The simulation of heavy rainfall episode over Mumbai: impact of horizontal resolutions and cumulus parameterization schemes

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Abstract In this study, the simulation of an extreme weather event like heavy rainfall over Mumbai (India) on July 26, 2005 has been attempted with different horizontal resolutions using the Advanced Research Weather Research Forecast model version 2.0.1 developed at the National Center for Atmospheric Research (NCAR), USA. The study uses the Betts–Miller–Janjic (BMJ) and the Grell–Devenyi ensemble (GDE) cumulus parameterization schemes in single and nested domain configurations. The model performance was evaluated by examining the different predicted parameters like upper and lower level circulations, moisture, temperature, and rainfall. The large-scale circulation features, moisture, and temperature were compared with the National Centers for Environmental Prediction analyses. The rainfall prediction was assessed quantitatively by comparing rainfall from the Tropical Rainfall Measuring Mission products and the observed station values reported in the Indian Daily Weather Reports from India Meteorological Department (IMD). The quantitative validation of the simulated rainfall was done by calculating the categorical skill scores like frequency bias, threat scores (TS), and equitable threat scores (ETS). It is found that in all simulations, both in single and nested domains, the GDE scheme has outperformed the BMJ scheme for the simulation of rainfall for this specific event.

1 Introduction

In numerical weather prediction, an accurate timely and location specific prediction is very important to minimize the loss of lives and damage to property due to strong winds and heavy precipitations associated with severe or very severe weather systems. For the better prediction of flash flood, it is necessary to understand the dynamics and physics of isolated

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heavy precipitation and other dynamical features associated with thunderstorms, tornados, etc. The extreme event becomes a matter of importance only when it comes as nature of a disaster with heavy loss of life and damage to property. One such phenomenon was the heavy rainfall episode over Mumbai on July 26, 2005. On that day, within a span of a few hours, northern Mumbai received unprecedented rainfall, with Santa Cruz recording 94.4 cm of rainfall for the day and more heavy rainfall of 104.9 cm at Vihar Lake located around 15 Km northeast of Santa Cruz. Bhandup located southeast of Vihar Lake received 81.5 cm of rainfall. Colaba in southern Mumbai, on the other hand, received only 7 cm. This event disrupted life, besides causing heavy damage to property and human life. Prior knowledge of such an extreme event by a day or a few hours could have minimized the loss of life.

The real-time forecast over Taiwan was carried out by Ching et al. (2005) by studying the typhoon Nida and a mesoscale convective system (MCS) during May 2004 using MM5 (Dudhia 1993; Grell et al. 1995) and WRF (Skamarock et al. 2005) mesoscale models. It was found that the timing of the MCS was captured slightly better by the WRF model than the MM5 model. However, the simulated rainfall amount in the WRF model was not large enough when compared with the observations. The predicted rainfall amounts in the MM5 were more consistent with the observations. The simulation of a high impact weather event over Israel was carried out with an observation-nudging-based rapid-cycling four-dimensional data assimilation and forecast (RTFDDA) system implemented in the WRF modeling (Rostkier-Edelstein et al. 2006) system. The WRF model was used for the simulation of thunderstorm at Machilipatnam over the east coast of India and a cyclonic circulation over Kerala (Vaidya 2007), and for the simulation of the extreme rainfall event of July 26, 2005 over Mumbai (Vaidya and Kulkarni 2007). In United States (US) this model was used for the prediction of warm season rainfall forecasts over the central US (Gallus and Bresch 2006). They have carried out a comparison of impacts of the WRF dynamic core, physics package, and initial conditions on warm season rainfall forecasts. A series of 15 simulations of weather events occurring in August 2002 were performed using the WRF model over a domain encompassing most of the central US to compare the sensitivity of the warm season rainfall forecasts with changes in the model physics, dynamics, and initial conditions. Chang et al. (2009) had carried out the impact of land surface parameterizations on the simulation of the July 26, 2005 heavy rain event over Mumbai, India. Sixteen numerical experiments were designed using two mesoscale models: the MM5 and the WRF, with three nested domains (30, 10, and 3.33 km grid spacing), for various land surface schemes and land use/land cover conditions. The study revealed that the simulations of rainfall using the WRF model was better than the corresponding MM5 model in terms of both location and intensity.

Now-a-days the accuracy and reliability of numerical weather prediction (NWP) have improved a lot because of advances in numerical techniques for assimilation of satellite data into the numerical model. However, still some limitations exist in the prediction of extreme weather events like the Orissa (India) supercyclone (29 October of 1999) over the Bay of Bengal or the extreme rainfall event of July 26, 2005 over Mumbai (India). Though some of the state-of-the-art non-hydrostatic and compressible mesoscale models like MM5 [developed by Penn-state University and National Center for Atmospheric Research (NCAR), USA] have been successfully used for the simulation of extreme events like tropical cyclones (Mohanty et al. 2004; Mandal et al. 2004; Singh et al. 2005), these models were not very successful for the prediction of the Mumbai rainfall event in hindcast mode. The purpose of this study is to examine the performance of the WRF modeling system for the simulation of the severe rainfall event of July 26, 2005 over Mumbai with varying horizontal resolutions and cumulus parameterization schemes. These limited

numbers of experiments will definitely give some clues about the performances of NWP model over the tropical Indian region.

The present study is organized in the following manner: Section 2 describes the methodology adopted for this study, which includes three subsections, viz., the synoptic and observed features related to Mumbai rainfall; the brief description of the model and experiments design; and the verification procedure. The Sect. 3 describes the results and discussion. Conclusions are given in Sect. 4.

2 Methodology

2.1 Synoptic and observed features of Mumbai rainfall

Generally, during the active phase of the southwest monsoon in July and August, the regions lying in the windward side of the Western Ghats (a north–south mountain range in the western zone of India) like the stations near Konkan and Goa, including Mumbai and coastal Karnataka (Fig. 1) get heavy rainfall because of the orographic effect (Rao 1976). The strong westerly moist wind from the Arabian Sea hits the hills of the Western Ghats and is lifted vertically upward during active monsoon and causes very heavy rainfall there. During this period, the strong westerly/southwesterly flow over the Arabian Sea also leads to the formation of offshore trough over the sea off the west coast, causing very heavy
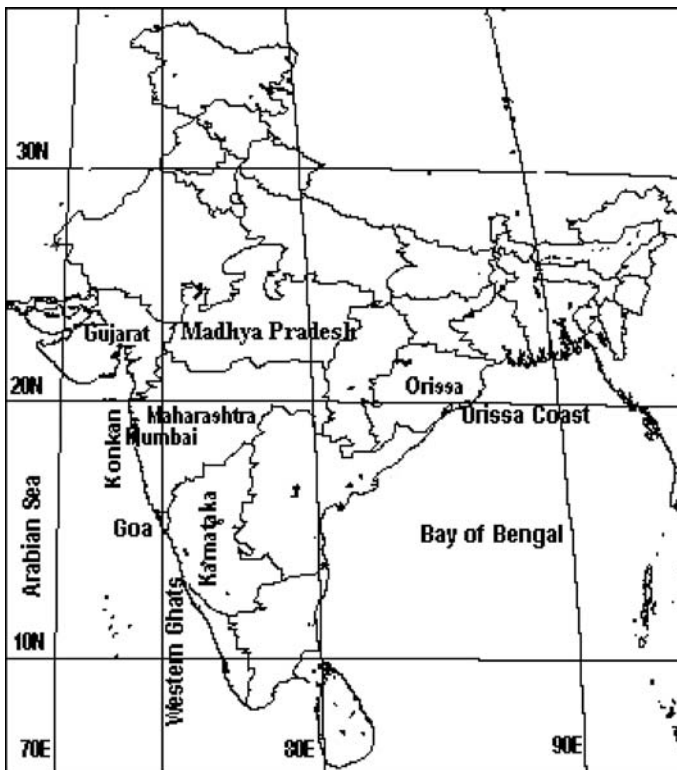
Fig. 1 A map of India showing important landmarks referred in the article

rainfall activity along the west coast of India, including Mumbai (George 1956). This westerly/southwesterly wind is also strengthened when the Arabian Sea branch of the monsoon is active or when a depression/low pressure area forms over the north Bay of Bengal and moves into Central India. Due to the presence of mid-tropospheric cyclone (MTC) Gujarat–Konkan coast also experiences very heavy rainfall up to 40 cm. During the onset phase of the southwest monsoon, heavy rainfall of more than 20 cm is quite common for Mumbai. Generally it is caused by a convergence of the dry winds from the north with the advancing moist southwesterly monsoon winds, which are coupled with the development of onset vortex either over the Arabian Sea or over the Bay of Bengal. However, during the active phase of monsoon, some special features of synoptic situation are conducive to the occurrence of very heavy rainfall over Mumbai, viz., the development of a low pressure area over the northwest Bay of Bengal, the intensification of monsoon trough and development of embedded convective vortex over the central parts of India, the strengthening of the Somali Jet, and the super-positioning of a mesoscale off-shore vortex over the northeast Arabian Sea and its northward movement.

On July 26, 2005, the summer monsoon was active and a low-pressure area was formed over the north Bay of Bengal on July 24 and became a well marked "low" when it reached inland. Due to this reason the monsoon trough shifted south of its usual position and a strong cross-equatorial flow was developed over there. As the cross equatorial flow from west mixed with the low-level jet, the strengthened westerly winds hit the Konkan and Goa coasts and caused a very heavy rainfall over these regions. On the next day (July 25), the rainfall band moved north, and large parts of Maharashtra, including Mumbai, received heavy rainfall on July 26. Some previous studies (Jayaram 1965; Sharma 1965) have showed that a diurnal pressure gradient of about 4–8 hPa along the west coast of India between 15 and 20° N was necessary for the occurrence of a heavy rainfall event in the Mumbai belt and during the large variation in rainfall over Mumbai, the westerly winds were of the order of 15–20 m/s with a depth of 3 Km. However, in the present case, 3-hourly surface chart has also shown that the pressure gradient of 4–6 hPa along the west coast between 15 and 20° N from 00Z to 12Z 26 July (Jenamani et al. 2006); westerly winds were also of the order of 15–25 m/s with a depth of 5.8 Km. Thus, the synoptic scale features were highly favorable for the occurrence of heavy rainfall, but the localized nature of the event and its strong intensity could not be anticipated.

