R_D$  is the gas constant of dry air;  $T_{vp}$  and  $T_{ve}$  are respectively, the virtual temperatures of the parcel and the environment at pressure  $p$ , LFC and LNB are levels of free convection and neutral buoyancy. Deep clouds can develop due to the ascent of air from a given level, only if its CAPE is greater than zero.

When disturbances occur, precipitation, strong winds and downdrafts decrease the energy of the air from a given level, only if its CAPE is greater than zero.

Normally, air is not saturated to start with and a finite vertical displacement (a few hundred metres to a few

kilometres) is needed for the rising air parcel to become saturated and reach the level of free convection. Some energy is required for this process, and is called convection inhibition energy (CINE)<sup>20</sup>

$$\text{CINE} = - \int_{\text{SURFACE}}^{\text{LFC}} (T_{vp} - T_{ve}) R_D d(\ln p).$$

It is expected that a larger value of CINE means an increased barrier to convection. If CINE is large, deep clouds will not develop even if CAPE is positive, while low values of CINE imply a favourable condition for convection.

Figure 6e shows values of  $\theta_e$  with height over Mumbai for the period 24–27 July, which covers a few days before the present rainstorm till 27 July. It shows that fall of  $\theta_e$  with height was high at 1200 UTC of 25 and at 0000 UTC of 26 July between 1000 and 925 hPa as well as 700 and 500 hPa respectively. Hence intense convective instability was present in the lower and mid-level a day before the start and at the time of occurrence of the present event which led to severe thunderstorm in the afternoon/evening of 26 July. We have also computed the net difference of  $\theta_e$  between 1000 and 500 hPa during these dates and the values are 39.2 K for 1200 UTC of 24, 38.3 K for 1200 UTC of 25, 39.1 K for 0000 UTC of 26, 9.5 K for 1200 UTC of 26, and 18.0 K for 1200 UTC of 27 July. This comparison also confirms that instability was very high before the occurrence of the event, which reduced significantly just following the event.

Figure 7a and b shows CAPE, CINE and precipitable water content (PWC) respectively from 22 to 28 July over Santacruz. Figure 7a shows continuous and steep increase in CAPE values from 702 J kg<sup>-1</sup> on 22 July to its highest values of 4341 J kg<sup>-1</sup> on 25 July, just one day before the occurrence of the rainfall event. The value decreased to 3267 J kg<sup>-1</sup> on the day of the occurrence of the rainfall and further reduced to 252 J kg<sup>-1</sup> on 27 July. It increased again after the event. Hence, CAPE increased by 3000–4000 J kg<sup>-1</sup> before convection and decreased by nearly similar magnitude following convection. It again recovered after 1–2 days causing another spell of heavy rainfall. Figure 7b also shows the presence of high CINE values of the order of –22.6 and –06.6 J kg<sup>-1</sup> on 23 and 24 July respectively, i.e. before the rainfall event and of –5.51 and –29.86 J kg<sup>-1</sup> on 27 and 28 July respectively, i.e. after the event with the lowest values of 0 on 25 and 26 July when the event occurred. Bhat *et al.*<sup>21</sup> also observed that CAPE decreased by 3000–4000 J kg<sup>-1</sup> following convection and recovered in a time period of 1–2 days, while CINE reached its lowest value on the day of rainfall.

When the disturbances attenuate, the air–sea fluxes increase the energy of the surface air, while the temperature of the air aloft decreases because of radiative cooling. These factors destabilize the atmosphere and build up CAPE. For the Pacific warm pool, when disturbances occur,

