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SIMULATION OF HEAVY RAINFALL OVER MUMBAI ON 26 JULY 2005 USING HIGH RESOLUTION ICOSAHEDRAL GRIDPOINT MODEL GME

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Abstract: In this paper an attempt has been made to simulate the exceptionally heavy rainfall event over Mumbai (Bombay) on 26 July 2005. Santa Cruz observatory near the International Airport of Mumbai recorded 944.2 mm of rainfall between 0300 UTC of 26 July 2005 and 0300 UTC of 27 July 2005 breaking all previous records. Some nearby places also recorded very heavy rainfall. Consequently, a deluge flooded the city and life in Mumbai came to a standstill. Mesoscale models or regional models are normally used to simulate such a small scale phenomenon. The model used in this paper to simulate the rainfall is the operational global numerical weather prediction model (GME) developed by the Deutscher Wetterdienst, The German Weather Service. Using European Center for Medium range Weather Forecast-ECMWF at T511 L91 data as the initial condition for the GME model, 24 hours accumulated precipitation has been computed. The model has a horizontal resolution of 40 km with 40 vertical levels and time step of 133s. The computed rainfall agrees reasonably well with the actual precipitation. The localized heavy rainfall might have occurred over Mumbai possibly due to several factors such as: well-marked low pressure over Orissa and adjoining Jharkhand with associated cyclonic circulation extending up to mid-troposheric level; off-shore trough on the west coast of India; low level jet over the peninsular India; intense convection and orographic lifting and interactions among these meteorological phenomena of different scales.

Keywords: Heavy precipitation, rainfall, GME, Icosahedral-hexagonal grids, Mumbai, India.

INTRODUCTION

The Asian summer monsoon, of which the Indian summer monsoon is a significant part, is a major phenomenon that affects the lives of a large number of people who live in the Tropics. Indian summer monsoon rainfall (ISMR) is characterized by widespread seasonal rainfall which is the most important climatic parameter with a high degree of variability both temporally and spatially. India receives about 80 % of the annual rainfall during the summer monsoon period (June-September). The variable nature of ISMR has a profound impact on the socioeconomic growth of the country. Therefore, the summer monsoon is inarguably one of the most important facets of life in India (Webster *et al*., 1998; Kripalani *et al*., 2003; Chaudhari *et al*., 2010).

The city of Mumbai, previously known as Bombay, is situated on the west coast of India. It is on the windward side of the Western Ghats (Sahyadri Mountain). The rainfall is higher on the Western Ghats. This is generally attributed to the forced ascent over the orography of the Western Ghats. The rainfall amounts of 10-30 cm in a day at and around the weather systems and on the west coast of India are quite common during the southwest monsoon season (Vaidya and Kulkarni, 2007). In the past, heavy rainfall events of the 50 cm in a day have also been reported at many places over the west coast of India (Rakecha *et al*., 1990; Dhar and Nandargi, 1998).

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An excellent example is the case of heavy rainfall over Mumbai on 26 July 2005. During the period 0300 UTC 26 July and 0300 UTC 27 July 2005 the meteorological station Santa Cruz (19.11° N, 72.85° E), in North Mumbai received unprecedented rainfall of 944.2 mm - the highest ever in the history of the city since records began. Some nearby places including: Vihar Lake about 15 km northeast of Santa Cruz (104.5 cm); Bhandup (81 cm); Bhivandi (75 cm); Thane (74 cm); Kalyan (62 cm); Dharabi (49 cm), and Panval (47 cm) also received such exceptional rainfall. This rainfall event had created damage to properties worth US $1250 million (at the time of writing) and caused many deaths with millions of people in Mumbai suffering immense hardship.

This unprecedented heavy rainfall event over Mumbai has attracted the attention of many researchers (Bohra *et al*., 2006; Jenamani *et al*., 2006; Litta *et al*., 2007; Kumar *et al*., 2008; Shyamala *et al*., 2006; Vaidya and Kulkarni, 2007). Litta *et al*. (2007) studied this extraordinary event with the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5), Vaidya and Kulkarni (2007) with Advanced Regional Prediction System (ARPS) Model developed by the Center for Analysis and Prediction of Storms of Oklahoma University and Kumar *et al*. (2008) with Weather Research and Forecasting (WRF) model. Generally, these types of models are capable of depicting mesoscale phenomena very well. The same accuracy can be achieved with the high resolution Numerical Weather Prediction (NWP) model.