On this day, Santa Cruz recorded 94.4 cm of rainfall, however, even higher rainfall of 104.9 cm was recorded at the Vihar Lake (Jenamani et al. 2006; Shyamala and Bhadram 2006). Although the UK Met Office Model (UKMO) was one of the few models that predicted up to 80 cm of rainfall in the retrospective mode over a smaller area covering Mumbai on July 26, 24-h in advance, most of the numerical models, both global and mesoscale, failed to simulate this catastrophic event in operational as well as in hindcast mode (Bohra et al. 2006). Here, an attempt has been made to simulate this event using the WRF model with varying grid resolution and different cumulus parameterization schemes. In this regard, a study by Vaidya (2006) using the Kain–Fritsch (KF) and the Betts–Miller–Janjic (BMJ) cumulus schemes in the Atmospheric Regional Prediction System (ARPS) model had shown that the different tropical events like low-pressure area, monsoon depression, and tropical cyclones are sensitive to the different cumulus schemes.

2.2 The WRF model and experimental design

The mesoscale model used in this study is the Advanced Research Weather Research Forecast (WRF-ARW) model version 2.0.1 developed primarily at NCAR with collaboration of

different agencies like the National Oceanic and Atmospheric Administration (NOAA), the
National Centers for Environmental Prediction (NCEP), the NOAA's Earth System Research
Laboratory (NESRL), University of Oklahoma, and many others. The development of the
WRF modeling system is to serve both operational forecasting and atmospheric research (
http://www.wrf-model.org). The WRF is a limited area, non-hydrostatic primitive equation
model with multiple options for various physical parameterization schemes (Skamarock
et al. 2005). The terrain following hydrostatic pressure with vertical grid stretching (σ) is
followed in vertical. The vertical co-ordinate is defined as $\sigma = (p_h - p_{ht})/\mu$, where
$\mu = p_{hs} - p_{ht}$, p_h is the hydrostatic component of the pressure, and p_{hs} and p_{ht} refer to the
values along the surface and top boundaries, respectively. The value of σ is 1 at the surface to 0
at the upper boundary of the model domain. This vertical co-ordinate is also called as a mass
vertical coordinate. Due to the meteorological complexities involved in simulating and
forecasting the heavy rainfall occurrences over a tropical region, use of the WRF modeling
system, both in single and in a nested configuration, has been selected for the present study. In
this study, the performance of the WRF model for the simulation of this excessive rainfall
event over Mumbai has been attempted using two cumulus parameterization schemes, the
Betts–Miller–Janjic (Janjic 1994, 2000) and the Grell–Devenyi ensemble (Grell and Devenyi
2002) schemes. The other different dynamical and physical options used in this study are
given in Table 1.

The Betts–Miller–Janjic (BMJ) scheme is a convective adjustment scheme and it is
derived from the original Betts and Miller (1986) adjustment scheme. In the BMJ scheme,
the deep convection profiles and the relaxation time are variables and they depend on the
cloud efficiency, a non-dimensional parameter, that characterizes the convective regime
(Janjic 1994). The cloud efficiency depends on the entropy change, precipitation, and mean
temperature of the cloud. The shallow convection moisture profile is derived from the
requirement that the entropy change be small and non-negative (Janjic 1994). Some
attempts have been made to refine the scheme for higher horizontal resolutions, primarily
through modifications of the triggering mechanism. In particular, a floor value for the
entropy change in the cloud is set up below which the deep convection is not triggered; in
searching for the cloud top, the ascending particle mixes with the environment, and the
work of the buoyancy force on the ascending particle is required to exceed a prescribed

Table 1 A summary of characteristics of the WRF model

S. No.	Characteristic feature	WRF
1	Nesting option used	Nest: 10 Km inner and 30 Km outer
2	Vertical coordinate	σ_p Terrain following mass vertical coordinate (Laprise 1992)
3	Horizontal grid	Arakawa C-grid
4	Time integration scheme	Third-order Runga–Kutta scheme
5	Microphysics	Single-moment 6-class graupel (WSM6) microphysics scheme
6	Convection	Grell–Devenyi ensemble scheme (Grell and Devenyi 2002) and Betts–Miller–Janjic (Janjic 1994, 2000)
7	Radiation	Rapid radiative transfer model (RRTM), Mlawer et al. (1997) for longwave and Dudhia (1989) for shortwave.
8	Planetary boundary layer (PBL)	MRF (Medium Range Forecast) Scheme, (Hong and Pan 1996)
9	Land surface model	Noah-LSM (Chen and Dudhia 2001)

Table 2 Design of the different experiments

S. No.	Experiments	Domain type	Resolution (Km)	Cumulus schemes
1	S20BMJ	Single	20	Betts–Miller–Janjic (BMJ)
2	S20GDE			Grell–Devenyi-ensemble (GDE)
3	S10BMJ		10	BMJ
4	S10GDE			GDE
5	N30BMJ	Nested (Outer)	30	BMJ
6	N30GDE			GDE
7	N10BMJ	Nested (Inner)	10	BMJ
8	N10GDE			GDE

positive threshold. The Grell–Devenyi ensemble (GDE) cumulus parameterization scheme consists of an ensemble of cumulus scheme in which multiple schemes are run within each grid box and the results are averaged to give the feedback of the model. All cumulus schemes in the GDE scheme are of mass–flux nature, differing in updraft and downdraft with entrainment and detrainment parameters, and precipitation efficiencies. The dynamic control closures are based on either convective available potential energy (CAPE), or low-level vertical velocity, or moisture convergence. Those based on CAPE either balance the rate of change of CAPE or relax the CAPE to a climatological value and those based on moisture convergence balances the cloud rainfall to the integrated vertical advection of moisture.

For this study, eight experiments were designed, viz., S20BMJ, S20GDE, S10BMJ, S10GDE, N30BMJ, N10BMJ, N30GDE, and N10GDE, respectively (Table 2). Out of which S20BMJ, S20GDE, S10BMJ, and S10GDE were in single domains with 20 and 10 Km resolutions using the GDE and the BMJ cumulus parameterization schemes having 179×150 grid points, covering the regions [58° E–91° E, 1° N–28° N] and [66° E–83° E, 12° N–25° N], respectively. The remaining were two-way nested domains experiments with 30 Km outer and 10 Km inner resolutions, using the same cumulus schemes (constituted another four sets of results) used for the single domain experiments, having 179×150 and 270×225 grid points in outer and inner domains, covering the areas [49° E–100° E, 2° S–36° N] and [62° E–87° E, 7° N–27° N], respectively. In the two-way nesting: first, the inner (fine) grid boundary conditions (i.e., the lateral boundaries) are interpolated from the outer (coarse) grid forecast, and later, the inner (fine) grid solution replaces the outer (coarse) grid solution for those grid points that lie inside the inner (fine) grid. This information exchanges between the grids in both the directions (coarse-to-fine and fine-to-coarse). Hence, the name is two-way nesting. In the vertical, the model has 31 vertical layers with the top model layer at 50 hPa. For each simulation, 48 h integration was started from 00 GMT July 25, 2005. The NCEP FNL (final analysis) $1° \times 1°$ 6-hourly data were used for preparing both initial and boundary conditions for the model integrations.

2.3 Verification procedure

The rainfall is one of the most important parameters for the tropical weather systems. Apart from the ground-based observations from IMD, the Tropical Rainfall Measuring Mission (TRMM) rainfall was used to verify the simulated rainfall. 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 provides systematic visible, infrared, and microwave measurements of rainfall in the tropics as key inputs to weather and climate research. The NCEP Global Data Assimilation System (GDAS) analyses were used to verify the simulated large-scale circulations pattern, moisture, and relative humidity fields. The precipitation fields are generally verified by the categorical skill score method, where forecast are varied against the occurrence or non-occurrence of specific categories of the predicted rainfall (Gandin and Murphy 1992). The common methods of categorical verification of the precipitation fields are based on the calculation of frequency bias B, threat score (TS), and equitable threat score (ETS). The area frequency bias B is defined as $B = F/O$, where F is the number of stations for which the model predicted rainfall amount exceeded a certain threshold and O is the number of stations that recorded at least the selected threshold. The TS and the ETS are defined as

$$\mathrm{TS} = \frac{\mathrm{CF}}{F + O - \mathrm{CF}}$$

and

$$\mathrm{ETS} = \frac{\mathrm{CF} - R}{F + O - \mathrm{CF} - R},$$

where R is a random forecast defined as the product of F and O, divided by the total number of N of verified stations: $R = FO/N$ and CF is the number of points where the rainfall from model forecast is equal to the observed one (Correct Forecast). The ETS is equivalent to TS with a correction to remove the frequency bias from the random hits. These statistical measures are used extensively for the evaluation of model forecast precipitation (Mesinger 1996; Lagouvardos et al. 2003; Mazarakis et al. 2006). The quantitative analysis of the simulated rainfall is carried out by calculating the frequency bias, TS, and ETS for the day 2, i.e., second 24 h of simulation in all the cases with respect to the TRMM rainfall. Apart from rainfall, the analysis of the simulated circulation features (850 and 300 hPa winds), thermal, and moisture fields were also discussed.

3 Results and discussion

Four sets of forecast results were obtained in each cumulus scheme for different resolutions (Table 2). The purpose of this study is to see the impact of two cumulus parameterization schemes in the WRF model for the simulation of this extreme rainfall event. Initially, the observed features, viz., large-scale upper and lower level circulation, moisture, and thermal structure from the NCEP GDAS analyses, ground-based observed rainfall from IMD and gridded observed rainfall from the TRMM were analyzed. Later, the performance of each scheme was presented here with respect to the upper- and lower-level wind, rainfall, moisture fields, and their thermal structure.