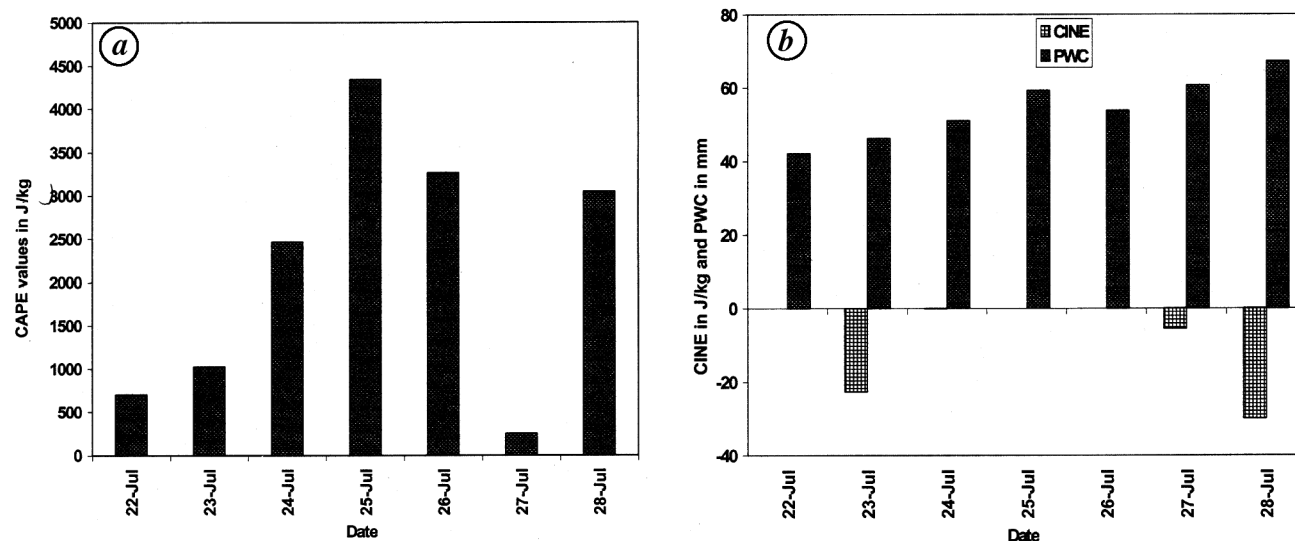


Figure 7. (a) CAPE values and (b) CINE and perceptible water content (PWC) during 23–28 July (all values are for 0000 UTC).

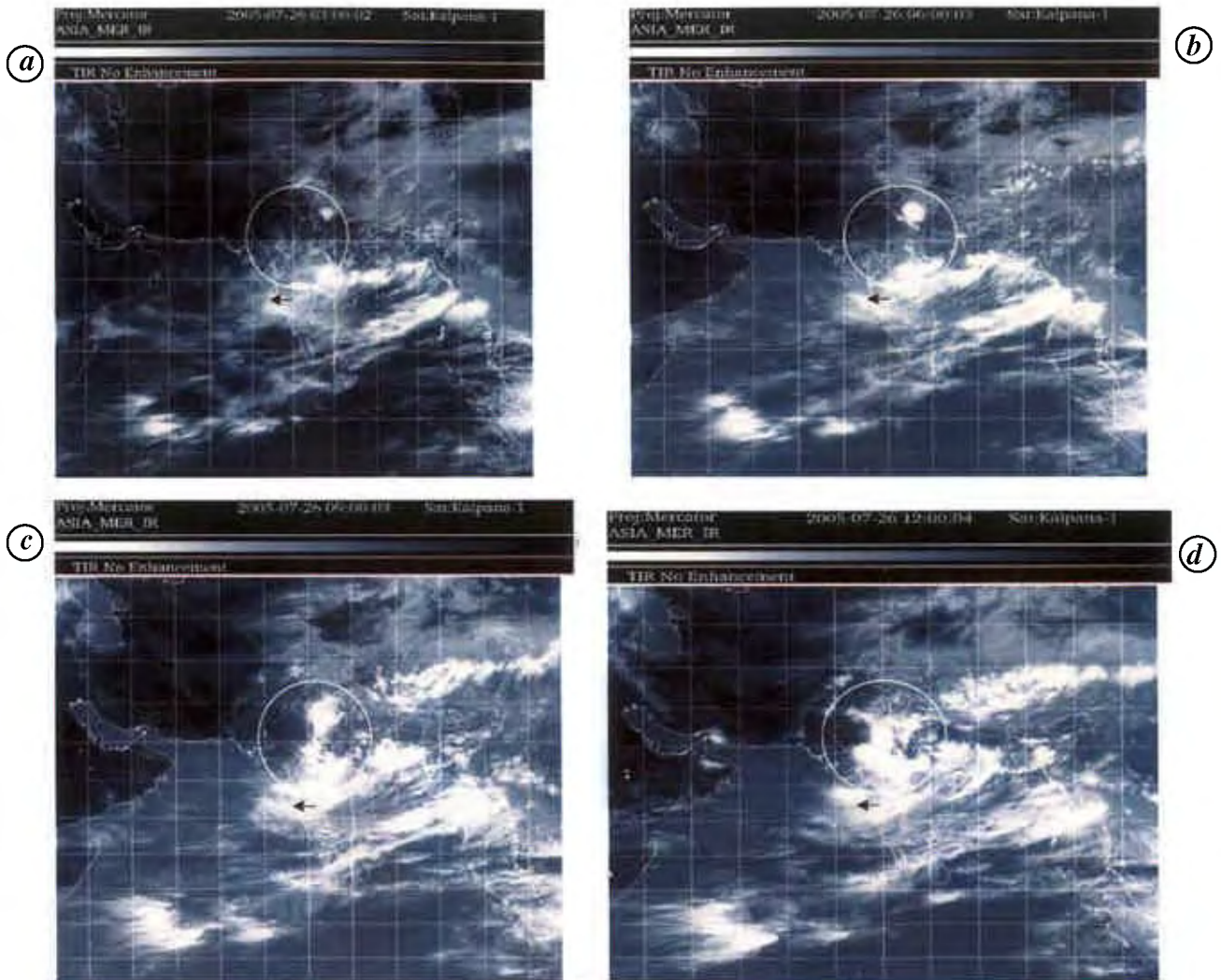
precipitation, strong winds and downdrafts decrease the energy of the air near the surface, while deep cloud activity makes the upper troposphere warmer. As a result, the atmosphere becomes less unstable and CAPE is substantially reduced during disturbances<sup>21,22</sup>. The period between successive disturbances is expected to depend upon the time it takes for CAPE to build up. Bhat *et al.*<sup>21</sup> have analysed the BOBMEX data and have shown for the Indian region that the magnitudes of CAPE and convective inhibition energy were comparable to those for the atmosphere over the west Pacific warm pool. PWC values in Figure 7c also show gradual increase in value from 42.1 mm on 22 July to 59 mm on 25 July one day before the event, followed by a decrease in value to 53.8 mm on the day of the event. It again shows a gradual increase in value to 67 mm on 28 July. Such a small decrease in PWC values on the day of the event followed by increase in PWC values the next day, may be attributed to prevailing strong westerly wind from the Arabian Sea in the large-scale flow, which persisted at the lower levels a few days before as well as a few days after the event.

