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EXCEPTIONAL RAINFALL EVENT OF 26th JULY, 2005 OVER MUMBAI – ANALYSIS OF RADAR ECHOES AND RAINFALL

1. Parts of Mumbai (Lat. 18.50º N, Long. 72.52º E) experienced unprecedented rainstorm on 26th - 27th July 2005. 24 hours rainfall ending at 0830 hours IST of 27th July at Santacruz airport (18.54º N, 72.49º E) at Mumbai was 94.4 cm. But, Colaba (19.0º N, 72.51º E), the other meteorological observatory, which is about 27 km away at the south-southwest, recorded only 7.4 cm rains 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 (Jenamani *et al*., 2006). As per calculation published by IWRS (2005), following important informations indicate necessity of huge investment in updating the old drainage system over Mumbai to avoid similar flooding over the city in future in case if it happens again.

(*i*) Consider a 10 km × 10 km area of a city (Actual intense rainfall occurred over an area of 35 × 20 km).

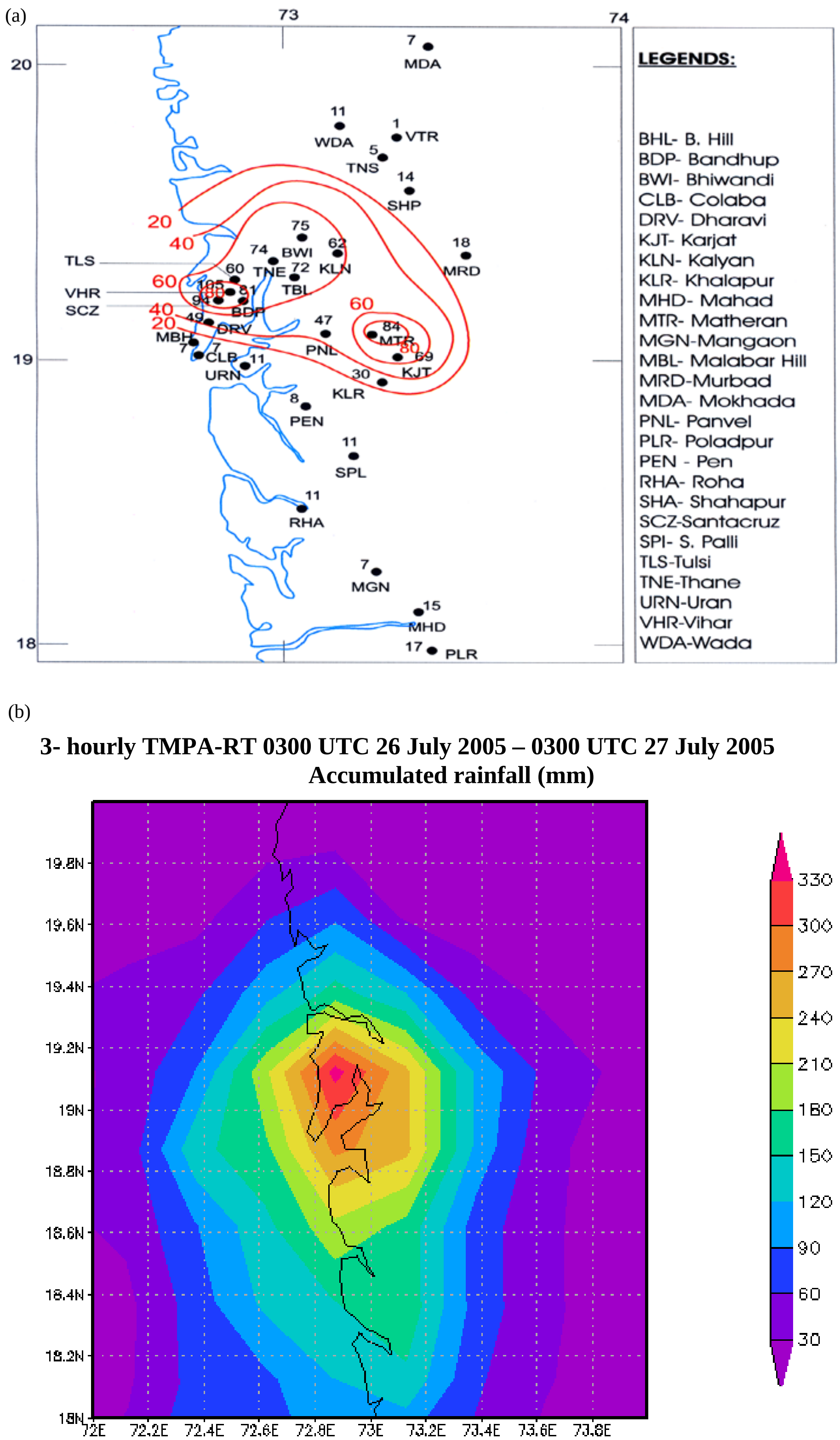
(*ii*) When 944 mm of rain would fall on this area, the total volume of water would be 94.4 mcm (million cubic meters) of water in 24 hours.

(*iii*) Draining off all this water in 24 hours itself, at the same rate as it arrived, would mean an outflow rate of 1092 cubic meters per second (Cumecs).