In this paper an attempt has been made to simulate the rainfall over Mumbai during this period with the high resolution operational global NWP model GME developed by the Deutscher Wetterdienst, the German Weather Service (Majewski *et al*., 2002). The GME model has geodesic grid. It has been named GME because it replaced operational Global Model (GM) and the regional model for central Europe (EM) (Majeswski *et al*., 2002). GME forecasts show realistic results. High resolution of GME model could simulate heavy rainfall over India reasonably well (Chaudhari and Oh, 2004). GME generally employs the same methods and procedures applied in other NWP grid schemes. However, the uniformity of the GME grid avoids unnecessary physics calculations over resolved high-latitude zones that commonly occur in grids with polar singularities (Majeswski *et al*., 2002; Chaudhari *et al*., 2007; Oh *et al*., 2005). In this study the authors have implemented a horizontal resolution of 40 km of the GME model with a time step of 133.3 s. Numerical experiments of heavy precipitation for GME has been done with different initial conditions (21, 22, 23, 24 ,25 and 26 July 2005).

GME MODEL AND NUMERICAL EXPERIMENTS

GME employs a grid point approach with a quasi-uniform icosahedral–hexagonal grid. Prognostic equations for wind components, temperature, and surface pressure are solved by the semi-implicit Eulerian method. Only the two prognostic moisture equations (specific water vapour content and specific cloud liquid water content) use semi-Lagrangian advection in the horizontal direction to ensure monotonicity and positive definiteness (Majeswski *et al*., 2002). GME constructs geodesic grid by starting with an ordinary icosahedron inscribed inside a unit sphere. The icosahedron has 12 vertices. As a first step in the construction of a spherical geodesic grid, each face of the icosahedron is subdivided into four new faces by bisecting the edges. This recursive bisecting process may be repeated until a grid of the desired resolution is obtained. Such grids are quasi-homogeneous in the sense that the area of the largest cell is only a few percent greater than the area of the smallest cell.

The model used in this study has a horizontal resolution of 40 km with 40 vertical levels. It has a total number of grid points per layer of 368,642.

By combining the areas of pairs of the original adjacent icosahedral triangles, the global grid can logically also be viewed as comprising 10 rhombuses or diamonds, each of which has ni x ni unique grid points, where ni is the number of equal intervals into which each side of the original icosahedral triangles is divided. For 40 km horizontal resolution of GME, ni is equal to 192. To facilitate the use of the model on parallel computer diamond-wise domain decomposition is performed. For the 2-D domain decomposition the $(ni + 1)^2$ grid points of each diamond are distributed to n1 x n2 processors. Thus, each processor computes the forecast for a sub-domain of each of the 10 diamonds. This is a simple yet effective strategy to achieve a good load balance among processors. Details of the model description are available in Majeswski *et al*. (2002).

A major advantage of the Icosahedral-hexagonal grid is the avoidance of the so-called "pole problem" that exists in conventional latitude-longitude grids. The singularities at the poles lead to a variety of numerical difficulties including a severe limitation on the time step size unless special measures are undertaken. These difficulties simply vanish for grids not having such singularities (Majeswski *et al*., 2002; Ringler *et al*., 2000, Chaudhari and Oh, 2004). GME uses hybrid vertical coordinate (Simmons and Burridge, 1981); GME is handled by a set of dedicated parameterization modules. Initialization schemes of GME are designed to remove noise from the forecast while introducing acceptably small changes to the analysis and forecasts. The GME model was implemented on CRAY X1E and IBM p695 super-computers. To ease the data visualization, selected forecast fields are interpolated horizontally from the icosahedraal-hexagonal grid to a regular latitude-longitude one. In addition, some multilevel fields are interpolated vertically from 40 model layers to selected pressure levels. The initial state for the model run was based on an operational analysis dataset from ECMWF. This dataset has a resolution of T511 and 91 vertical levels.