Various satellite pictures of 26 July available for the Indian region received either through Indian satellite (*Kalpana-1*) or other international satellites are analysed at different resolutions to identify whether any area over Mumbai had distinct intense convective clouds which may correspond to the most severe mesoscale rainstorm that occurred on 26–27 July. Unfortunately, no such distinct cloud mass could be identified to have direct correspondence with the present severe rainstorm over Mumbai. However, we analysed these pictures to identify characteristics of development of clouds on a larger scale that might have worked as a feeder band for the occurrence of the present rainstorm.

From satellite pictures given in Figure 8, one can hardly find the development of any intense convective cloud

over the area north of 20°N of India in the 0300 UTC pictures, in contrast to maximum area covered by clouds at its southern parts. Development of similar cloud pattern is normally observed over India during the revival of break monsoon, which has been studied earlier by Jena-man<sup>6</sup>. Hence the present analysis of satellite pictures also confirms that the severe rainstorm occurred when monsoon was in its revival phase. Together with this, one may also note the development of new intense convective clouds in the area demarcated by white circle in the 0900 and 1200 UTC pictures (Figure 8), mostly confined to the northeast of Mumbai. At 0300 UTC, the same area was mostly free from clouds, while at 0600 UTC, only one cloud cell had been clearly developed. Later, the same cloud cell further developed in a north-south orientation as marked in a line in the satellite pictures at 0900 UTC (Figure 8c) and 1200 UTC (Figure 8d). These newly developed clouds in the afternoon are associated with intense convection which caused severe thunderstorm/rainstorm northeast of Mumbai. Hence, these pictures confirm that afternoon convection was more intense and extended in the northeast of Mumbai than southeast, where rainfall was high. One may also note the presence of intense convective clouds from these pictures over Central India associated with the low-pressure area.

Outgoing Longwave Radiation (OLR) as observed through satellites, is an index of convective activity/cloudiness. Cloudy skies generally disrupt the OLR. Hence, higher the fractional cloudiness, lower are the OLR values. In other words OLR would have an inverse relation with rainfall but the relationship is not one-to-one<sup>23</sup>. Spatial analysis of OLR data from Indian satellite (*Kalpana-1*) on 26 July for different synoptic hours does not show the presence of any area near Mumbai with lowest OLR contour compared to that of Central India, where large-scale intense convective clouds were present due to the fast