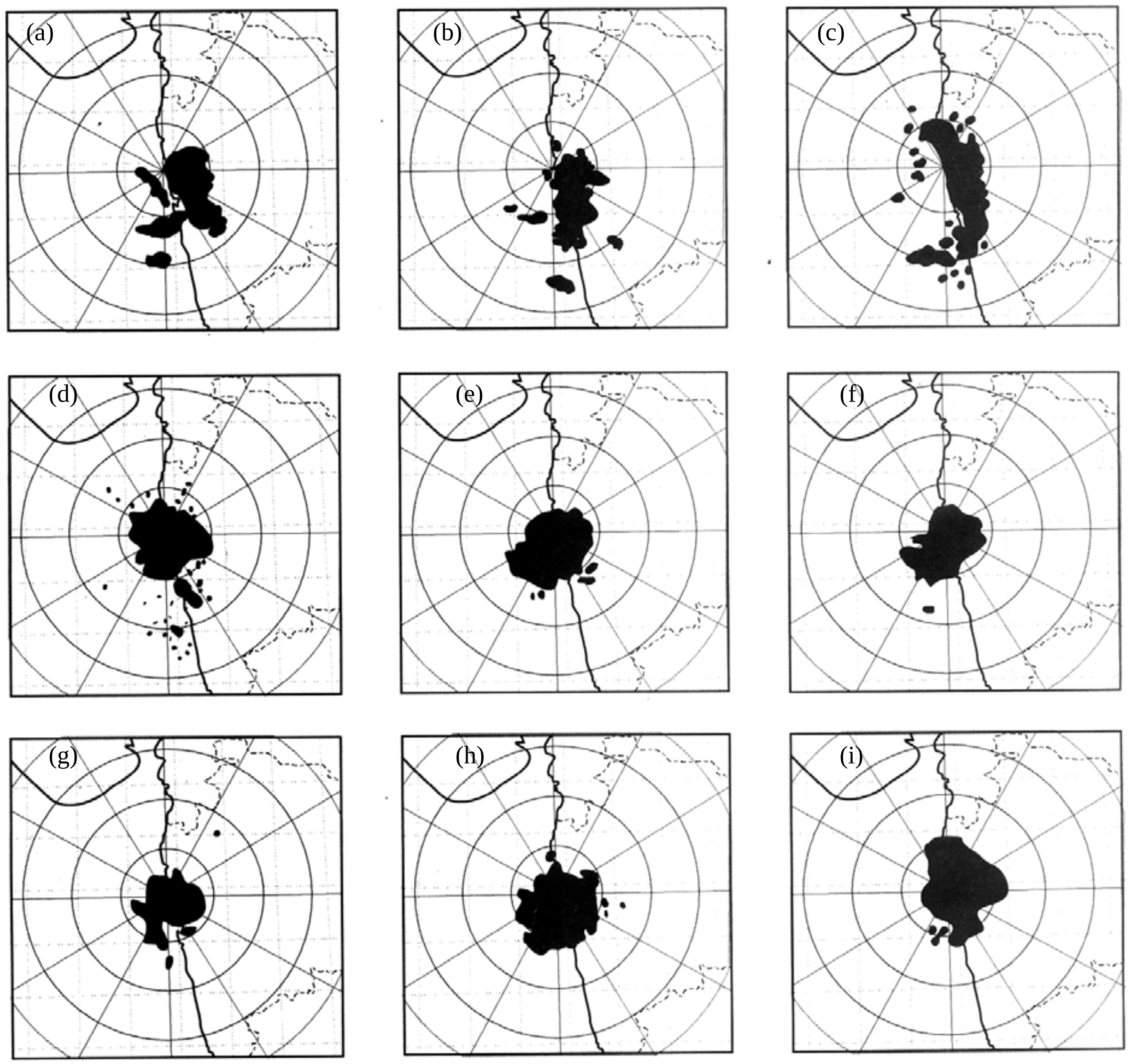
(*iv*) Compare this with Sardar Sarovar main canal, which has a capacity of 1133 Cumecs.

(*v*) Thus, a city wanting to drain without inundation a 1-day rainfall of 944 mm, would have to have a drainage canal as large as the Sardar Sarovar main canal, for every 10 × 10 km area. For the area 35 × 20 km of Mumbai which had received most intense rainfall, nearly 3 such main canals are needed to be built, with a network of appropriately large feeder canals to avoid any water logging/flooding.

Typical June–September wet-day average rainfall at Mumbai is around 18 mm day^{-1} with a daily standard deviation of 28 mm day^{-1}. Hence more than 900 mm of rain in one day as realized with the present severe rainstorm represents an extreme event or outlier more than 22 standard deviations greater to that of the mean. Jenamani *et al*. (2006) has first attempted to study different observational characteristics of the rainfall event and their possible causes using conventional surface rainfall and upper air data. Their study mainly focused on rainfall analysis at meso-scale, thermal and moisture analysis, characteristics of air masses responsible for the event, convective instability analysis, finding interaction

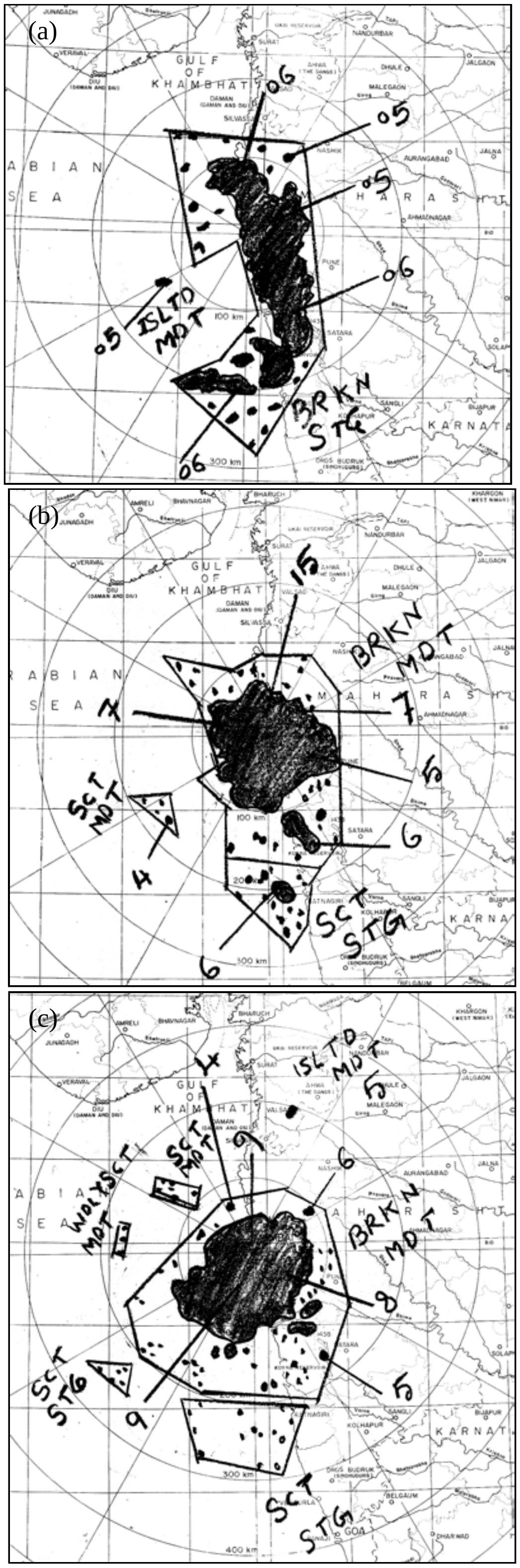


Figs. 1(a&b). Rainfall recorded on 27th July over Mumbai (Meso-scale Rainfall Analysis) (a) Using surface rainfall observations and (b) Using TRMM rainfall analysis