Numerical experiments with GME were conducted with initial conditions on 21, 22, 23, 24, 25 and 26 July, 2005. The model runs were performed for 168 hours. The results of heavy precipitation events on 26 July 2005 were further analyzed.

RAINFALL CLIMATOLOGY OF MUMBAI

As discussed above, Mumbai is located on the windward side of the Western Ghat whose oreography plays a very important role in producing heavy rainfall. The average height of the Western Ghat is about 1.2 km. Mumbai begins to encounter heavy rainfall during the onset of the southwest monsoon (approximately the 10th June) as well as during the active phase of the monsoon. It also receives some rainfall during the withdrawal phase of the southwest monsoon in October, but the amount is very rarely high.

During onset, the rainfall is mainly associated with the convergence of moisture from the southwesterly winds coming from the Arabian Sea and northerly winds from the northern parts of India coupled with the onset vortex. During the active phase which normally takes place in July and August, heavy rainfall is experienced due to one or a combination of some or all of the following meteorological conditions:

-Strengthening of the Arabian Sea Monsoon current;
-Formation of the mesoscale offshore vortex over the Arabian Sea;
-Formation of Low Level Jet (LLJ) over the peninsular India;
-Formation of Mid Tropospheric Cyclone (MTC) over Gujarat and adjoining region;
-Formation of Low pressure system over the Northwest Bay of Bengal;
-Intensification of the Monsoon Trough.

The mean rainfall distribution as well as the mean number of rainy days over Santa Cruz is given in Table 1. (© Government of India, India Meteorological Department, 1999). The table clearly shows that during the southwest monsoon period studied, Santa Cruz received 2053.5 mm rainfall.

It may also be noted that more than 41 % of the seasonal rainfall was realized during the 24 hour period starting from 0300 UTC on 26 July 2005 to 0300 UTC on 27 July 2005: more than the mean monthly rainfall for the month of July.

	Colaba		Santa Cruz	
Month	Rainfall (mm)	Number of Rainy Days	Rainfall (mm)	Number of Rainy Days
Jan	0.5	0.1	0.6	0.1
Feb	1.0	0.1	1.5	0.1
Mar	0.3	0.1	0.1	0.0
Apr	1.9	0.2	0.6	0.1
May	11.0	0.9	13.2	1.0
Jun	583.6	15.4	574.1	14.9
Jul	750.4	22.0	868.3	24.0
Aug	460.9	20.8	553.0	22.0
Sept	258.6	12.2	306.4	13.7
Oct	64.9	3.1	62.9	3.2
Nov	10.4	0.8	14.9	1.1
Dec	3.1	0.2	5.6	0.4

Table 1. Mean rainfall distribution and mean number of rainy days over Colaba and Santa Cruz (© Government of India, India Meteorological Department 1999).