On July 26, 2005, the summer monsoon over major parts of the country particularly over the west coast and the peninsular India was active and a low-pressure area formed over the North Bay off Gangetic West Bengal and Orissa coast on July 24 and becomes a well-marked low when it reached inland. Due to this reason, the monsoon trough moved south of its normal position and a strong cross-equatorial flow was developed. As the cross-equatorial flow moved to the west and mixed with low-level jet and strengthened the westerly wind, which hits the Konkan and Goa coasts, it resulted in heavy rainfall over

(a) 12Z 850 hPa Winds analysis   **(b)** 12Z 300 hPa Winds   analysis
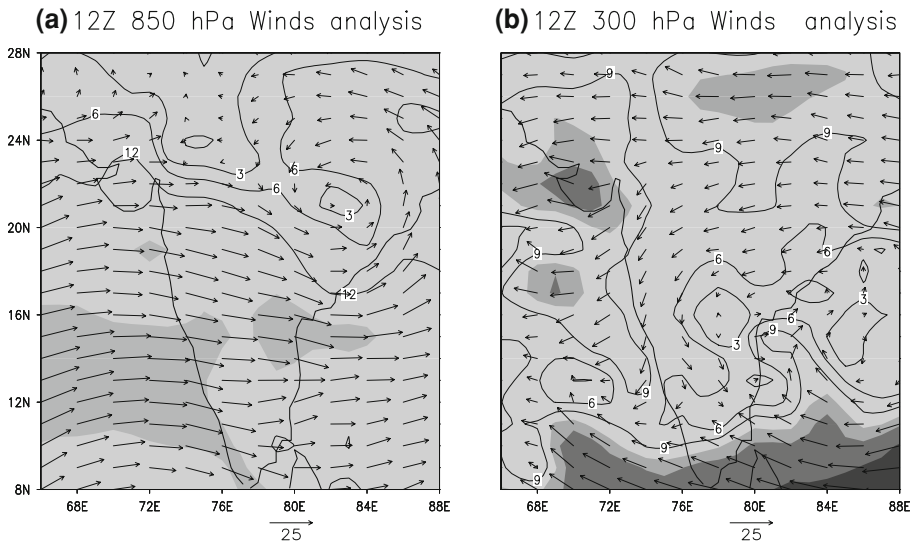
Fig. 2 The NCEP analyses: winds (m/s) along with magnitude at 12Z July 26, 2005: **a** 850-hPa, **b** 300-hPa, (Contour levels 3, 6 and 12; winds with 20 m/s and 25 m/s are shaded for (**a**) and for (**b**) contour levels 3, 6, and 9; winds with 12, 15 and 20 m/s are shaded)

these regions. On the next day (25 July), the rainfall band moved north and large parts of Maharashtra, including Mumbai, received heavy rainfall on July 26. Both the lower- and upper-level large-scale flow pattern over the Indian region were analyzed with 850 and 300 hPa winds valid at 12Z July 26, 2005 from the NCEP analyses and shown in Fig. 2a, b. This showed the presence of strong cyclonic circulation, which extended up to the mid-troposphere over Orissa and eastern part of Madhya Pradesh. This was associated with a well-marked low-pressure system near the surface. It also showed the presence of strong westerly or northwesterly winds with a speed of 20 m/s in the lower level at 850 hPa (Fig. 2a) over the western coast of India including Mumbai. This lower level strong westerly or northwesterly winds become easterly or northeasterly at 300 hPa (Fig. 2b) with a speed of 6–12 m/s over Mumbai. It was also found by analyzing the other level winds on July 26 (12Z), i.e., during the occurrence of heavy rainfall, there was a sudden increase of wind speed between 925 and 850 hPa followed by an abrupt decrease in the subsequent levels, with direction changing from westerly to northeasterly with height. This was basically due to the veering of wind with height during the occurrence of this extreme event. Thus, the synoptic scale features were highly favorable at times for the occurrence of heavy to very heavy rainfall over the western coast of India including Mumbai.

Figure 3a, b shows the 24-h observed rainfall valid at 00Z on July 27, 2005 over Mumbai and neighboring stations, as recorded by IMD and observed by TRMM. On this day, Santa Cruz and its nearby station Vihar Lake, 15 Km northeast of Santa Cruz, recorded 94.4 and 104.9 cm rainfall. However, thereafter, the amount of rainfall decreased in the northeast of Santa Cruz, with Bhandup and Tulsi reported 81.5 and 60.1 cm of rainfall, respectively (Jenamani et al. 2006). Some other northeast stations like Bhiwani, Thane, and Kalyan reported 75, 74, and 62 cm of rainfall, which are farther northeast of Santa Cruz. Moreover, Colaba and Malabar Hills, which are south of Santa Cruz, recorded 7.3 and 7.4 cm of rainfall. The maximum rainfall measured by TRMM was only 32 cm;

Fig. 3 Twenty four-hour cumulative rainfall (cm) valid at 03Z July 27, 2005 observed by **a** IMD at different stations near Mumbai and **b** TRMM

however, the position was captured very well when compared with the rainfall pattern as recorded by IMD. The rainfall recorded by IMD is a point measurement, while the resolution in the TRMM rainfall is 0.25° both along scan and pixel, and this can be one of the reasons for their differences in magnitude. Though the TRMM rainfall is a merged derived product from both IR and microwave measurements, sometimes TRMM underestimate the rainfall near the surface due to warm clouds. Figure 4 shows 6-hourly accumulated rainfalls from the TRMM over Mumbai starting from 06Z July 25, 2005 to 00Z July 27, 2005. It clearly shows a localized area of heavy precipitation directly over Mumbai at 12Z, 18Z of July 26, 2005 and 00Z of July 27, 2005, of the order of 8–16 cm (Fig. 4f–h). The TRMM pictures showed the location of intense rainfall very accurately; however, the magnitude was underestimated.

The NCEP temperature and the relative humidity fields were also critically analyzed at the lower and upper levels for the period of July 25–27, 2005 to find the exact nature of the thermodynamic structure during this event. Figure 5a, b shows the 850- and 300-hPa temperature valid at 12Z of July 26, 2005. It is observed that warm isotherms were lying to the north and west of Mumbai in the Arabian Sea at lower levels. Also, advection from the west at these levels was due to the strong westerlies (Fig. 5a) from the Arabian Sea, thus bringing the warm and moist air from the west. The latitude-height cross-section of relative humidity from the NCEP analyses shows (Fig. 6a, b) that the relative humidity was more than 90–95% at various levels up to 400 hPa around Mumbai (average along 72.5° E–73.5° E) between 06Z and 12Z of July 26, 2005. At 12Z of July 26, 2005, air was relatively dry in the middle troposphere at 750–550 hPa in the south of Mumbai, which resembles the actual observations as reported by the IMD. Strong vertical wind shear along with an updraft in the low levels might have influenced the development of additional lifting needed for the occurrence of this severe localized rainfall at Mumbai. The study by Jenamani et al. (2006) showed, with different observational data from the IMD, that the vertical uplifting of moist air masses were the highest at 12Z July 26, 2005, among all observations between 24 and 27 July 2005. The rainfall rate was the largest over Mumbai during 09Z–15Z July 26, 2005.

The simulated 850-hPa winds valid at 12Z July 26, 2005 over the Indian region from the different experiments are presented in Fig. 7. All experiments, both in coarse and fine resolutions, predicted the strong westerly or northwesterly winds over the western coast of India with a maximum speed of 20 m/s. The experiment S10GDE simulated wind of magnitude 20 m/s over Mumbai (Fig. 7b), whereas in all other simulations, winds of magnitude 12 m/s was observed on this region. Both the schemes showed the presence of strong cyclonic circulation over Orissa and the eastern part of Madhya Pradesh, though the centre of the low was simulated a bit eastward as compared to the analyses. Figure 8 shows the simulated 300-hPa winds valid at 12Z July 26, 2005 from the different experiments. All experiments except N30BMJ (Fig. 8g) and N30GDE (Fig. 8h) have simulated the upper level easterly or northeasterly flow reasonably well, with speed of approximately 12 m/s over Mumbai. As a whole, both upper- and lower-level large-scale circulation features were simulated reasonably well by both the schemes.
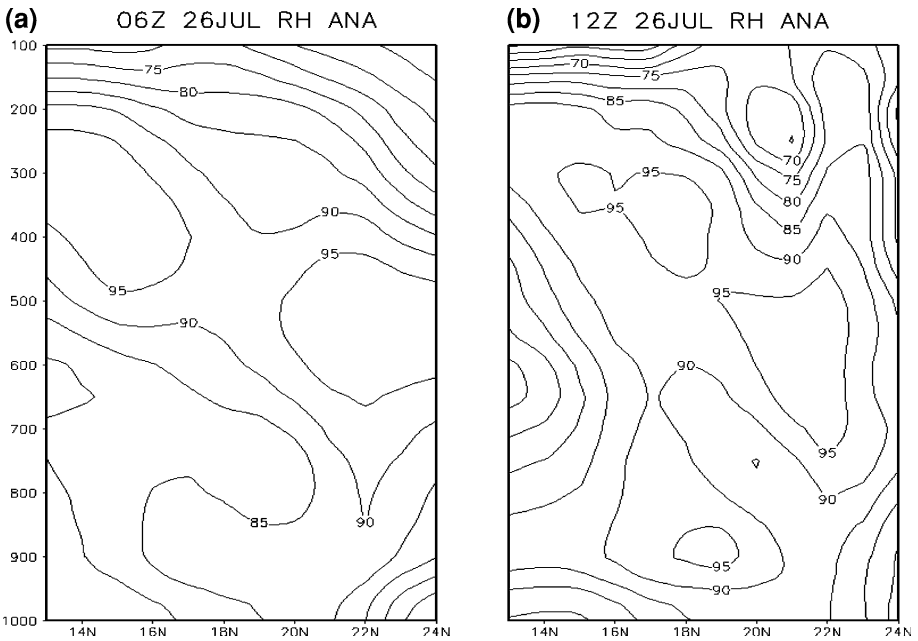
Figure 9 shows the simulated 24-h cumulative rainfall from the different experiments valid at 00Z on July 27, 2005 over Mumbai. It is observed that the maximum rainfall simulation from S10BMJ and S10GDE (Fig. 9a, b) was 32 and 80 cm, respectively, but the position was a bit eastward from the observed location. However, this centre of maximum rainfall was reduced drastically in the experiments S20BMJ and S20GDE with simulated rainfall amounts 4 and 32 cm, respectively (Fig. 9c, d). The specific location of the intense rainfall around Mumbai was very well simulated in S20GDE, though the
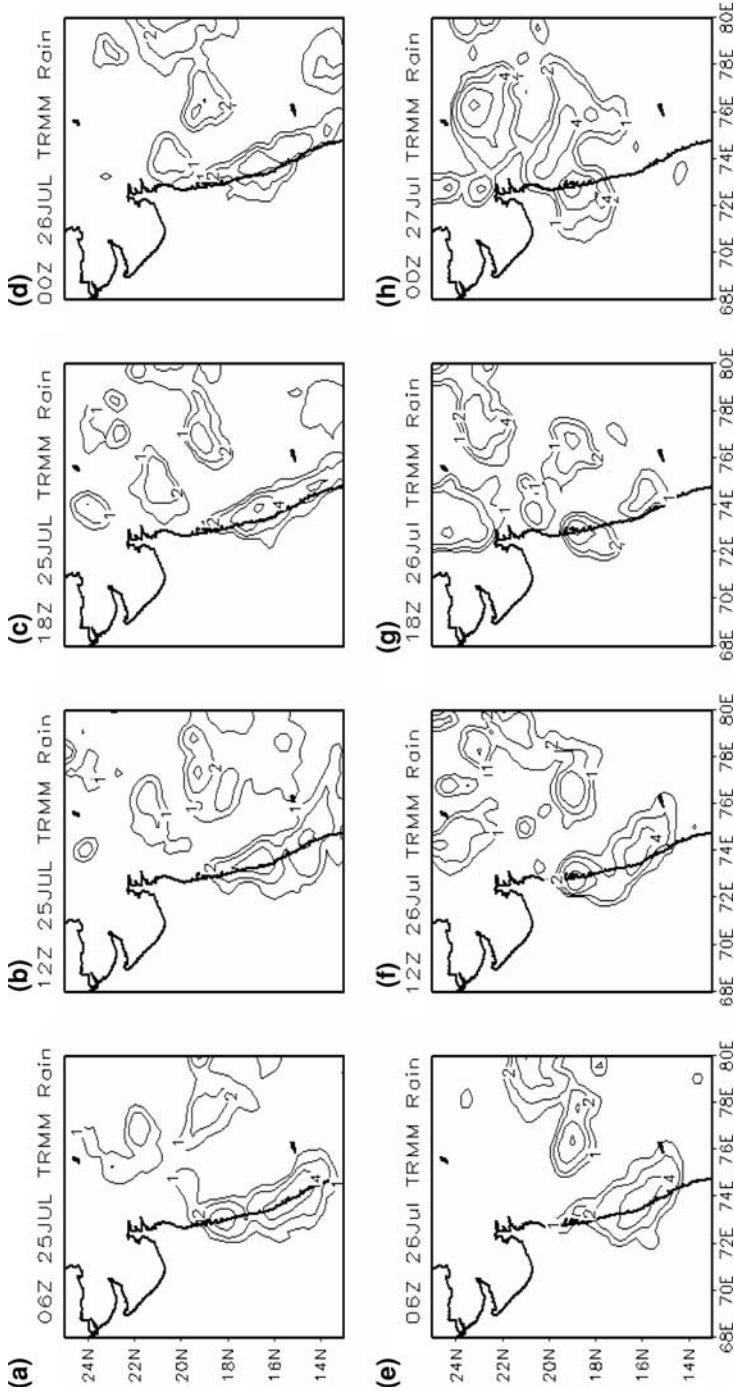
Fig. 4 Six hourly accumulated rainfall (cm) from the TRMM: July 25, 2005 **a** 06Z, **b** 12Z, **c** 18Z, July 26, 2005 **d** 00Z, **e** 06Z, **f** 12Z, **g** 18Z, and **h** 00Z July 27, 2005 respectively. (Contour levels 1, 2, 4, 8, 16, 32, and 48)