Figs. 2(a-i). Evolution of highest reflective areas from radar echoes of Intense convective clouds taken from S-band Radar operated at 3-hourly synoptic time intervals from IMD which is located at Colaba, Mumbai (a) at 0000 UTC, (b) at 0300 UTC, (c) at 0600 UTC, (d) at 0900 UTC, (e) at 1200 UTC, (f) at 1500 UTC, (g) at 1800 UTC, (h) at 2100 UTC (all are for 26th July) and (i) at 0000 UTC of 26-27th July, 2005

between large scale-synoptic scale-meso-scale features and the possible role of orogrpahy in causing the event. Subsequently, Shyamala and Bhadram (2006) have also analyzed its rainfall characteristics using station data and attempted to find how interaction between meso-scale and large scale have resulted such exceptional rainfall event over the city. However, the spatio-temporal evolution of the present exceptional heavy rainfall event, *e.g.*, direction or location from which such unusual high rainfall/convection event was initiated first, direction at which it was moved or various locations where high rainfall have been observed with corresponding timings when rainfall rate was highest at respective places and finally the place at which it was dissipated, still remain unknown. Also such high rainfall event being occurred exactly at the coast where Mumbai is located, rainfall variation towards the Sea side associated with the present event remains a mystery in the absences any conventional observations over the Sea. The main objective of the present study is to address these problems using surface rainfall data from IMD and 3-hourly TRMM rainfall data available from NASA. We have further used 3- hourly



Figs. 3(a-c). Evolution of highest reflective areas and Height of the clouds from radar echoes (a) at 0600 UTC, (b) at 0900 UTC and (c) at 1200 UTC of 26 July, 2005

radar echoes including their highest reflective areas maps and their heights to identify how cloud development characteristics have been varied both temporally and spatially corresponding to high resolution observed rainfall data both from surface and TRMM data associated with the event [Fig. 1(a)] as analyzed in Jenamani *et al*. (2006) in similar scales using only surface rainfall data. The present study also attempts to find whether areas of highest rainfall contours and time of occurrences of highest rainfall intensity in rainfall map matches with areas of highest reflectivity and time of cloud tops reaching highest heights correspondingly by plotting both data in suitable geographical maps and comparing them graphically. Such type of validation study, if done for Indian region for such an important rainstorm, will also help in understanding the complex relationship between cloud characteristics and rainfall they produced and certainly will have tremendous application in the forecast verification when it will be simulated from various NWP models by various centers in their experimental studies in future.

2. *Data and methodology* - Data from India Meteorological Department and 3-hourly accumulated TRMM grid point rainfall data available at very high resolution of 0.25 × 0.25 (for more see http://disc2.nascom.nasa.gov/Giovanni/tovas/realtime.3B42RT.shtml) have been used for the present study.

3. *Radar Data-3-hourly Spatio-Temporal Analysis against surface rainfall* - We have plotted 3-hourly spatial evolution of highest reflective areas of IMD's S-band Radar located at Colaba, Mumbai in Figs. 2 (a-i) in radar projected map from 0000 UTC of 26th till 0000 UTC of 27th taken in 3-hourly fixed synoptic time intervals for meso-scale study (see high resolution map of Mumbai given in Fig. 1(a) as base map in order to superimpose approximate position of different stations having very high rainfall with subsequent radar maps of highest reflectivity) with respective major geographic location also plotted in original maps in Fig. 3. We have given original 3-hourly evolution of cloud characteristics as observed by radar operator, *e.g.*, highest reflective areas with bold shadings, cloud shapes and heights of different cloud cells which reached up to significant heights around Mumbai in Figs. 3(a-c) for 0600 UTC, 0900 UTC and 1200 UTC respectively during when 3-hourly rainfall intensity which was increased significantly from 2 cm (0600 UTC - 0900 UTC) to 38 cm (0900 UTC - 1200 UTC) (Fig. 4) over Santacruz with light rain continuing at Colaba which is 27 km at its south-southwest [Fig. 1(a)] as base map in order to match approximate positions of stations which are not also specified in these maps). A closure view in these original geographical projections of radar maps in Fig. 3 also