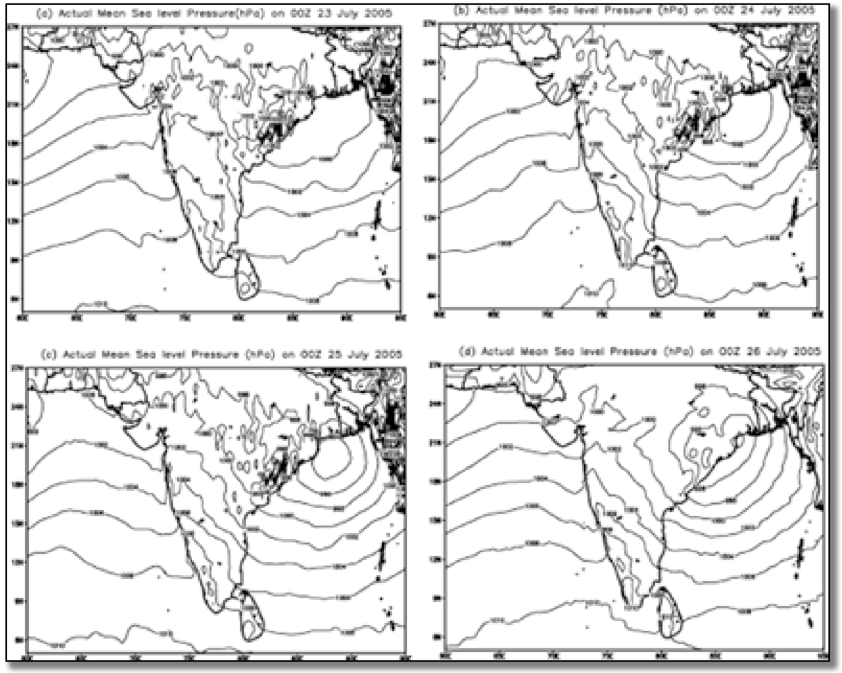

Figure 1. GME simulated mean sea level pressure at 0000 UTC on (a) 23 July, (b) 24 July, (c) 25 July, and (d) 26 July 2005.

PREVAILING SYNOPTIC CONDITIONS DURING THE STUDIED PERIOD

A low pressure area formed over the northeast of the Bay of Bengal and adjacent coastal areas on 23 July 2005. It intensified and moved inland. On the 26th July it lay over Orissa and the adjoining Jharkhand with an associated cyclonic circulation extending up to the mid-tropospheric level (Figure 1a-d and Figure 2a-d).

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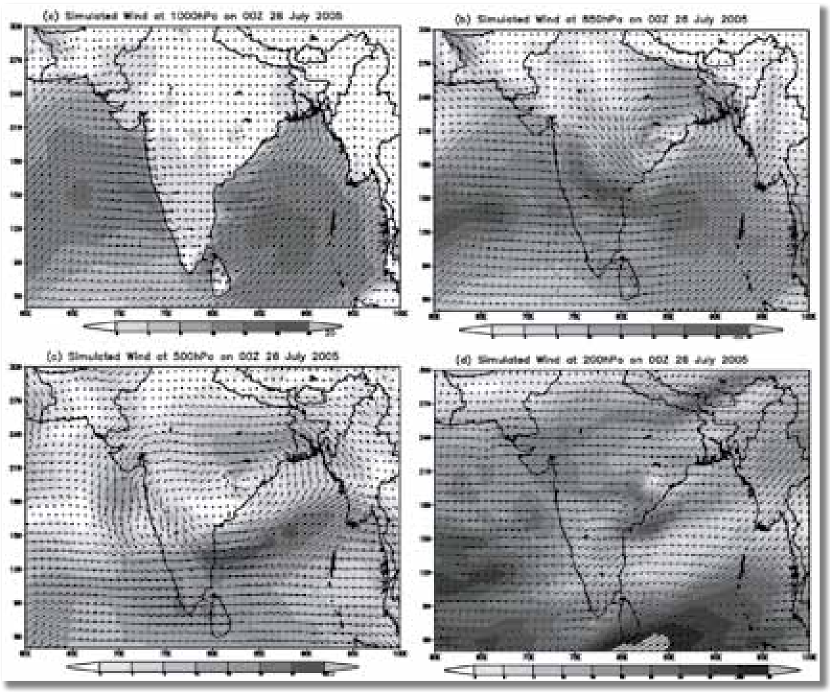

Figure 2. GME simulated wind patterns at 0000UTC on 26 July 2005 at (a) 1000 hPa (b) 850 hPa (c) 500 hPa (d) 200 hPa.