**Figure 8.** *Kalpana-1* pictures at 3-hourly intervals from 0300 UTC of 26 July.

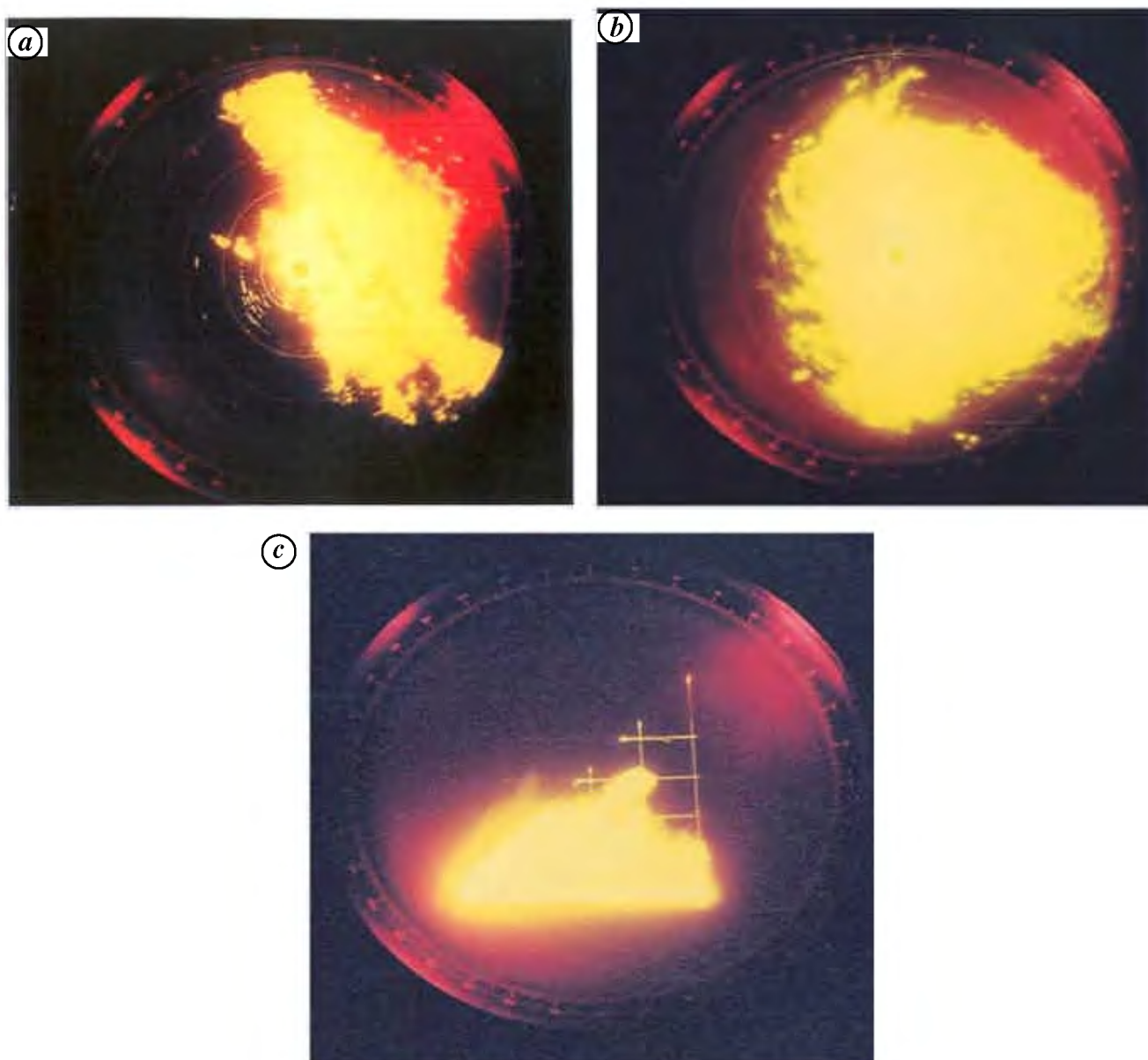
movement of the low towards central Madhya Pradesh from Orissa on this day. Analysis of grid point OLR data around Mumbai showed that the values at the grid nearest to Mumbai decreased to the lowest of  $115 \text{ W/m}^2$  at 0900 UTC from  $157 \text{ W/m}^2$  observed at 0300 UTC on the same day. It may be noted that the rainfall intensity had reached its highest ever value between 0900 and 1200 UTC, as shown in Figure 3 *a*.

We have analysed all pictures of *S*-band radar taken by IMD, Mumbai. The two main types of scans carried out by *S*-band radar for detecting characteristics of different clouds around the given location are the Plan Position Indicator (PPI) and the Range Height Indicator (RHI) scans. When scanning in PPI mode, the radar holds its elevation angle constant, but varies its azimuth angle. The returns can then be mapped on a horizontal plane. When scanning in RHI mode, the radar holds its azimuth angle constant but varies its elevation angle. The returns can then be mapped on a vertical plane. In other words, PPI and RHI images

represent respectively, a horizontal and vertical cross-section of reflecting clouds.

Figure 9 *a* and *b* shows radar pictures for 1130 h IST and 1430 h IST respectively, at PPI mode. Figure 9 *c* shows the radar picture for 1430 h IST at RHI mode. Figure 9 *a* shows that at 1130 h IST, formation of clouds is mainly confined to the northeast sector with northwest to southeast elongation and anvil shape, while in Figure 9 *b*, at the 1430 h IST, it took an oval shape with diameter of nearly 80 km due to the development of new intense clouding at its southsoutheastern sector. Further, clouds were mostly developed at the eastern half of the radar circle in both the pictures, where very high rainfall had occurred (Figure 1).