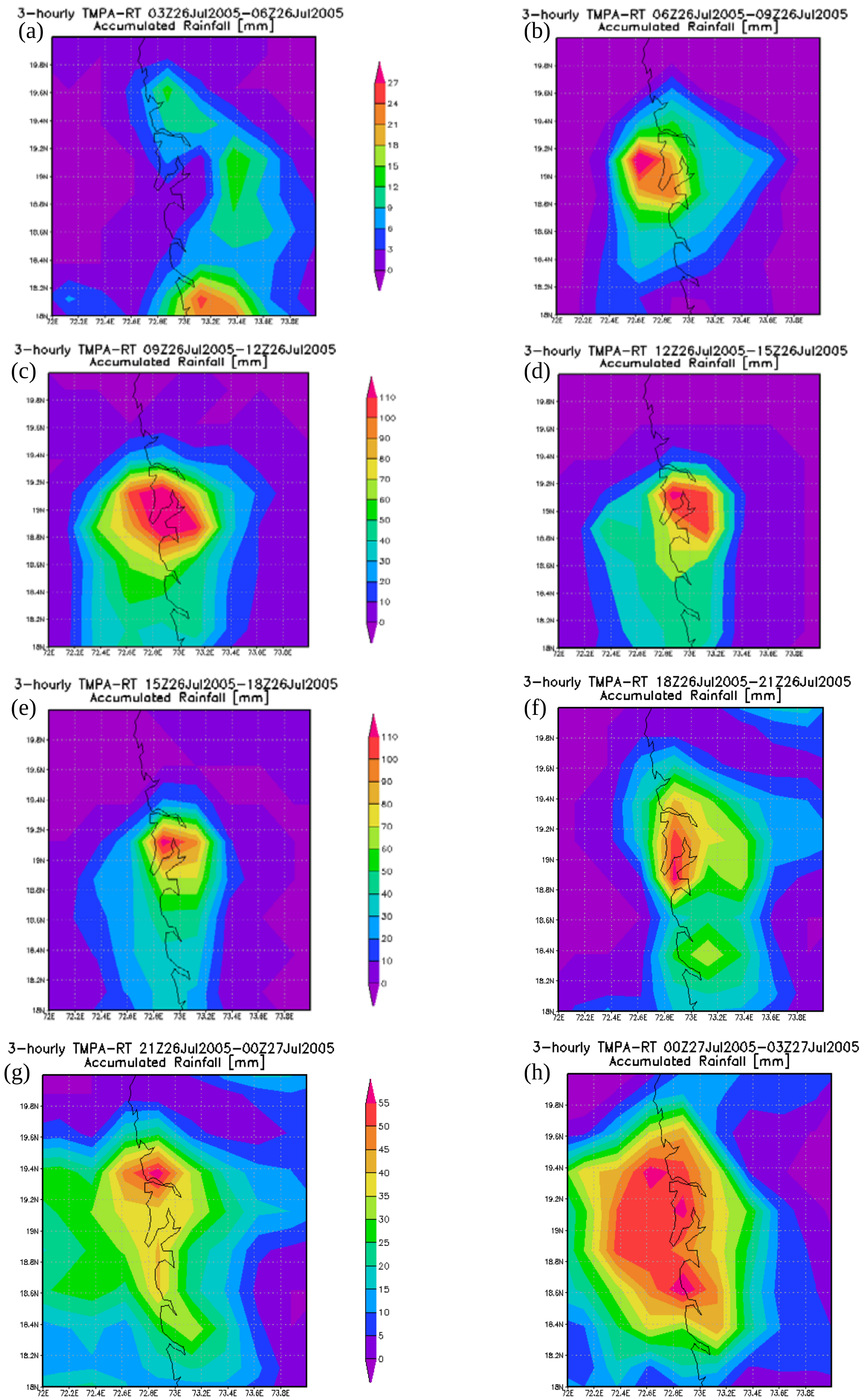


Fig. 4(a-h). Rainfall observations as measured from TRMM at 3-hourly intervals over Mumbai area and adjoining Sea on 26th and 27th of July 2005 shows that only location of 3 rainfall stations are specified which are with in first circle of radar having radius of 100 km. These are center of radar, *i.e*., Colaba, Thane which is at 30 deg. direction in north-northeast with nearly 40 km from Colaba and Alibag (Panvel) which is at 150 deg. direction in south-southeast with nearly 30 km from Colaba. It may be noted from Fig. 3 that the area at northeast but close to Santacruz which is demarcated for highest rainfall occurrence in association with present rainfall event, is in the same direction as Thane.

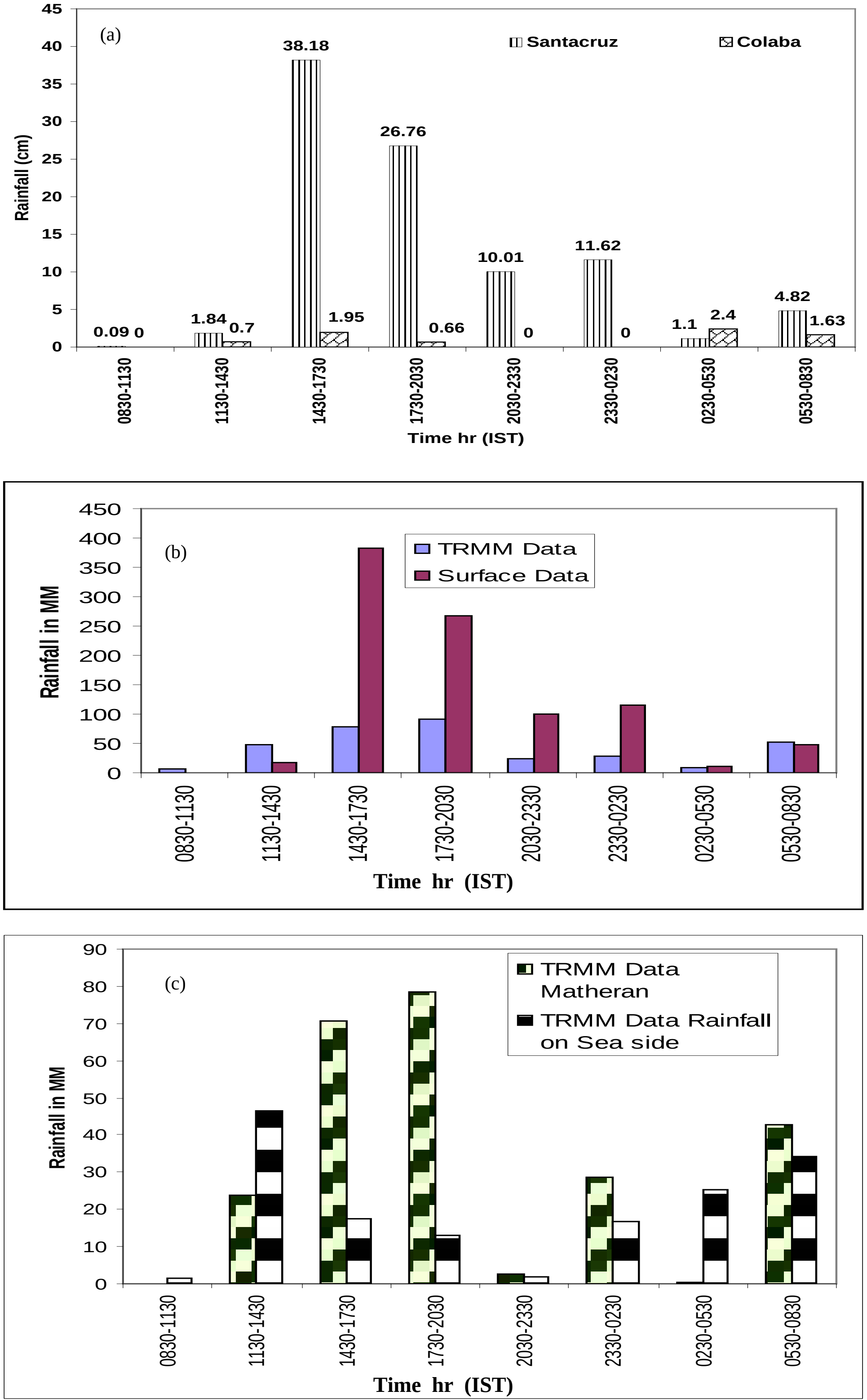
A comparison of Fig. 1(a) with Figs. 2(a-h) & Figs. 3(a-c) shows that all the high rainfall reported stations in the present severe rainstorm remained confined within the 100 km radar circle centered at Colaba and lay to its northeast sector. From all 3-hourly Radar data analysis, it is also observed that heights of clouds having location out side its first radar circle of 100 km did not reach more than 6 km as detected by radar. Hence we have analyzed characteristics of radar data which are with in 100 km. Further, since Fig. 1(a) shows two distinct rainfall maxima occurrences with in 100 km radar circle corresponding to highest rainfall contours of 90-105 cm rainfall observed at 25-35 km north-northeast of Colaba with its center near Thane- Santacruz and 2nd highest rainfall contours of 60-84 cm observed at 40-50 km at east of Colaba with its center near Matheran- Karjat. It is very much necessary to critically analyze all radar data for validating against very high resolution ground rainfall observations for both of these high rainfall contours as observed in Fig. 1(a) for same areas from radar pictures plotted in geographical maps.