There was an offshore trough near the entire West Coast of India on the 26th July. It may be noted that the monsoon trough was also located near its usual position. The LLJ was present also (Figure 2b). All these conditions normally give rise to heavy rainfall over Mumbai. However, the question is: are these the only reasons for the unprecedented rainfall that occurs over Santacruz annually? Since very heavy rainfall was recorded over a very small area it appears that some sub-grid scale meteorological phenomena in the order of Meso-beta or Meso-gamma might also be present on that fateful day 26 July 2005. These sub-grid scale phenomena are normally associated with strong convective activity. Thermodynamic parameters like Convective Available Potential Energy (CAPE), Convective Inhibition Energy (CIN) and Precipitable Water Content (PWC) may give the exact details on this. Jenamani *et al*. (2006) have computed and presented the time series of CAPE, CIN and PWC over Santa Cruz from the radiosonde observations taken at 0000 UTC of 22 July to the 28 July 2005. They have reported that the numerical value of CAPE and PWC are less on the 26th July than on the 25th July. The rainfall recorded over Santa Cruz from 0300 UTC on the 25th July to 0300 UTC on the 26th July was only 11.9 mm. The numerical values of CAPE were 702 J kg – 1, 1000 J kg – 1, 2500 J kg – 1, 4341 J kg – 1 and 3267 J kg – 1 on 22, 23, 24, 25 and 26 July 2005 respectively; CIN values are 0, - 22.6 J kg – 1, - 6.6 J kg – 1, 0, 0 on the 22nd, 23rd, 24th, 25th and 26th July respectively. These values suggest that intense convective instability was present and the convection began building up from the 22nd July and reached a maximum on the 25th and the pre-built CAPE was released by strong convection: just one day before the event took place. While low values of CIN imply a favourable condition for convection, the critical value of CIN above which convection cannot occur has not been established.

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But zero CIN indicates that there was no inhibition for the convection to build up. The PWC reported were 4.2 cm, 4.5 cm, 5.0 cm, 5.9 cm and 5.4 cm on 22nd, 23rd, 24th, 25th and 26th July respectively. The PWC values also increased gradually from the 22nd July reaching a maximum on the 25th July.

RESULTS AND DISCUSSION

The model used in this study has a horizontal resolution of 40 km, 40 vertical levels and a time step of 133.3s. The data used was ECMWF at T511 L91 and the model run was performed on CRAY X1E and IBM p695 computers. The simulation of rainfall was done with the initial conditions on 21, 22, 23, 24, 25 and 26 July 2005. These have been presented in Figure 3a-f. The model shows rainfall between 50 and 60 cm with the initial conditions on the 21st, 22nd, 23rd, 24th, 25th and 26th July. The actual rainfall is 94.42 cm. To demonstrate the model's capability, an experiment was also conducted to simulate a contrasting situation by targeting a relatively dry period.