Figure 9 *c* shows a cloud top of about 17 km height, about 10 km away from the centre. A scan of successive radar observations shows that the cloud of highest vertical growth was constantly observed at a distance of 15–20 km north of Colaba. This indicates that some clouds were of



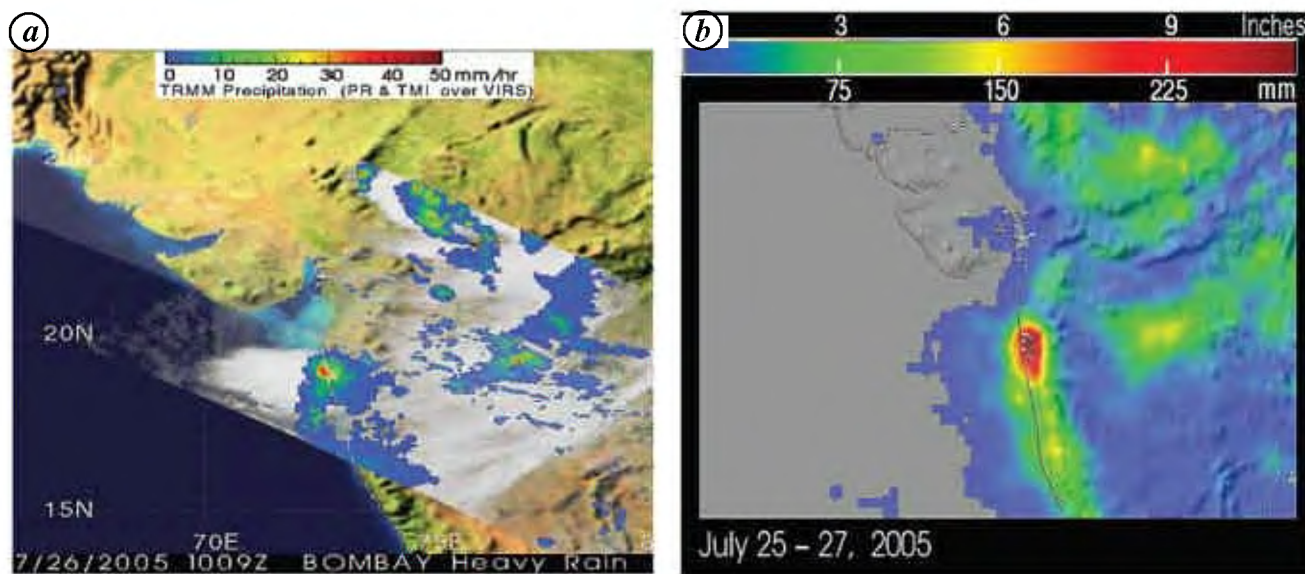
**Figure 9.** PPI and RHI cloud photographs from the storm detecting radar at Mumbai on 26 July 2005. *a*, PPI at 1130 h IST having radar range at 100 km with each range ring of 20 km scale. *b*, Same as in (*a*), but at 1430 h IST. *c*, RHI at 1430 h IST having radar range at 50 km with scale height as 5 km each in vertical, while horizontal scale is 10 km each.

intense convective type, which resulted in severe rain-storm over Mumbai. It may be noted that the present radar is not capable of measuring any characteristics of the present rainfall event, including rainfall rate or its spatial characteristics. Hence, pictures available from other agencies, e.g. Tropical Rainfall Measuring Mission (TRMM) are also referred.

TRMM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA), to monitor tropical and subtropical precipitation and to estimate its associated latent heating. TRMM (<http://trmm.gsfc.nasa.gov/home-page.html>) provides systematic visible, infrared and microwave measurements of rainfall in the tropics as key

inputs to weather and climate research. Satellite observations are complemented by ground radar and rain-gauge measurements to validate the satellite rain estimation techniques. TRMM satellite has been collecting rainfall data since its launch back in November 1997.

TRMM captured an image of the rain over Bombay at 15:39 h IST on the 26 July 2005 (Figure 10 *a*). The image displays the horizontal distribution of rain intensity as obtained from the TRMM sensors. Rain rates in the central part of the swath are from the TRMM Precipitation Radar (PR), the only radar capable of measuring precipitation from space. Rain rates in the outer swath are from the TRMM Microwave Imager (TMI). The rain rates are over-



**Figure 10.** *a*, TRMM captured image of the rain rate over Mumbai at 15.39 h IST on 26 July 2005. *b*, Rainfall accumulation from the TRMM-based near-real time multi-satellite precipitation analysis at the NASA Goddard Space Flight Center for the period 25–27 July 2005.

laid on infrared (IR) data from the TRMM Visible Infrared Scanner (VIRS). The image shows a localized area of heavy precipitation (red area) directly over Mumbai, of the order of 4–5 cm per hour.