(a) 850hPa Temp 26JUL ANA   **(b)** 300hPa Temp 26JUL ANA
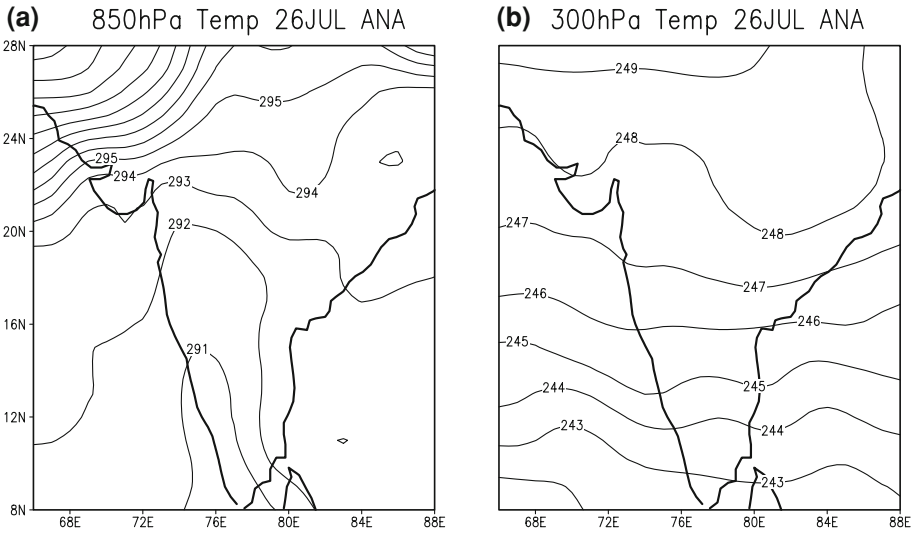
Fig. 5 Analyzed temperature (K) from NCEP at 12 Z July 26, 2005: **a** 850-hPa and **b** 300-hPa

(a) 06Z 26JUL RH ANA   **(b)** 12Z 26JUL RH ANA

Fig. 6 Analyzed latitude-height cross-section of the relative humidity (%) from NCEP at 72.5° E–73.5° E of July 26, 2005 **a** 06 Z and **b** 12 Z