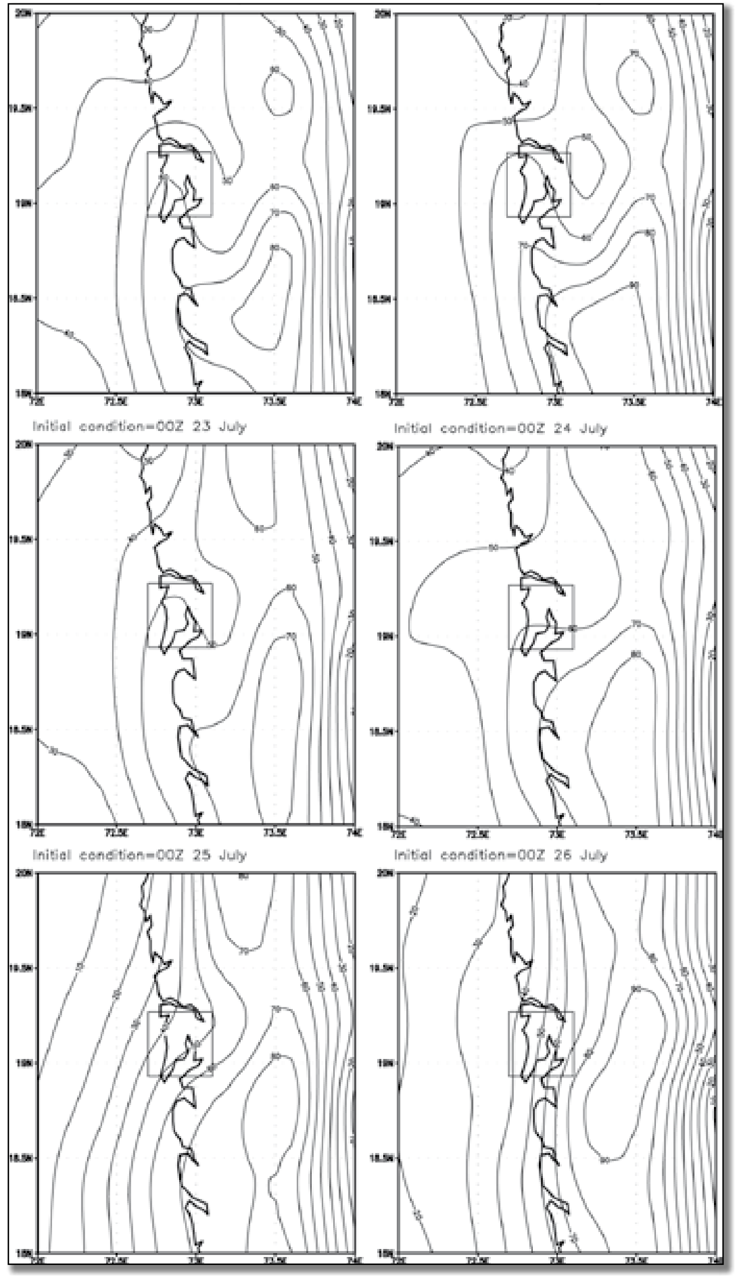


Figure 3. GME simulated rainfall patterns over Mumbai and adjacent region during 0300 UTC 26 July - 0300 UTC 27July 2005 starting with initial conditions of (a) 21 July, (b) 22 July, (c) 23 July, (d) 24 July, (e) 25 July and (f) 26 July 2005.

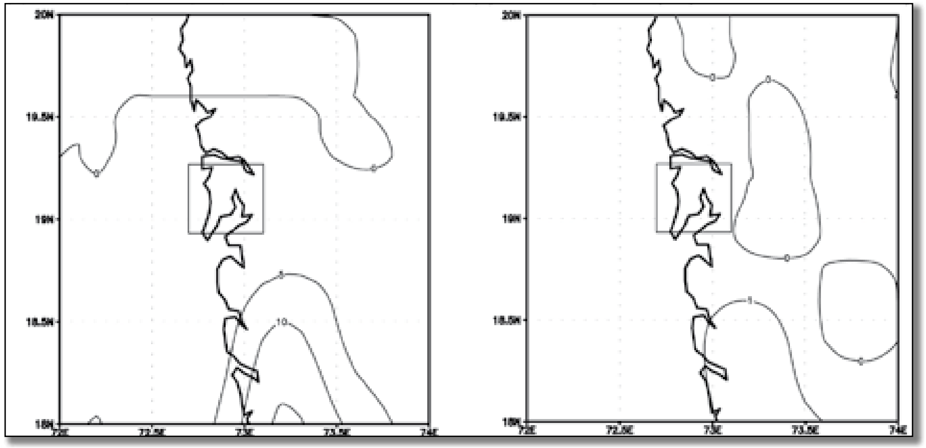
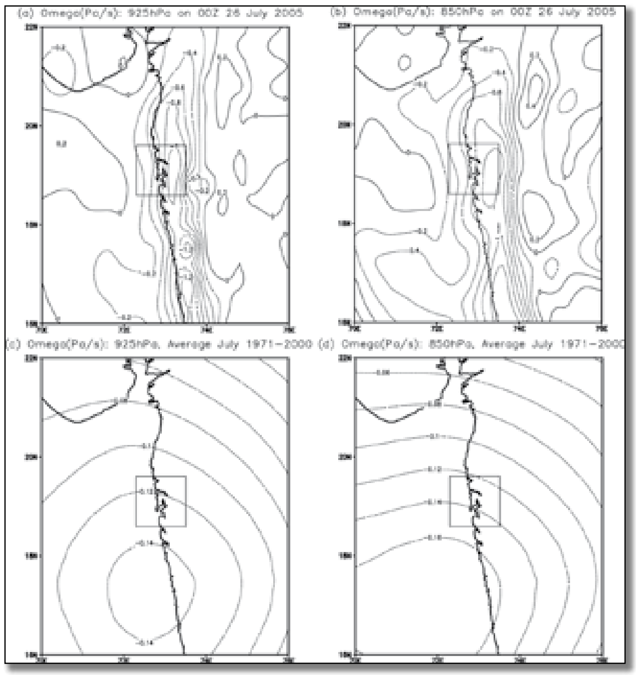


Figure 4. GME simulated rainfall patterns over Mumbai and adjacent region during (a) 0300 UTC 8 July – 0300 UTC 9 July 2005 (b) 0300 UTC 9 July – 0300 UTC 10 July 2005 with initial conditions of 8 July 2005.