Analysis of 3 hourly Radar Imageries with in 100 km of Bombay starting form 0000 UTC of 26th July in Fig. 2(a) shows that an area of moderate convection extended from just north of Colaba more than 100 km to southeast of Colaba with the height of the highest cloud top of 5 km to the east of Colaba and 2nd highest height of 4 km at north of Colaba. By 0600 UTC [Fig. 2(c)], the area of convection organized further into a comma shaped extending from the radar center at Colaba up to about 100 km north of Colaba with the height of the highest cloud top of 6 km by extending up to 100 km to the south-southeast of Colaba with 2nd highest cloud height of 5 km to east of Colaba [Fig. 3(a)]. By 0900 UTC [Fig. 2(d)], the convection organized further covering a circular area of about 80 km radius around Colaba. Fig. 3(b) shows that the highest cloud top of 15 km was observed at this time about 25 km to the north of Colaba near Thane (station is indicated by line drawing towards the location in Fig. 3(b) which is exactly located over the highest rainfall contour which was observed near Santacruz and Thane as in Fig. 1(a). In fact, cloud reached up to ever highest height at this particular time. This was also the time when the most intense rains were realized in the next 3 hours in Fig. 4(a). The 2nd highest cloud height at the east was 7 km which is at distance of 60 km east-northeast of Colaba which is exactly located over the 2nd high rainfall contour which was observed near Matheran-Karjat as in Fig. 1(a). Another cloud echo with a cloud height of 7 km (3rd highest cloud) had also been reported by the radar at 0900 UTC [Fig. 3(b)] which lay over the Sea at its west-northwest direction for which no surface rainfall observations are available to make any validation.

During the subsequent observation, *i.e*., at 1200 UTC [Fig. 2(e)], the total area of convection which lay centered over Colaba before, shifted gradually westwards with larger part of the cloud mass lay to the southwest of Colaba over the Arabian Sea. However, the highest cloud tops at 1200 UTC [Fig. 2(e)], were still being reported to the north and east of Colaba corresponding to earlier two high rainfall areas as noted before, though the cloud tops had decreased compared to earlier one to about 9 km and 8 km respectively [Fig. 3(c)]. The 3rd one had cloud height of 9 km which lay over the Sea for which again no surface rainfall observations are available to make any validation.

By 1500 UTC [Fig. 2(f)], the highest cloud tops were still being reported to the north and east of Colaba, the highest cloud tops again increased to about 10 km and 11 km respectively (Cloud heights are not shown for remaining observations because of want of space) with observation reporting for the first time in the day that the height of the latter cloud corresponding Matheran-Karjat rainfall event growing more compared to former one, *i.e*., Santacruz-Thane rainfall event. In fact, comparison with all other 3-hourly observations show cloud tops correspond with 2nd high rainfall reached to the highest height at this time. Hence, the present study show that if the Santacruz-Thane severe rainstorm was most intense between 0900-1200 UTC [Fig. 1(a) and Fig. 4(a)], as surface land rainfall and 3-hourly rainfall data at Santacruz are available then Matheron-Karjat severe rainstorm become most intense at 1500 UTC as per RADAR data. In other ward, in the absence of any 3-hourly surface recording observations over the latter high rainfall area after Santacruz, one may confirms from present data validation study that the most severe spell of the present extreme event might have started from Santacruz side at 0900 UTC and from Matheran side at 1500 UTC (we have also further verified and reconfirmed it afterwards from TRMM data). By 1500 UTC [Fig. 2(f)], the 3rd one cloud height was again reported as 9 km which continued to lay over the Sea for which again no surface rainfall observations are available to make any validation.

By 1800 UTC [Fig. 2(g)], the highest corresponding cloud tops were still being reported to the north and east



Figs. 5(a-c). Point rainfall observations as measured from (a) Surface IMD 3-hourly observation at Santacruz and Colaba, (b) TRMM at Santacruz (highest rainfall location) for validating against surface records and (c) Matheran (2nd higher rainfall location) and over the Sea west of Colaba (3rd higher rainfall location associated with the present event) on 26th and 27th of July 2005 of Colaba though the cloud tops decreased at this time to about 8 km and 10 km respectively compared to their previous heights. At this time, observation also reported the cloud height of the corresponding, *i.e*., Santacruz-Thane rainfall event, was less compared to the latter one, *i.e*., Matheran-Karjat rainfall event.