The second image (Figure 10*b*) shows rainfall accumulation from the TRMM-based, near-real time Multi-satellite Precipitation Analysis (MPA) at the NASA Goddard Space Flight Center, USA for the period 25–27 July 2005. The dark red area of heavy rainfall (indicating a foot of rain) is concentrated right over Mumbai and shows localized extreme rainfall values of the order of 22–30 cm.

## Discussion

It is well known that orography at the Western Ghats plays an important role in enhancing rainfall over the west coast, including that of Mumbai<sup>1</sup>. Except this, climatological data over different parts of Mumbai region show a large difference of seasonal mean monsoon rainfall, e.g. Colaba, Santacruz and Matheran. Colaba and Santacruz differ in seasonal mean monsoon rainfall amounts by 12%, though both stations are located within a distance of nearly 27 km. A hillock of 300 m within 5 km of Santacruz apparently accounts for this increase<sup>1</sup>. Matheran, which is close to the coastal stations of Mumbai and having height of 756 m, gets high rainfall because of its location on the plateau of a minor range, almost at the beginning of its lee side.

While analysing the micro characteristics of the present rainfall event in Figure 1, observations also confirm the occurrence of two high rainfall areas, one near Santacruz and the other near Matheran. Hence the effect of orography

cannot be completely ruled out. We have not shown any result as evidence to prove how much orography has contributed. However, to elucidate the effect of orography, we would like to show variation of climatological rainfall at coastal stations and rainfall at hill stations located over the crest/top of the Western Ghats available from an earlier study<sup>1</sup>. Rainfall enhancement on account of orography may depend on the slope of the ground, height, configuration of land around the synoptic system and strength of westerly winds to stations. Height alone is not a decisive factor on the role of orography. Agumbe (with height from sea level 659 m) in the Western Ghats gets 718 cm, while Cherrapunji (1313 m) gets 837 cm. In the Western Ghats, Mahabaleshwar at nearly twice the height as that of Agumbe, records 16% less rainfall compared to the latter. Hence the effect of orography, if any, in causing the present rainstorm over Mumbai needs to be studied critically. An important question arises: ‘*Is the deluge in Mumbai an impact of climate change?*’

Scientifically speaking, global warming is expected to accelerate the hydrological cycle and lead to precipitation extremes in some areas at the cost of other places, where droughts may develop. The Intergovernmental Panel on Climate Change<sup>24</sup> outlined in its Third Assessment Report, the likelihood of occurrence of such extremes with higher frequencies in the 21st century. Simple extremes, such as higher maximum land temperatures and more intense precipitation, are projected to be likely with increased chances of their occurring repeatedly<sup>25,26</sup>. These amplified simple extremes could lead to extreme weather events like drought and flooding. Current trends in one-day and multi-day precipitation events are revealing. It seems there is now a tendency to have more days with heavier