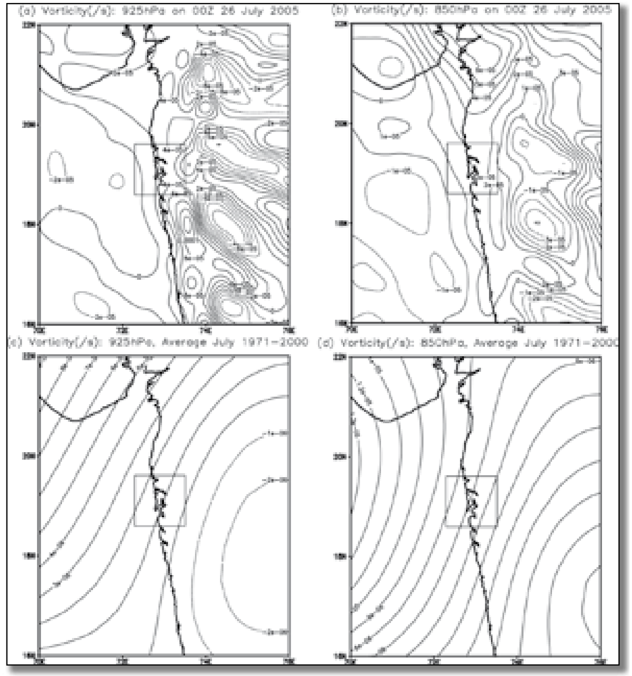
Mumbai was almost dry on 9 and 10 July 2005. The results of this experiment are presented in Figure 4a-b. The simulation of rainfall was done with the initial atmospheric conditions from 8 July 2005.

Figure 5. GME simulated Vertical p – Velocity (Omega) at (a) 925 hPa, (b) 850 hPa, at 0000UTC, 26 July 2005; 30 year Average of Omega at (c) 925 hPa and (d) 850 hPa.



The model shows very little rainfall during the period of 0300 UTC on the 8th July and 0300 UTC on the 9th July (between 0 and 5 mm) as well as during the period 0300 UTC on the 9th July and 0300 UTC on the 10th July (between 0 and 1 mm). It can, therefore, be concluded that the model has been able to simulate such a small scale phenomenon reasonably well, keeping in mind that GME is a global model and not a regional or mesoscale model.

The vertical pressure velocity (Omega), vertical component of vorticity and horizontal divergence in the lower levels have also been computed and presented along with average values computed from the NCEP/NCAR reanalyzed data for the period 1971 to 2000 in Figures 5, 6 and 7 respectively.



From these figures it can be seen that the model simulated vertical pressure velocity values are the same with respect to the magnitude of the average vertical pressure velocity, whereas the vertical component of vorticity is higher than the average value. The model simulated a vertical component of vorticity between 2×10-5 and 4×10-5 s-1 in the lower levels, whereas the climatological values are usually much lower in those levels. There is a strong convergence near Mumbai in the lower level (-6×10-5s -1 at 925 hPa). CAPE values indicate strong convection over Mumbai.

Normally, heavy precipitation is associated with intense convection with a large amount of moisture convergence.

Figure 6. GME simulated Vertical component of Vorticity at (a) 925 hPa, (b) 850 hPa at 0000UTC, 26 July 2005; 30 year Average of Vertical component of Vorticity at (c) 925 hPa and (d) 850 hPa.

The offshore trough might have provided moisture convergence and the convection aided by orographic lifting. The synoptic conditions and thermodynamic features of the 26th July suggest that there was interaction between the synoptic scale systems and the mesoscale systems to give rise to such record breaking precipitation in Mumbai.