During the subsequent 2 observations, *i.e*., 2100 UTC [Fig. 2(h)] of 26th July and 0000 UTC of 27th July [Fig. 2(i)], the same pattern of highest cloud tops to the north and east of Colaba continued though the cloud tops has decreased further to about 8 km. However, cloud heights corresponding to the 3rd one which were remained below 7 km at 0900 UTC could be grew up to only 9 km both at 1200 UTC and 1500 UTC [Fig. 3(c)] as per radar report over the Sea, were weakened suddenly and remained 5 km afterwards at 1800 and 2100 UTC [Figs. 2(g&h)] and hence whatever rainfall it might have produced must be less than earlier two high rainfall area corresponding to Santacruz-Thane and Matheran-Karjat areas. In fact, we have used TRMM's 3-hourly rainfall data in Sec. 4 for these three corresponding locations to confirm and compared rainfall intensity of all these three heavy rainfall locations which we detected in the present study from surface rainfall data and RADAR echo analysis especially the 3rd heavy rainfall area which we identified over the Sea from RADAR echoes only. We have also compared their corresponding temporal evolution in Sec. 4 from 3-hourly TRMM data for confirming timings of latter two rainfall locations by validating against 3-hourly surface rainfall available for 1st highest rainfall located over Santacruz as 3-hourly rainfall data from surface are not available for other two locations.

4. *TRMM rainfall data- 3-hourly Spatio-Temporal Analysis against surface rainfall and RADAR data* - Fig. 1(b) shows 24 hours cumulative rainfall measured from space by TRMM for the day Mumbai and its sub-urban region experienced the high rainfall. One can find from comparison of Fig. 1(a) with Fig. 1(b) that though both spatially are well compared, intensity of the highest rainfall contours are underestimated as observed from TRMM data which are of less than half or one third compared to that of surface observed rainfall contours for same period. One can also find the NW-SE orientation of the rainfall contours located just at the northwest sector of Colaba from TRMM in Fig. 1(b) which is nearly of same orientation as observed from surface rainfall in Fig. 1(a) and distribution of highest heights of clouds from RADAR echoes in Figs. 2 and 3. Because TRMM also could capture the spatial distribution well, we have plotted 3-hourly cumulative rainfall contours to see the spatial and temporal evolution of the rainfall contour at each 3-hours time step in Figs. 4(a-h) starting from 0300-0600 UTC without giving much stress to the value of the contours. Fig. 4(a) shows though no significant rainfall has been observed between 0300-0600UTC over the region and adjoining Sea, there was a sudden burst of the rain between 0600-0900 UTC in Fig. 4(b) over an area with highest contours located completely over the Sea at northwest of Colaba. The latter high rainfall zone moved eastwards thereafter by 1200UTC and partly enter into land at north of Colaba [Fig. 4(c)] by expanding to more areas. By 1500 UTC and 1800 UTC [Figs. 4(d&e)], the highest rainfall contour was restricted to northeast of Colaba and remained confined to only over land though orientations were changed which can be well comparable to surface rainfall's highest rainfall contour as observed in Fig. 1(a). At 1800 UTC - 2100 UTC [Fig. 4(f)], the highest rainfall contour was observed only to the southeast of Colaba while in the next two subsequent synoptic hours [Figs. 4(g&h)], it was located near Santacruz where highest rainfall contour located in Fig. 1(a).

Figs. 5(b&c) shows the temporal variation of 3-hoursly cumulative rainfall amounts observed from TRMM corresponding to three locations 19.2º N / 72.8º E, 19.0º N / 73.2º E and 19.2º N / 72.6º E, corresponding to Santacruz-Thane rainfall event, Matheran-Karjat rainfall and 3rd high rainfall over the Sea at west of Colaba as detected from comparison study of surface rainfall and RADAR echoes in Sec.3 for confirmation and comparison of timings of occurrences of highest rainfall over these locations including their 24-hours rainfall amounts. In Fig. 5(b), we have also plotted 3-hourly surface rainfall data which is only available for Santacruz against TRMM rainfall data over same station. It shows both are well comparable as the timings of highest rainfall amounts recorded at 0900-1200 and 1200-1500 UTC from surface data with timings of highest cloud heights from RADAR, have also been captured well in TRMM data for same hours. One may further note that from Fig. 5(b) that the significant fall of rainfall amount in next 3-hours and then the subsequent slight raise in rainfall amount have been well captured by TRMM with further high values recorded at last synoptic hours and hence matching well with each other. Hence TRMM data can be considered as a suitable rainfall data for comparing intensity and temporal variation of latter two events as we did in Fig. 5(c) in the absence of their 3-hourly data from surface stations. It shows the highest rainfall occurrence timing over 2nd high rainfall area in order as identified before over Matheran-Karja at 1200-1500 UTC, the timing of reporting of highest cloud height from RADAR in the same sector. But, Fig. 5(c) shows the timing of 3rd high rainfall area over the Sea at 0600-0900 UTC from TRMM which is correspond to cloud height of 7 km at 0900 UTC the 3rd highest cloud height [Fig. 3(b)] located over the Sea detected by RADAR. Hence, analysis and validation of surface rainfall, RADAR data and TRMM rainfall data