magnitude of rainfall was less as compared to the observation. Figure 9e, h shows the simulated rainfall from the two nested experiments. The outer domain, which was 30 km resolution, shows very poor rainfall around Mumbai using the BMJ scheme, while in the GDE scheme, the rainfall maxima was 48 cm, and the centre of the maximum rainfall was
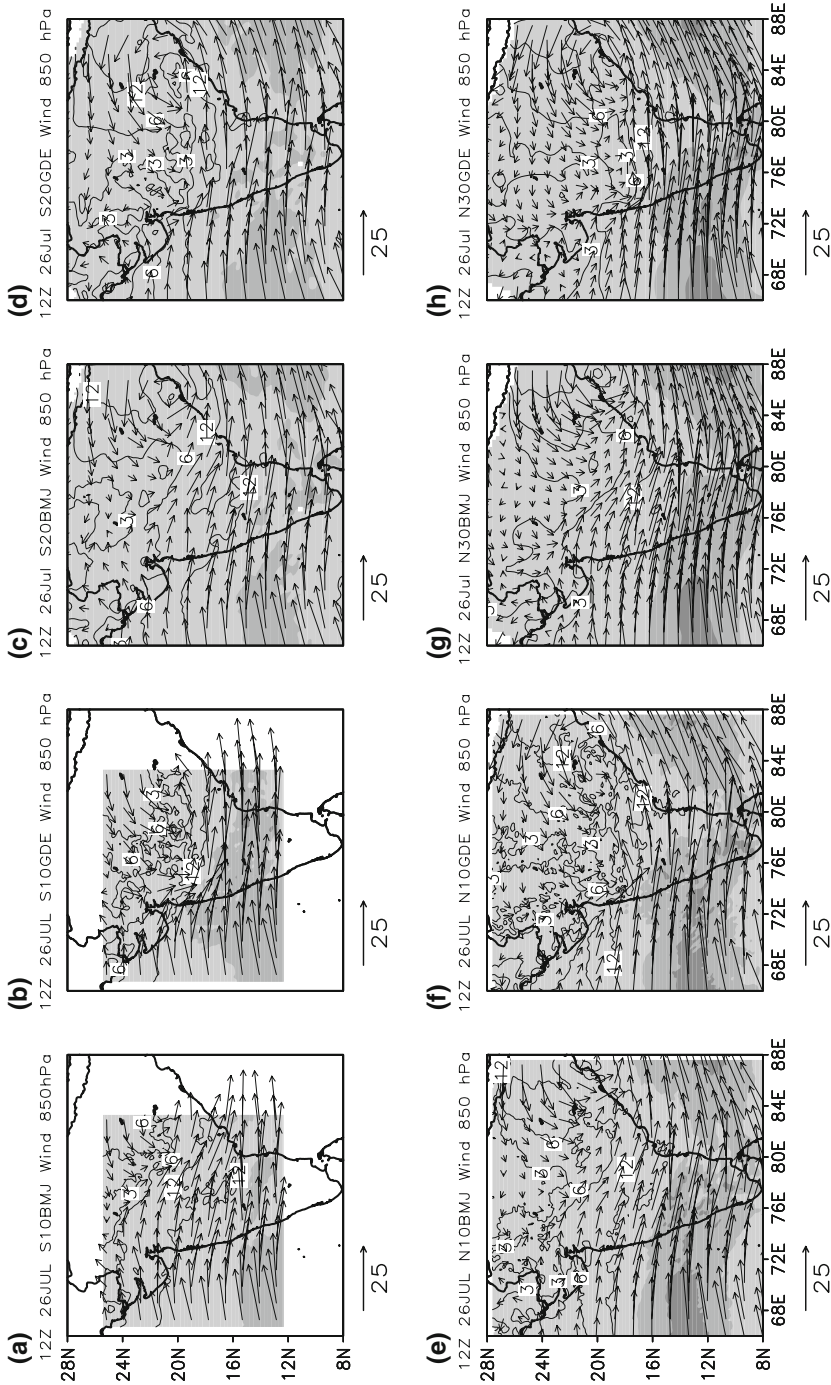
Fig. 7 The simulated 850-hPa winds (m/s) along with magnitude valid at 12Z July 26, 2005 from the different experiments: **a** S10BMJ, **b** S10GDE, **c** S20BMJ, **d** S20GDE, **e** N10BMJ, **f** N10GDE, **g** N30BMJ, and **h** N30GDE. (Contour levels 3, 6, and 12; winds with 20 and 25 m/s are shaded)
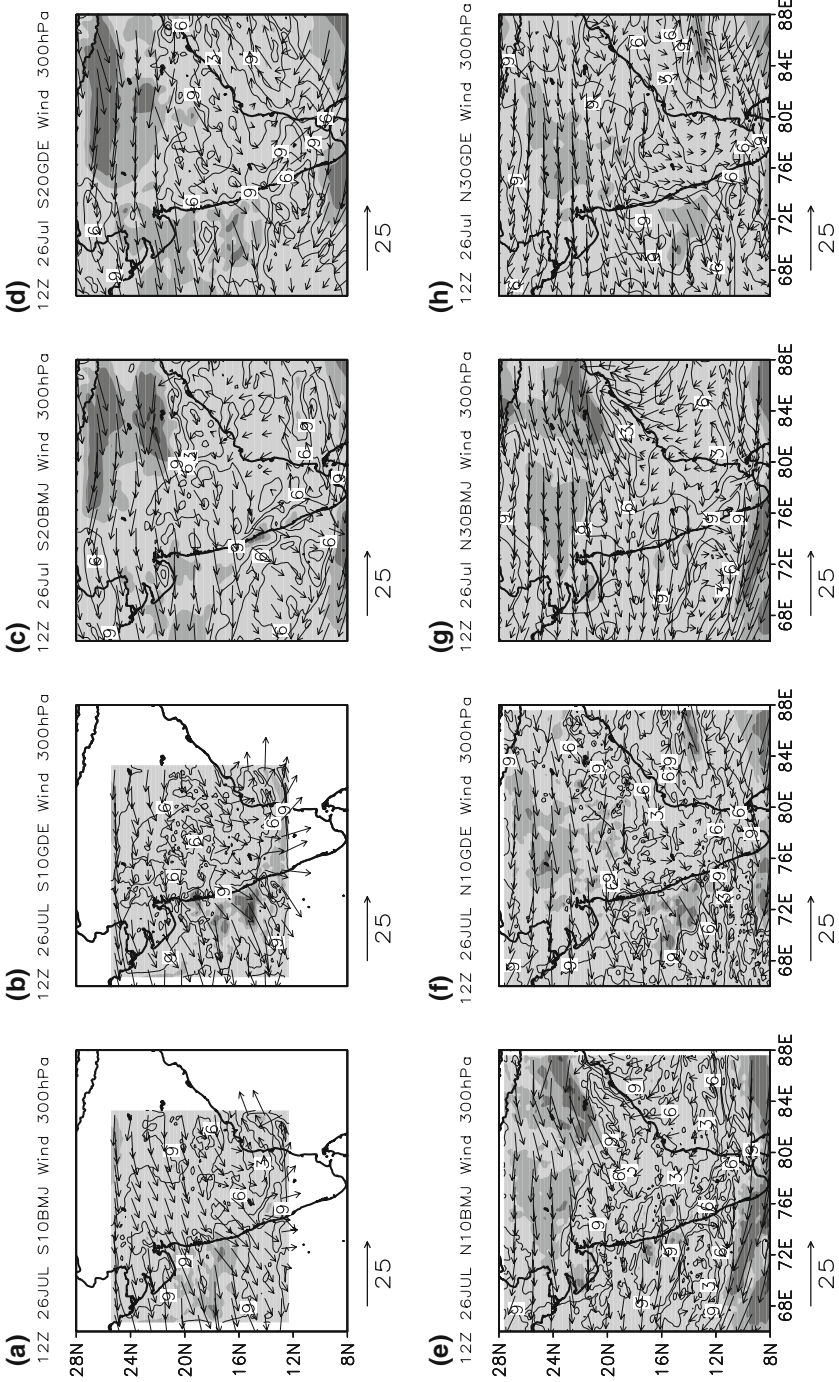
Fig. 8 The simulated 300-hPa winds (m/s) along with magnitude valid at 12Z July 26, 2005 from the different experiments: **a** S10BMJ, **b** S10GDE, **c** S20BMJ, **d** S20GDE, **e** N10BMJ, **f** N10GDE, **g** N30BMJ, and **h** N30GDE. (Contour levels 3, 6, and 9; winds with 12, 15, and 20 are shaded)
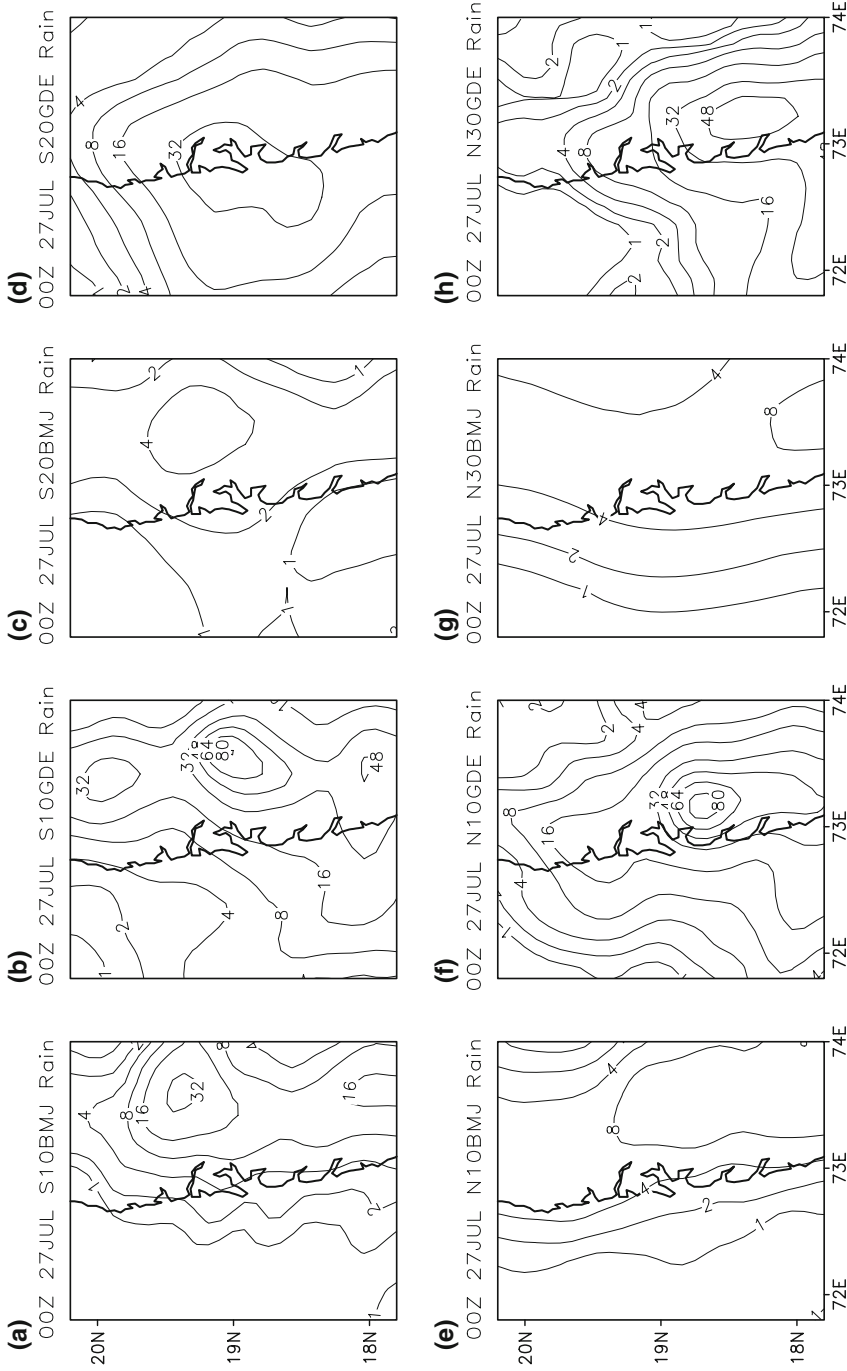
Fig. 9 Simulated 24-hour cumulative rainfall (cm) valid at 00Z July 27, 2005 from the different experiments: **a** S10BMJ, **b** S10GDE, **c** S20BMJ, **d** S20GDE, **e** N10BMJ, **f** N10GDE, **g** N30BMJ, and **h** N30GDE. (Contour levels 1, 2, 4, 8, 16, 32, 48, 64, 80, and 96)

also moved southward from the actual position (Fig. 9g, h). Both the schemes simulated unrealistic rainfall along the Western Ghats in all experiments. However, in the inner domain, simulated rainfall pattern from the GDE scheme (Fig. 9f) around Mumbai resembles well with the observation with maximum rainfall of 80 cm as compared with the BMJ scheme (Fig. 9e) where maximum rainfall was only 8–16 cm. Though the N10GDE has simulated the maximum rainfall of 96 cm, but its centre of maximum was 50 Km south of its actual position. In the BMJ scheme, the centre of maximum was shifted southward and both the schemes simulated unrealistic rainfall along the Western Ghats. This clearly indicates that the GDE scheme has outperformed the BMJ scheme in all experiments, either in coarse or fine resolutions. The coarse resolutions experiments S20BMJ and N30BMJ have not simulated the observed features of rainfall. It is found from the simulated 24-h cumulative rainfall for July 26, 2005 that fine resolution (10 Km) experiments have been able to reproduce the observed features quite well as compared to their coarse resolution counterpart.

The simulated 6-hourly cumulative rainfall from the fine resolution experiments S10BMJ, S10GDE, N10BMJ, and N10GDE were analyzed and a qualitative comparison with the TRMM merged rainfall was carried out. The simulated 6-hourly cumulative rainfall from S10BMJ, S10GDE, N10BMJ, and N10GDE valid at 06Z, 12Z, and 18Z July 26, 2005 and 00Z July 27, 2006 are shown in Figs. 10 and 11, respectively. The structure and pattern of the simulated rainfall using the GDE scheme resembles well with the TRMM observation, but the BMJ scheme has not simulated the observed pattern of rainfall accurately at 06Z July 26, 2005. The structure of rainfall in S10GDE was simulated more accurately as compared to N10GDE, where the centre of maximum was slightly shifted southward. This might be due to the interaction of N10GDE with N30GDE in the nested experiment, where the error from 30 Km resolution has transferred to 10 Km inner domain during the model integration through boundaries. At 12Z, both the schemes have simulated realistically a localized area of heavy precipitation around Mumbai. The quantum of rainfall predicted by the GDE scheme was around 16 cm in both S10GDE and N10GDE, which was more realistic as compared to 8 cm for S10BMJ and 4 cm for N10BMJ. The S10GDE and N10GDE have also simulated unrealistic rainfall along the Western Ghats both on 06Z and 12Z. At 18Z, the GDE scheme has overestimated the rainfall, but both the schemes have simulated the localized area of very heavy rainfall over Mumbai. TRMM shows rainfall of around 16 cm at 00Z July 27, 2005 over Mumbai and in the simulation using the GDE scheme also showed very heavy precipitating zone there in both S10GDE (Fig. 10g) and N10GDE (Fig. 11g). However, the BMJ scheme has failed to capture such intense rainfall at 00Z 27 July (Figs. 10h, 11h). One of the major limitations of all simulations was that none of the schemes either at coarser or finer domains have been able to simulate the observed rainfall over the northwestern part of India.