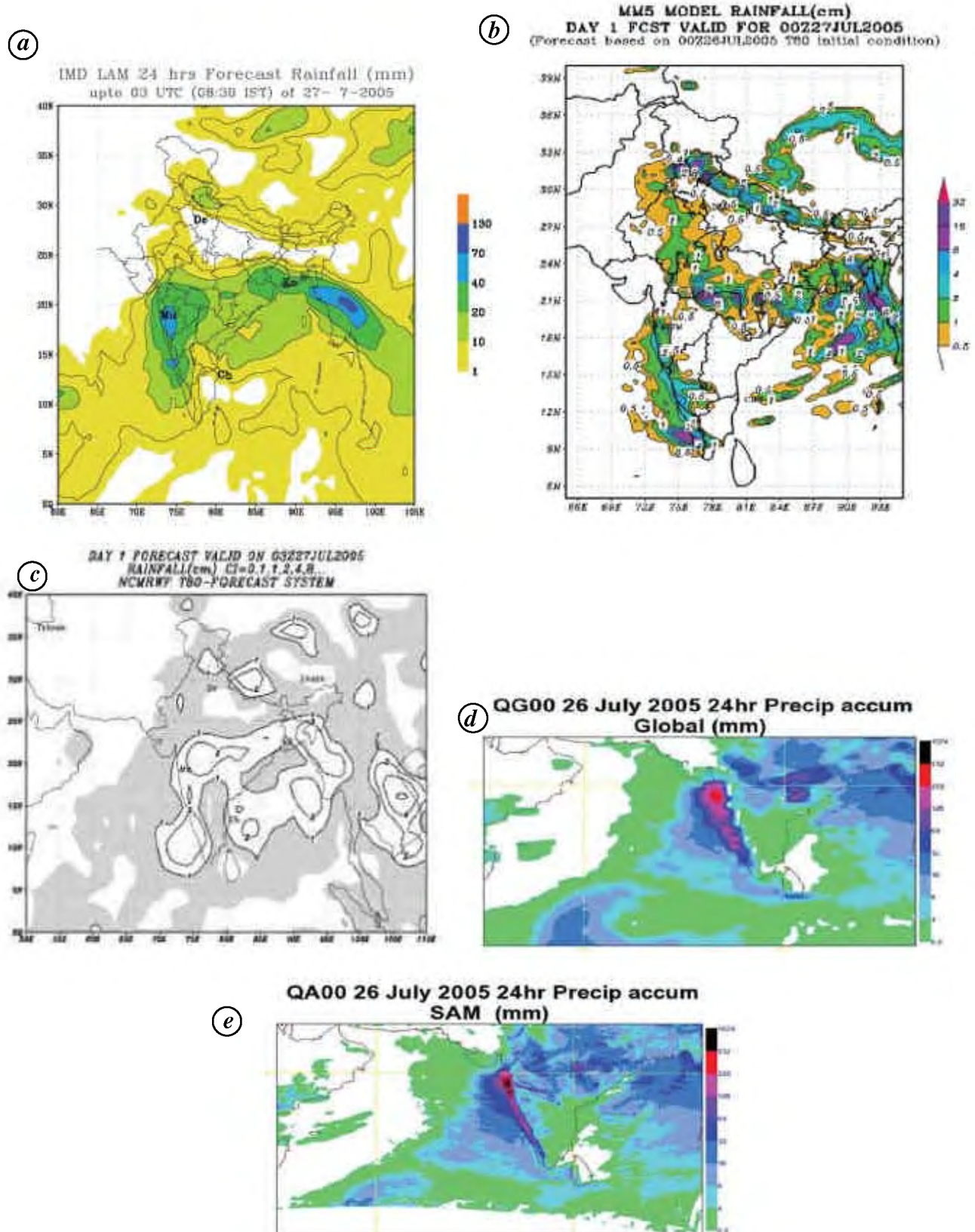
24-h precipitation, even if some of these areas are experiencing a decrease in total annual rainfall. This is yet to be confirmed from larger datasets.

The case of India is interesting while looking at extreme weather events. For a country that has more than 60% of its population relying on agriculture directly or indirectly, the impact of extreme weather events is critical. In the last decade, India has been repeatedly battered by monsoon droughts in 2002 and 2004. Also, one must take into account whether an extreme event is truly *extreme*. The natural variability of extreme weather events is still to some extent unknown, since most historical records on events can only stretch back to less than a hundred years. The cycles that extreme weather events undergo may be on a timescale that is longer than our records, thus making them difficult to foresee. For example, statistically speaking, the probability of an extreme annual precipitation event of 1 in 1000 years still falls within the range of a 'normal' climate. An event that may seem extreme to us may be a purely random variation or part of the natural variability of the earth's climate in the last four hundred years or more. How can the public be better informed about extreme weather events? Historical records do provide some reliable insight into the frequency and intensity of extreme weather events. Yet, as mentioned before, these records are insufficient to give an accurate picture of what to expect. Predictive climate models have been utilized to analyse extreme weather events, but unpredictability of extreme weather events is impeding the process. However two earlier studies<sup>27,28</sup> have improved our confidence in estimating the risk of flooding and extreme precipitation. The first study<sup>27</sup> found that the frequency of severe floods in large river basins has increased during the 20th century. It was established that the likelihood of this increase arising from natural climate variability is small. The other study<sup>28</sup> analysed the output of 19 climate models, predicting that wet winters will be five times more likely in northern and central Europe over the next century. It was also estimated that the Asian monsoon region will experience an increase in wet summers of a similar scale, escalating the risk of flooding in already flood-prone areas. So, the debate continues<sup>29</sup>. No clear consensus exists linking the frequency and intensity of extreme weather events to changes in climate patterns, but it would be reckless not to expect that climate change will have some impact on extreme weather events. Today, there are over five billion people living on the earth, often in areas that are known to be vulnerable to extreme weather events. The potential for catastrophic damage and loss of lives is enormous. There is an urgent need for better understanding of the changing climate patterns in a regional scale over the Indian subcontinent and how they affect extreme weather events over India. Further study, especially on the natural variability and cycles of extreme weather events as well as data on a smaller (i.e. local) scale is required before making any remark on the role of climate

change in the occurrence of the present extreme rainfall event as observed over Mumbai.