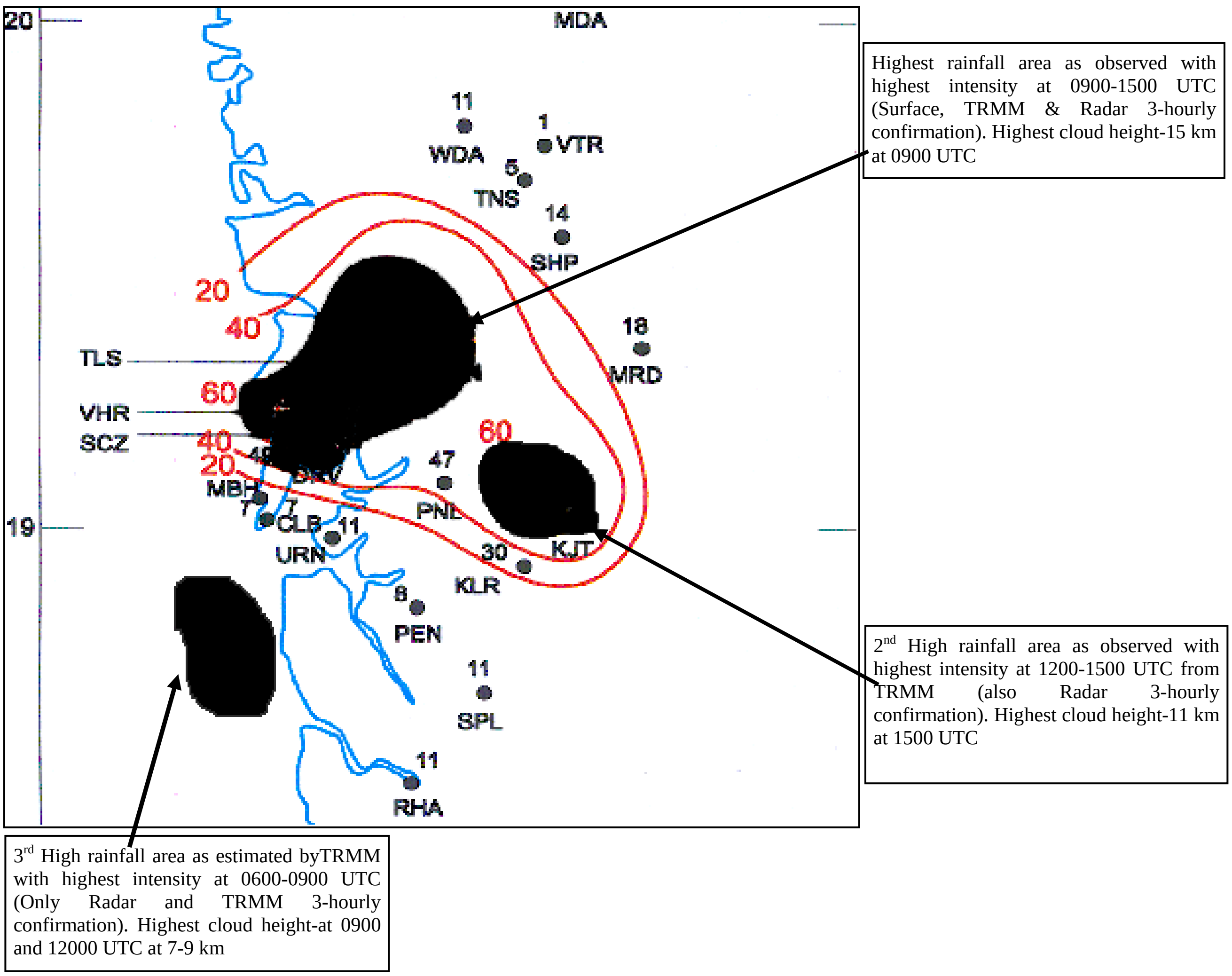
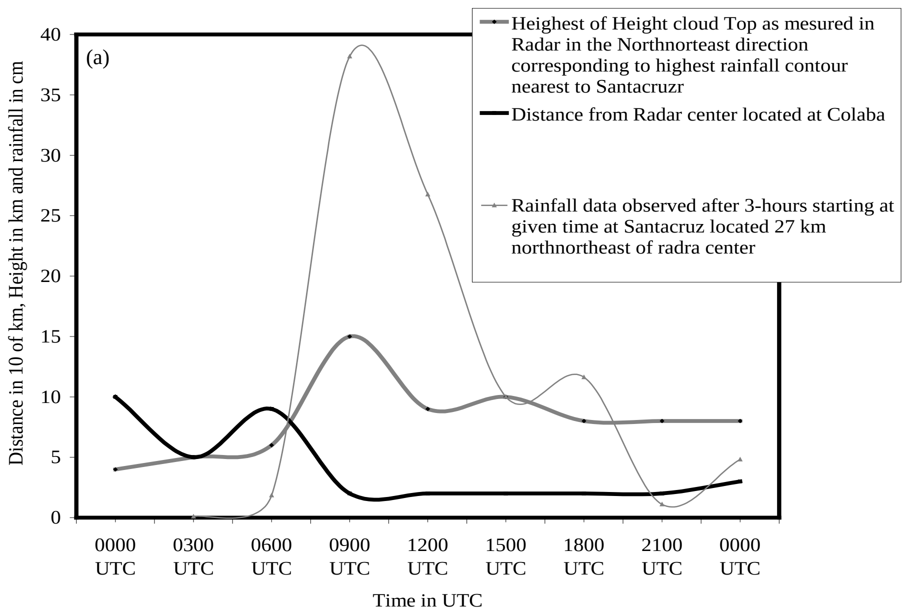
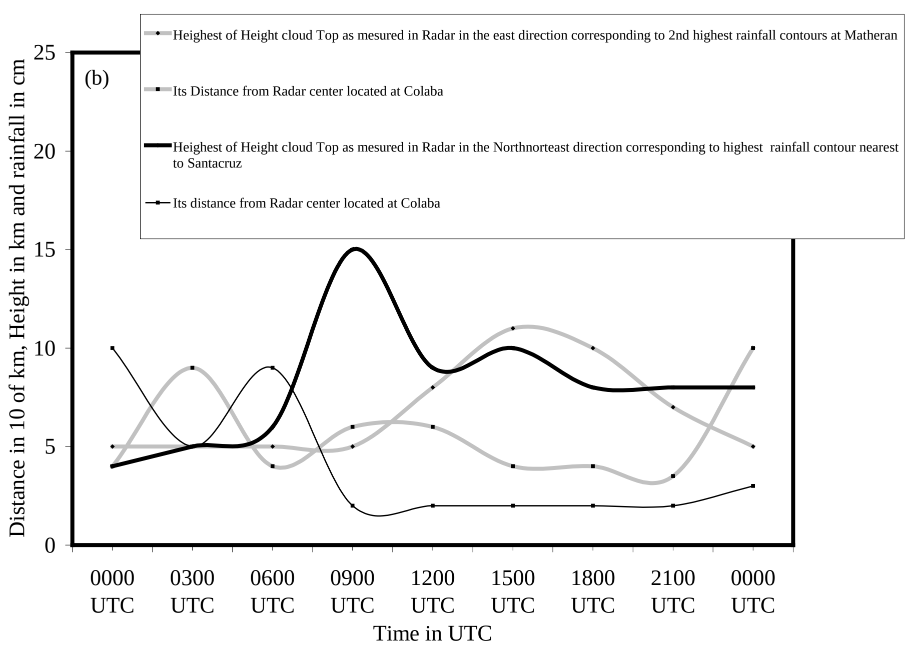