Figure 12a shows the 6-hourly cumulative maximum rainfall time series from the different experiments. It is seen from the figure that the experiments N10GDE, N30GDE, and S10GDE have captured the observed episodic nature of heavy rainfall quite well. The position of the simulated maximum was a bit east of actual maximum in the case of S10GDE, while it was south in the case of N10GDE and N30GDE. Since in the two-way nesting the inner (fine) grid forecast replaces the outer (coarse) grid forecast for those grid points that lie inside the inner (fine) grid, so the rainfall maxima time series of N30GDE was not very different from that of N10GDE. The experiments S20GDE and S10BMJ have also tried to simulate the observed increasing trends, however, failed to pickup the observed strength. However, none of the other experiments using the BMJ scheme has been able to simulate the observed features. The frequency bias for the last 24-h simulation
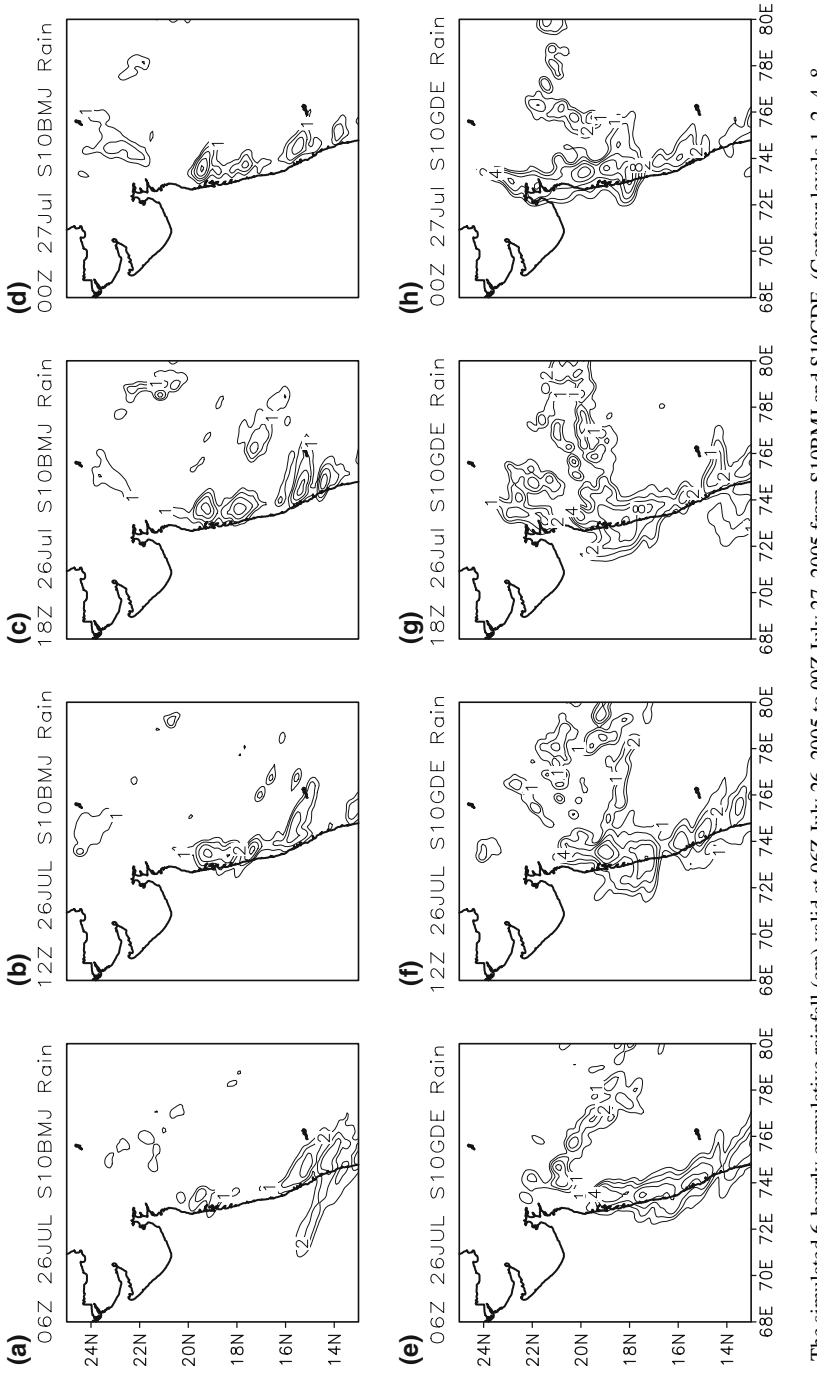
Fig. 10 The simulated 6-hourly cumulative rainfall (cm) valid at 06Z July 26, 2005 to 00Z July 27, 2005 from S10BMJ and S10GDE. (Contour levels 1, 2, 4, 8, 16, 32, and 48)
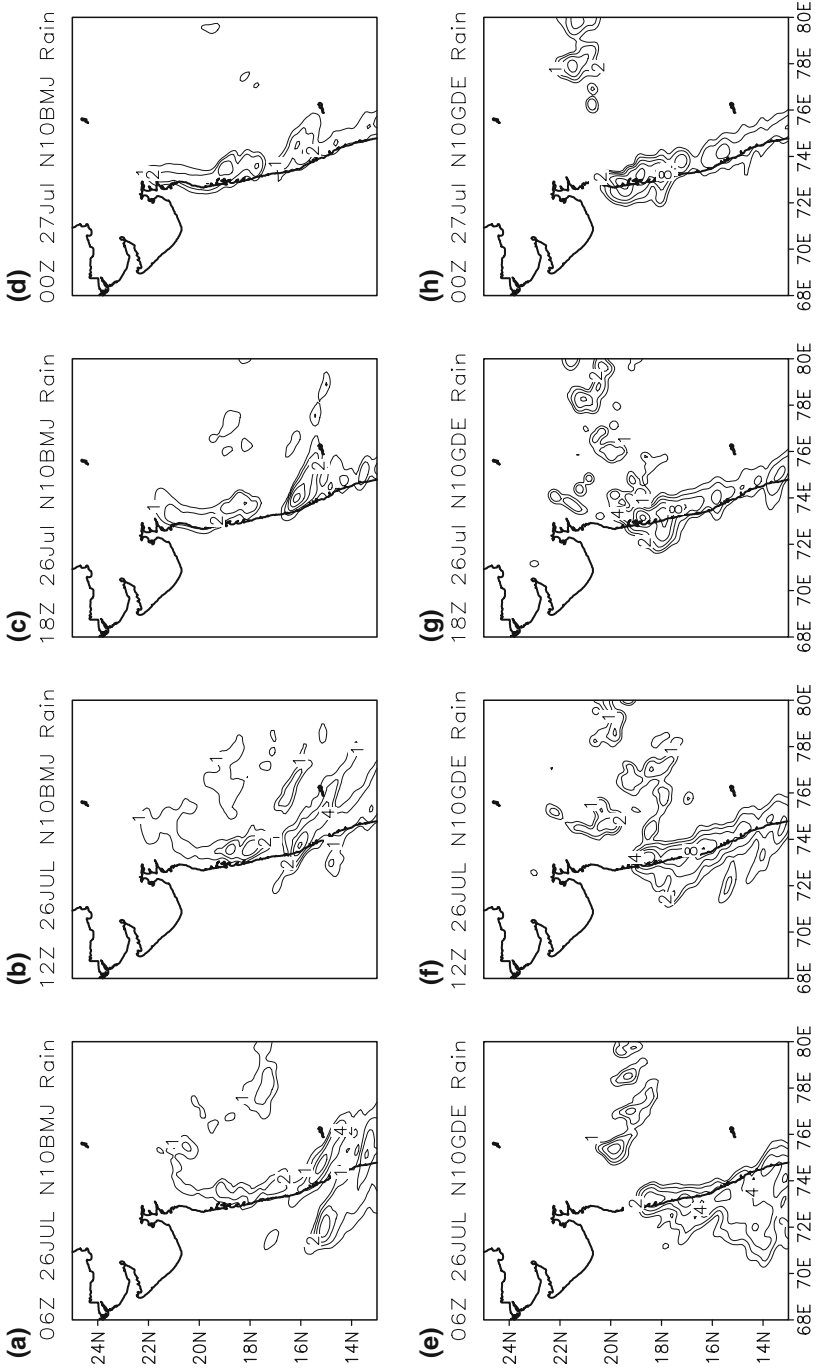
Fig. 11 The simulated 6-hourly cumulative rainfall (cm) valid at 06Z July 26, 2005 to 00Z July 27, 2005 from N10BMJ and N10GDE. (Contour levels 1, 2, 4, 8, 16, 32, and 48)