With our present limited understanding about the role of different factors that caused such unusual rainstorm over Mumbai, another important challenge before us is how better India and other global forecasting centres are equipped both technically and scientifically to forecast important events, either in real time or for academic interest. To briefly explain this, such forecasting accuracy of different operational models available from different Numerical Weather Prediction (NWP) centres in India and abroad are analysed to find their levels of skills for predicting severe rainstorms. We have not considered forecast products beyond 24 h in advance, because in the present case rainfall is due to mesoscale weather system embedded on highly favourable synoptic/large-scale pattern. NWP models generally lose their skill in predicting such events with increase in forecasting time period. Mesoscale/regional models normally perform better in simulating the localized heavy rainfall event compared to global models. Though both adequate and accurate surface and upper air data are a prerequisite, they need to be appropriately assimilated on very high resolution to capture the phenomenal rainstorm discussed above. IMD is going out in a big way for modernization and upgradation of its observing and forecasting system at the earliest. However, it is still working under constraints, where it is not possible to run high resolution models due to lack of high power computing resources and also because the kind of data required to be fed into these models are at present lacking. At present, IMD is running regional and mesoscale models ([www.imd.gov.in](http://www.imd.gov.in)) with initial and boundary conditions either from National Center for Medium Range Weather Forecasting (NCMRWF) or NCEP, USA at coarse resolution, which is not sufficient enough to resolve features responsible for predicting such devastating mesoscale rainfall events. We reproduce results of integration of our regional and mesoscale models. Figure 11 a and b shows rainfall forecast of Limited Area Model (LAM) and mesoscale model (MM5) used operationally by IMD valid for 24 h of 0000 UTC of 27 July. Though both the models brought out in general the spatial distribution of rainfall over the west coast as was observed, the highest rainfall of 4–7 cm predicted by both the model was small.

Figure 11 c shows rainfall forecast from global model (T80) used operationally by NCMRWF ([www.ncmrwf.gov.in](http://www.ncmrwf.gov.in)) valid for 24 h of 0000 UTC of 27 July. We have also considered 24 h rainfall forecast of Eta model from the same centre. Though both the models were able to predict the observed spatial pattern of rainfall over the west coast, the highest rainfall over the west coast predicted was less: 1–2 cm in the global model and 8–16 cm in the Eta model, values below the realized rainfall of 94.4 cm. Among the global model products available from other centres of the world, IMD at present receives its products



**Figure 11.** The 24-h forecast of rainfall as simulated by different NWP models valid for 27 July 2005: (a) LAM, (b) MM5, and (c) T-80. d, An UK Met. Office Model could predict up to 30 cm of rain on 26 July, 24 h in advance. e, Re-run (not on real time) of UK Met. Office high resolution model predicted up to 80 cm of rain in Mumbai on 26 July, 24 h in advance.

regularly through global telecommunication system (GTS)/Internet. The COLA (Center for Ocean–Land–Atmosphere) model of USA also gives station-specific forecast ([www.monsoondata.org/wx/meteogram2.html](http://www.monsoondata.org/wx/meteogram2.html)) for Asian monsoon region. Its 24 h meteogram for Mumbai shows only 4 cm of rainfall for 24 h. It is not possible to validate European Center for Medium Range Weather Forecasting (ECMWF) model forecast, as we did not get any rainfall forecasts from ECMWF operationally. It only provides forecasts of large-scale flow pattern for 850, 500 and 200 hPa. These forecast charts more or less matched with the observations.

In Figure 11 *d* and *e*, we have given 24 h rainfall forecast of UK Meteorological Office (UKMO) model, which was on real-time basis and the re-run of this model from UKMO after the event respectively. The UKMO Model could predict up to 30 cm of rain on 26 July, 24 h in advance over the Konkan coast, with highest reaching up to 51 cm (Figure 11 *d*). A re-run of this model by incorporating more data, predicted up to 80 cm of rain in a small area covering Mumbai on 26 July (Figure 11 *e*), 24 h in advance, which is somewhat close to the observed amount of 94.4 cm over Santacruz.

Latest observing systems based on modern technology as available, e.g. Doppler Radar, TRMM, etc. could be helpful in monitoring successfully different development aspects of the present rainstorm. In fact, TRMM (Figure 10) was the only observing system which could measure the prevailing intensity of rainfall rate and spatial distribution of the present rainstorm that occurred over Mumbai. This shows the capability of satellite-based observations to monitor such intense events and a more frequent coverage of the area could enable now casting of same. The proposed Doppler weather radars would supplement such space-based observations and become an effective aid in monitoring and now casting of such events. For highly vulnerable and economically important centres like Mumbai, a network of Doppler weather radars would certainly go a long way in meeting this requirement. Also, occurrence of such high rainfall over the west coast of India has again re-established the fact that both the coasts of India are highly vulnerable to disastrous weather and hence some observatories along both the coasts urgently require to be equipped with modern instruments like wind profilers, well-calibrated automatic surface weather stations, etc.

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