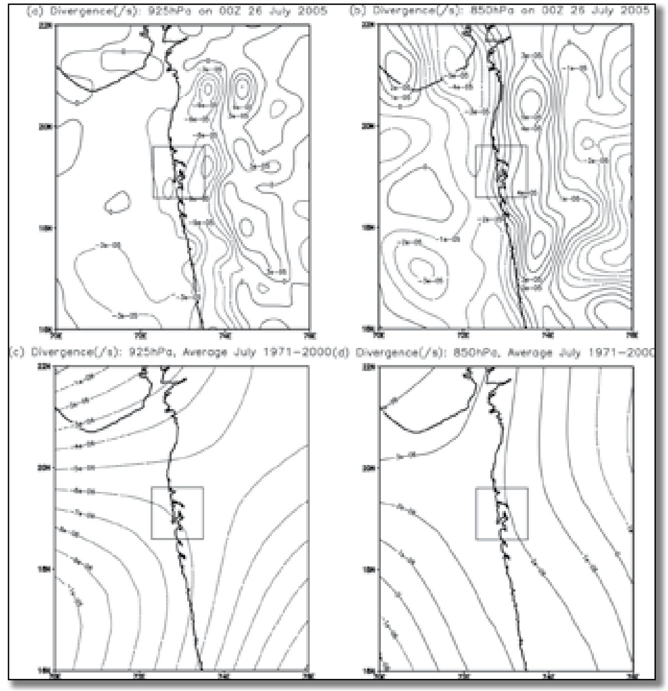


Figure 7. GME simulated Horizontal Divergence at (a) 925 hPa, (b) 850 hPa at 0000UTC, 26 July 2005; 30 year Average of Horizontal Divergence at (c) 925 hPa and (d) 850 hPa.

The PWC computed by Jenamani *et al*. (2006) revealed that the amount of precipitation from the convective system exceeded by more than one order of magnitude of the water content on the fateful day 26 July 2005. This means that an anomaly occurred whereby the output is more than the input. In the absence of radiosonde data, PWC could not be computed at the synoptic hours 0300, 0600, 0900, 1200 UTC for Santa Cruz on 26 July 2005. Actually, heavy spells of rain of 38.18 cm and 26.76 cm were recorded at Santa Cruz in the 3 hour periods between 0900 UTC and 1200 UTC and 1200 UTC and 1500 UTC respectively on 26 July 2005 (Jenamani *et al*., 2006). It is very difficult to explain from the conventional method why the PWC values are one order of magnitude less than the actual rainfall diagnosed by the research.

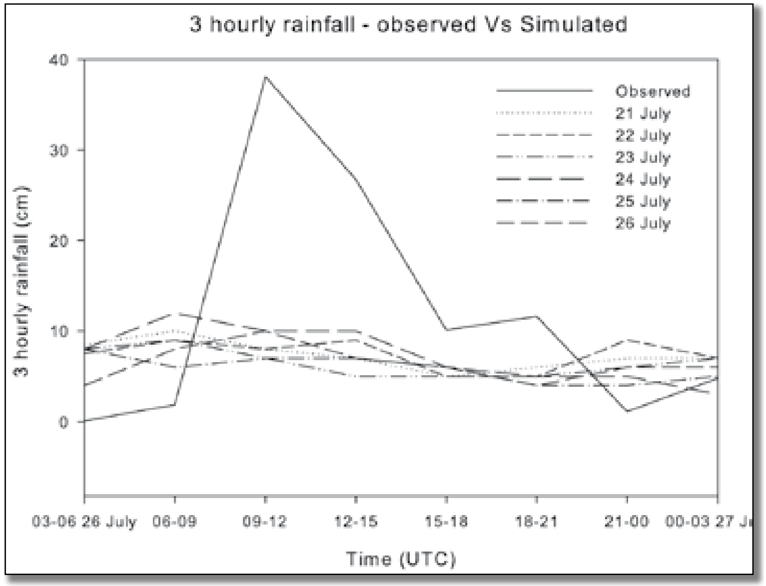


Figure 8. Three hourly rainfall by observation and model over Mumbai "

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