Fig. 6. Areas of high rainfall over Mumbai as analyzed from High density station's rainfall data and Radar estimation-A Spatio-temporal evolution

hereby confirms that these locations were three areas around Mumbai where very high rainfall were observed if all land and adjoining Sea areas were considered. Also, 24-hours cumulative rainfall amounts of these places when estimated from TRMM data, it shows the highest rainfall observed over Santacruz areas, 2nd high rainfall over Matheran which we also identified from surface observed isotach rainfall analysis before and the 3rd higher rainfall in order was located over the Sea. We have presented their timing of high rainfall areas in schematic diagram in Fig. 6 as interpreted from the timings of the clouds highest heights from RADAR echoes in all sectors around Colaba and TRMM 3-hourly rainfall data around Mumbai, by considering their observations taken at 3-hourly intervals covering all 24-hours. The present analysis (Fig. 6) show 2nd high rainfall area had highest rainfall intensity at 1200-1500 UTC and 3rd high rainfall area had of highest rainfall intensity at 0600-0900 UTC as cloud echoes reached to higher heights during respective radar observations. In other word, spell of most intense rainfall was first experienced over the West of Colaba over the Sea (3rd in order of rainfall value) at 0600-0900 UTC followed by that of occurrence of Santacruz-Thane area (the ever highest rainfall values) which was at 0900-1500 UTC which again was followed by another high rainfall area (2nd in order of rainfall values) over Matheran-Karjat area which was experienced at 1200-1500 UTC which is after 3-hours of that occurrence of Santacruz-Thane area (the highest rainfall areas). Hence the rain producing convection was first initiated between 0600-0900 UTC at noon at the Sea side northwest of Colaba, which might have entered land at north of Colaba and gave such exceptional high rainfall over Santacruz areas in subsequent 6 hours between 0900-1500 UTC. Then during the course of its movement, it





Figs. 7(a&b). Temporal evolution of highest height of cloud mass in the high reflective areas of Radar centered at Colaba and its distance from the center as measured by Radar on 26th -27th July with Cloud echoes lies within the direction of (a) 350 Deg. – 10 Deg. (*i.e.*, north-northeast) and (b) 80 Deg. – 100 Deg. (*i.e.*, east)

might have regenerated or moved to Matheran area by 1200-1500 UTC to produce the 2nd high intense rainfall over the area.

5. *Temporal evolution of highest height of cloud mass in the high reflective areas of Radar echoes against surface rainfall* - It may be noted from all radar pictures given Figs. 2 and 3 that the continuous presence of the most intense convective clouds with very high cloud tops with in 100 km circle over two different areas with one near Thane-Santacruz area having nearly 25-35 km at north of radar center at Colaba and another one near Matheran-Karjat area with nearly 40-50 km at its east have been exactly matched with high rainfall areas as

found in the analysis in Fig. 1 corresponding to highest rainfall contours of 90-105 cm observed near Santacruz, about 27 km at north of Colaba and 2nd highest rainfall contours of 60-84 cm observed at Matheran about 40-50 km east of Colaba. It is interesting to note the validation of radar observations as done in earlier section with surface one in spatial scale. In the present section, for making a proper validation in temporal time scale, we have plotted temporal evolution of highest height of cloud mass of the high reflective areas of Radar centered at Colaba as shown in Figs. 2 & 3 and its distance from it as measured by Radar on 26th - 27th July from 0000 UTC of 26th till 0000 UTC of 27th in Fig. 7(a) and in Fig. 7(b) corresponding to Cloud echoes lies within the direction of 350 Deg. –10 Deg. (*i.e*., north-northeast direction which correspond to highest rainfall contour over Santacruz-Thane rainfall (as plotted in Fig. 1) and 80 Deg.–100 Deg. (*i.e*., east which correspond to 2nd highest rainfall contours of 60-84 cm observed at east of Colaba over Matheran-Karjat area) respectively.

We have also simultaneously plotted 3-hourly rainfall as observed over Santacruz in Figs. 7(a). Fig. 7(a) corresponding to highest rainfall area, shows clearly that as at 0900 UTC, as cloud echoes came near to Colaba to about 25 km with its vertical growth increased exponentially, then realized rainfall also shoot up which was followed by similar simultaneous fall of growth of clouds vertically and rainfall realized though distance more or less remaining same from Colaba. With this, radar data validate well with surface rainfall in case of 3-hourly temporal intensity analysis using both data. However, in absences of 3-hourly surface rainfall data for any station located in 2nd high rainfall area, we have plotted together radar parameters as observed in case of Santacruz rainfall event in Fig. 7(a) whose data are already validated, with that of radar parameters for 2nd high rainfall area in Fig. 7(b) in order to see their difference and similarities if any during their temporal evolution. It shows clearly that by 1500 UTC, cloud echoes came near to Colaba to about to 40 km from east and its vertical growth increased to 10-11 km which was followed afterwards at 2100 UTC, by similar simultaneous fall of growth of clouds vertically and increased in distance of cloud. Comparison of characteristics of highest rainfall area with that of later one show clearly 6-hours before the later one, cloud associated with former event growing vertically to higher height with decreasing distance from the center.

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