for the different rainfall threshold (in mm) is shown in Fig. 12b. It is clearly visible from the figure that frequency bias scores in the BMJ scheme was around 1 (the perfect score) in all the precipitation threshold up to 200 mm rainfall threshold. In the GDE scheme, except for rainfall threshold 15 of mm, the bias score was always >1. This shows that the GDE scheme has a tendency to enlarge the forecast precipitation areas. The TS values (Fig. 12c) for the GDE scheme was higher when compared to the BMJ scheme for all precipitation thresholds up to 200 mm. This shows that the performance of the GDE scheme was better
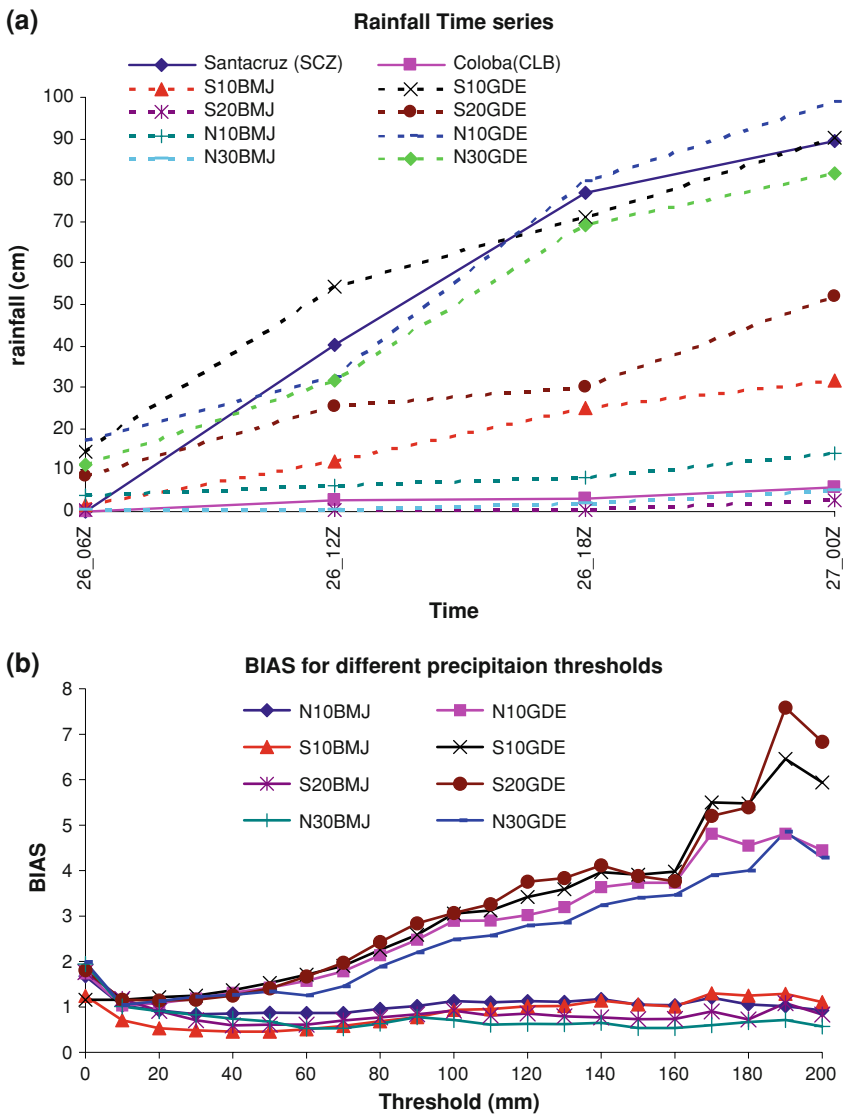
Fig. 12 **a** Time series of 6-hourly cumulative maximum rainfall from different experiments and corresponding observed rainfall recorded at Santa Cruz and Coloba. **b** Bias score for various precipitation threshold (mm) for last 24 h forecasts from the different experiments. **c** Same as in (**b**) but for threat score. **d** Same as in (**b**) but for ETS

(c)   **Threat Score (TS) for different precipitation thresholds**

(d)   **ETS for different precipitation thresholds**
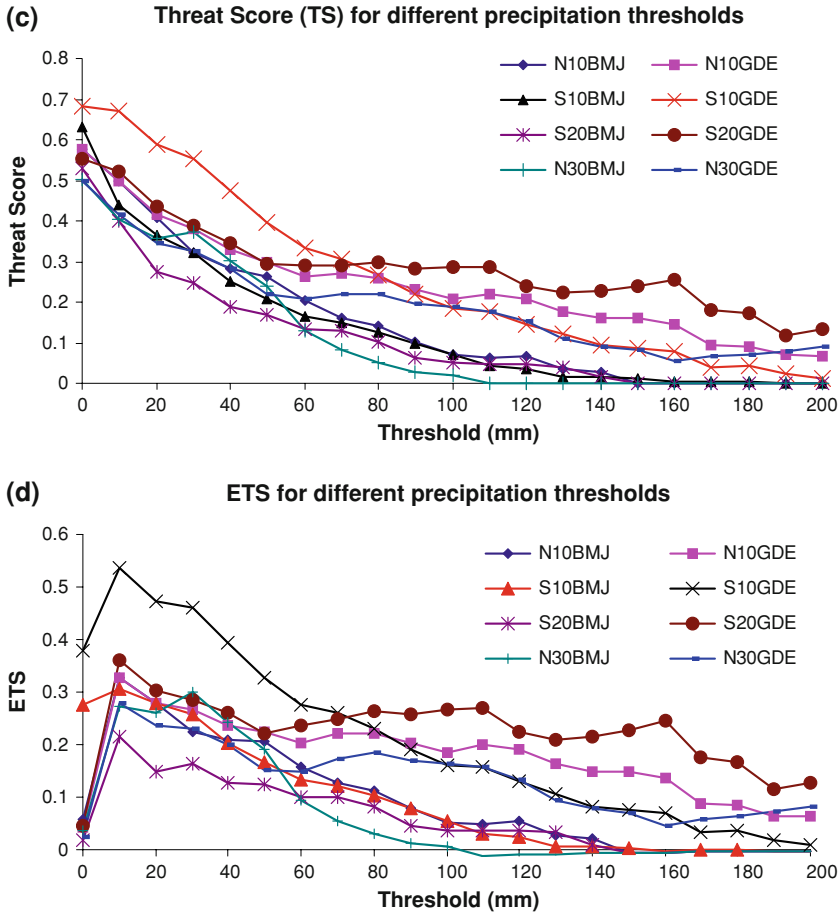

Fig. 12 continued

when compared to the BMJ scheme for the precipitation up to 200 mm. It is also noted from the Fig. 12b and c that high bias has helped for the TS values for higher precipitation thresholds in the experiments N10GDE, S10GDE, S20GDE, and N30GDE, respectively. The equitable TS for the last 24-h simulation for the different thresholds are also shown in Fig. 12d. The experiment S10GDE has shown a maximum score of 0.53 at 10 mm rainfall threshold, which then decreases gradually, while S10BMJ has shown scores of 0.30 at the same threshold. At all precipitation thresholds up to 200 mm, the S10GDE has outperformed the S10BMJ simulations. The outer (N30GDE) and inner (N10GDE) domains of the GDE scheme have also shown maximum scores of 0.27 and 0.32 at 10 mm rainfall threshold, while the corresponding BMJ scheme has shown a maximum score of 0.32 at 10 mm threshold in the inner domain (N10BMJ) and 0.30 at 30 mm threshold in the outer domain (N30BMJ), respectively. In the experiment S20GDE, the maximum score was 0.36 at 10 mm threshold, while the corresponding S20BMJ has a maximum score of 0.27 at this threshold. Except N30BMJ, in all the cases, the ETS score was higher in the GDE scheme when compared with the corresponding experiments with the BMJ scheme for all

precipitation thresholds. Quantitatively, as a whole, the simulation using the GDE scheme was better as compared to the BMJ scheme for this specific case, though both the schemes have failed to simulate the exact location of intense rainfall over Mumbai.

The simulated 850-hPa temperature valid for 12Z July 26, 2005 (Fig. 13) from all the experiments resembles well with the observed features. It is observed that the structure of the isotherms was almost the same in all the experiments except some small scale features were simulated in fine resolution (viz. 10 Km) experiments (Fig. 13a, b, e, f). The simulated 300-hPa temperatures valid for 12Z July 26, 2005 (Fig. 14) also show the warmer isotherm in the upper level when compared with the NCEP analysis. Figure 15 represents the simulated latitude-height cross-section of relative humidity from the different experiments around Mumbai (average along 72.5° E–73.5° E) for 12Z July 26, 2005. All experiments have simulated the observed features of relative humidity reasonably well at different resolutions. The fine resolution experiments like S10BMJ, S10GDE, N10BMJ, and N10GDE (Fig. 15a, b, e, f) were showing very high relative humidity, maximum up to 95%, through out 400-hPa over Mumbai. One interesting feature was that vertical area covering more than 95% relative humidity was more in all experiments using the GDE scheme than the corresponding experiments using the BMJ scheme. This shows that the GDE scheme is more sensitive to the tropical extreme event like the Mumbai rainfall of July 26, 2005.

4 Conclusions

A qualitative assessment of the simulation of unprecedented rainfall event of July 26, 2005 over Mumbai has attempted with the WRF model at different resolutions both in single and nested domains using the BMJ and GDE schemes. The large-scale circulation features including moisture and temperature patterns both at upper- and lower-level in all simulations resemble well with the NCEP analyses. The localized heavy precipitation around Mumbai was not captured very well using both the schemes, but in 20 Km, the GDE scheme (S20GDE) has simulated the observed rainfall structure around Mumbai. However, the simulated rainfall in the GDE scheme has come very close to the observation in the 10 km resolution of single domain and nested domains experiments both inner (10 Km) and outer (30 Km), though there were some differences in their actual positions. The GDE scheme has outperformed the BMJ scheme in all experiments for the simulation of rainfall both in fine as well as coarse resolution. The dynamic control of the GDE scheme is based on CAPE or low-level moisture convergence, and finer grid results from this scheme matched well with the observations. Though, CAPE or low-level moisture convergence play important role in the development of convection anywhere in the globe, however, its influence in the tropical convection is very crucial. Thus, it might be concluded that the CAPE and low-level moisture convergence might be one of the factors responsible for the high vertical instability of the atmosphere around Mumbai on this extreme event. Probably, the most encouraging aspect of this study is the very significant forecast skill displayed, though in hindcast mode, on the very complex system of extreme rainfall event of Mumbai, in the WRF model with the GDE scheme with 10-Km horizontal resolution both in single and nested domain within 30–50 Km east of actual position. This was a very preliminary attempt with the WRF model and further testing of more case studies with higher and improved version of the WRF model as well as incorporation of different satellite data, Doppler Radar data, through the WRF data assimilation system is required. Although the above conclusions are based on very limited number of experiments, this study can provide
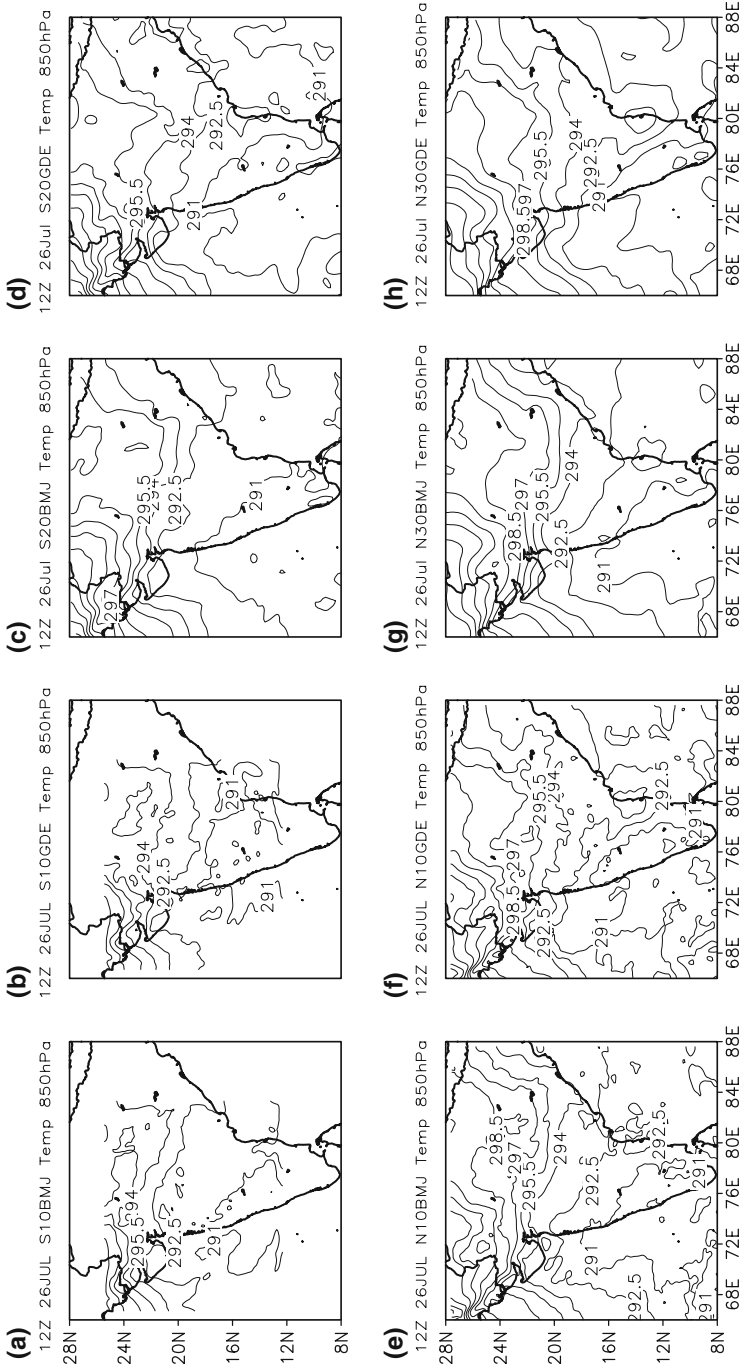
Fig. 13 The 850 hPa simulated temperature (K) valid at 12Z July 26, 2005 from the experiment **a** S10BMJ, **b** S10GDE, **c** S20BMJ and **d** S20GDE (*upper panel*); **e** N10BMJ, **f** N10GDE, **g** N30BMJ, and **h** N30GDE (*lower panel*). (Contour level 1.5)
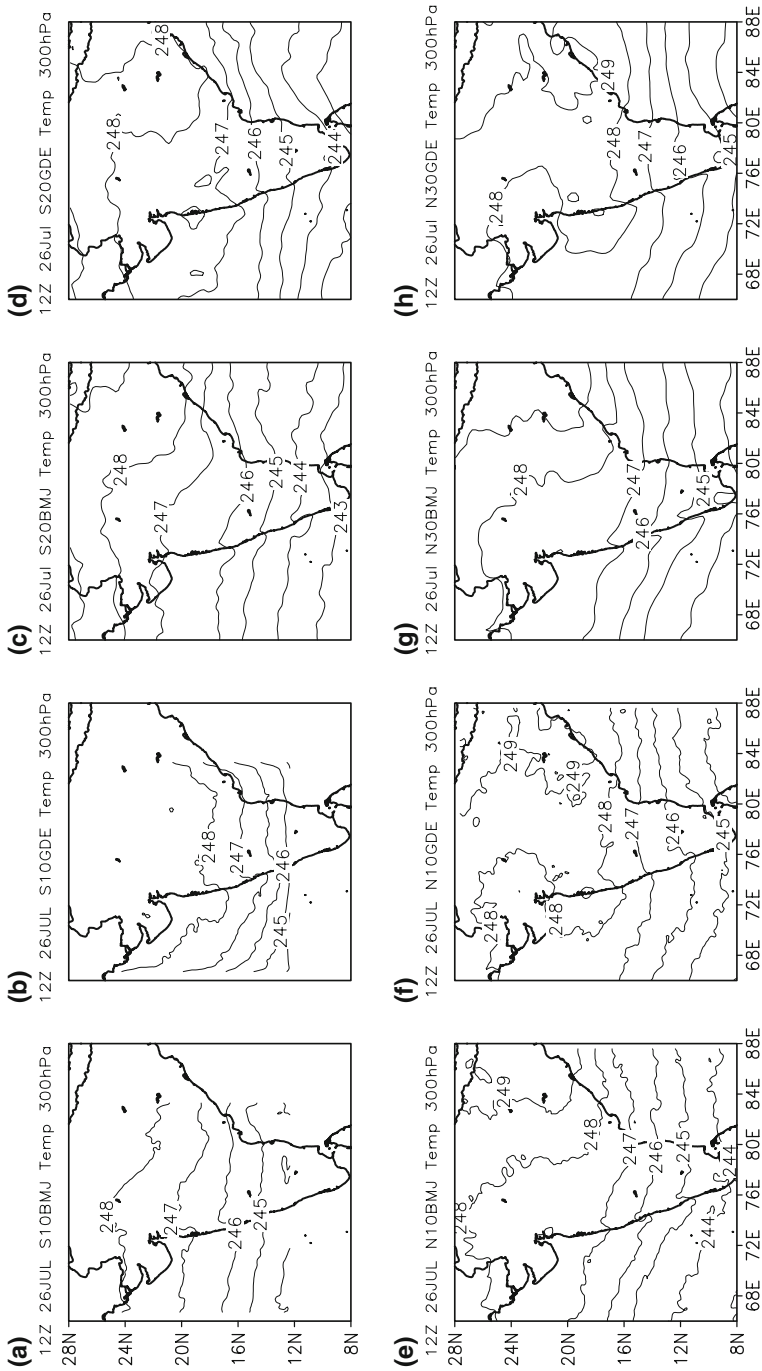
Fig. 14 The 300 hPa simulated temperature (K) valid at 12Z July 26, 2005 from the experiment **a** S10BMJ, **b** S10GDE, **c** S20BMJ and **d** S20GDE (*upper panel*); **e** N10BMJ, **f** N10GDE, **g** N30BMJ, and **h** N30GDE (*lower panel*). (Contour level 1)
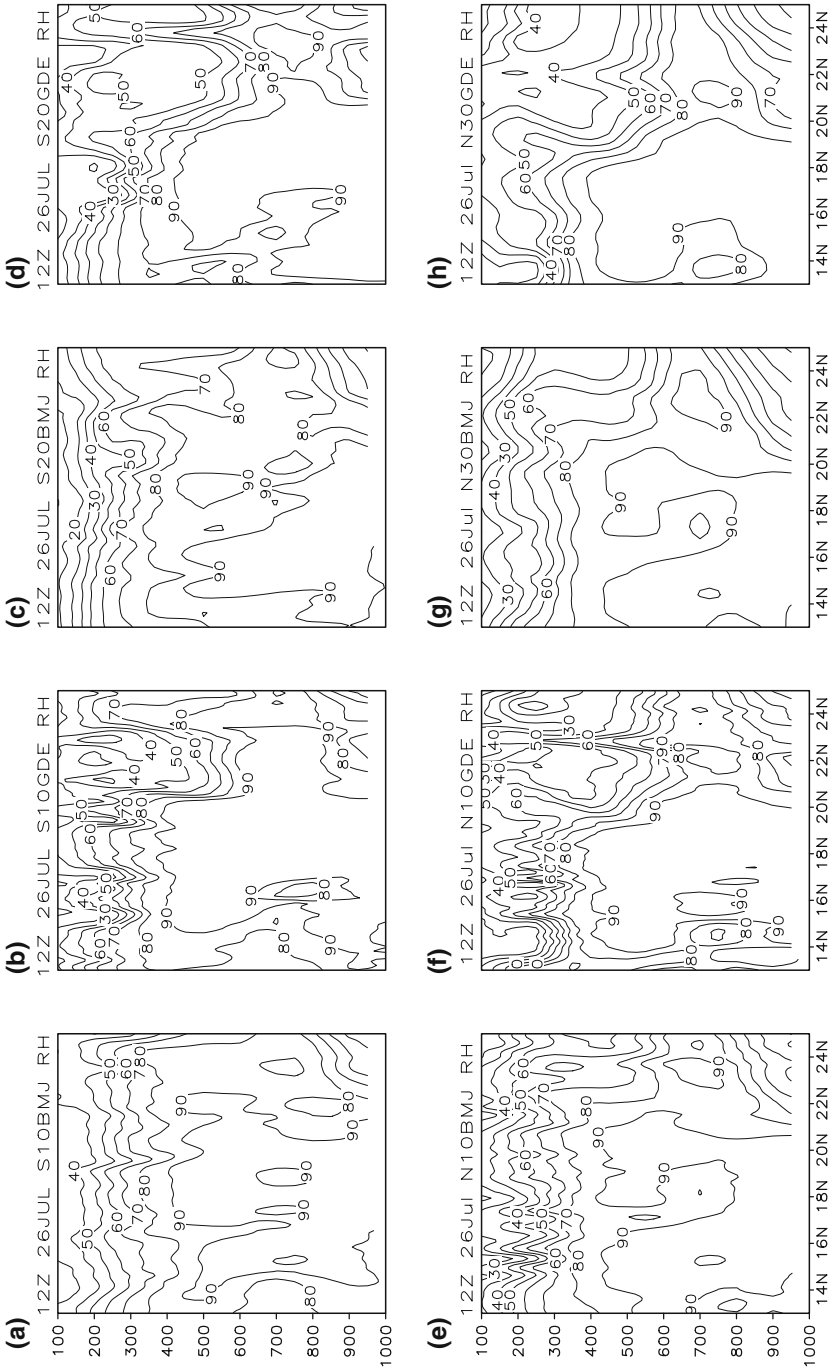
Fig. 15 The latitude-height cross-section of relative humidity (%) valid at 12Z July 26, 2005 from the different experiments: **a** S10BMJ, **b** S10GDE, **c** S20BMJ, **d** S20GDE, **e** N10BMJ, **f** N10GDE, **g** N30BMJ, and **h** N30GDE. (Contour level 10)

some insight to the WRF model users over the Indian region and prompt the modeling community to pursue and evaluate real-time quantitative precipitation forecasting.

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