Mesoscale Simulation of a Very Heavy Rainfall Event over Mumbai, Using the Weather Research and Forecasting (WRF) Model

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ABSTRACT

The simulation of a severe weather phenomenon, in this case the unprecedented heavy rainfall over Mumbai in India on July 26, 2005, was selected for this study. The mesoscale numerical weather prediction model used here utilized the Advanced Research Weather Research Forecast model (version 3.0.1), as developed at the National Center for Atmospheric Research (NCAR) in the USA. The study used the Kian-Fritsch (KF), Betts–Miller–Janjic (BMJ) and Grell–Devenyi ensemble (GD) cumulus parameterization schemes across three nested domain configurations. The precipitation simulation results were compared with rainfall observation data from the Tropical Rainfall Measuring Mission. The NCEP analyses, with a 1 x 1 degree resolution and 26 levels, were utilized to verify the simulation’s resulting large-scale circulation pattern, moisture content and relative humidity fields. The 24-hour simulated cumulative rainfall data was created from the different measurements taken at 0300 UTC on July 27, 2005 over Mumbai. It can be observed that the maximum rainfall simulated from the KF, BMJ and GD schemes at 0000 UTC on July 25, 2005, under the initial conditions, was 48, 64 and 32 cm respectively, while the TRMM shows a maximum rainfall of 32 cm at that time. The centre of maximum rainfall was reduced drastically for all 0000 UTC measurements taken on July 26 (the following day), where the initial condition experiments simulated a rainfall amount of only 16 cm. The specific location of the intense rainfall around Mumbai was very-well simulated in the BMJ for 0000 UTC July 25 initial conditions.

Keywords: Heavy rainfall; Cumulus parameterization; WRF model.

1. INTRODUCTION

Severe weather systems are generally associated with strong, gusty winds and heavy precipitation. The numerical prediction of such events remains one of the most challenging problems in the field of meteorology. Most of the global models developed thus far generally underestimate the total rainfall produced in any heavy precipitation event, and also contain errors in terms of their prediction on the timing and...
location of the event. [1-3] For a better prediction of flash floods, it is necessary to understand the dynamics and physics associated with isolated heavy precipitation and the dynamic features associated with thunderstorms and tornados etc. Heavy rainfall occurs frequently around Mumbai during the summer monsoon season. The rainfall over the northern parts of Mumbai on July 26, 2005 was extremely heavy. On that day, within a span of a few hours, northern Mumbai received record rainfall [4, 5], with Santacruz recording 94.4 cm of rainfall for the day; whilst heavy rainfall of 104.9 cm was recorded at Vihar Lake, located around 15 kilometers northeast of Santacruz. Bhandup, located southeast of Vihar Lake, received 81.5 cm of rainfall, whilst Colaba in southern Mumbai, on the other hand, received only 7 cm.

Figure 1. A Map of India and of Mumbai.

Figure 2 shows 24 hours of rainfall valid at 0000 UTC on July 27, 2005 in Mumbai and in neighboring weather stations, as recorded by the India Meteorological Department (IMD) and observed by the Tropical Rainfall Measuring Mission (TRMM). Jenamani et al. [4] studied the daily rainfall statistics for Mumbai using observation data spanning more than 100 years, and showed that the heavy rainfall recorded on July 26, 2005 was the highest ever recorded in Mumbai.

This event disrupted lives, causing heavy damage to property as well as deaths and injuries. Prior knowledge of such an extreme event by even a day or just a few hours could have minimized the loss of life [6]. This severe weather phenomenon caused around 500 deaths and costs one billion US Dollars in damage [7]. Although the Meteorological Office (UKMO) model was one of the few models that predicted up to 80 cm of rainfall over a small area of Mumbai on July 26, - 24 hours in advance, most of the numerical models, both global and mesoscale, failed to simulate this catastrophic event in an operational or hindsight mode [6]. Although some modeling studies of this extreme rainfall event [8-10] have been reported in a hindsight mode, none of the operational models gave an accurate real-time prediction. The study of Deb et al. [8], examined the performance of the WRF modeling system (version 2.0.2) for the simulation of this severe rainfall event, using varying horizontal resolutions and
cumulus parameterization schemes. The model's performance was evaluated by examining the different predicted parameters, such as upper and lower level circulations, temperature, moisture content and rainfall. Their study found that the GD cumulus parameterization had a high predicting capability when compared to the BMJ scheme for this event. However, Chang et al. [9] studied the impact of land surface parameterizations on a simulation of the July 26 event using two meso-scale models: the MM5 and the WRF. This results showed that the rainfall simulations produced using the WRF model were better than the corresponding MM5 model in terms of both location and intensity. The WRF model was also used to study the various small- to large-scale dynamical interactions, such as the formation of convective cells and large-scale wind circulations, interactions that resulted in the localized and heavy precipitation over Mumbai on that day [10].

The purpose of this study is to identify the impact of three cumulus parameterization schemes in the WRF model, used for the simulation of this extreme rainfall event, and also to reveal the sensitivity of the initial conditions. Taking the observed features, such as large-scale upper and lower level circulations, moisture content and the thermal structures from the NCEP analyses, the gridded, observed rainfall from the TRMM was analyzed. The performance of each scheme is presented here, with respect to the upper- and lower-level circulations, thermal structures and the contour of rainfall.

This scientific study is structured as follows: Section 2 describes the model and the experimental design, and after that, Section 3 describes the results and discussion. The conclusions are given in Section 4.

Figure 2. 24-hour cumulative rainfall (cm) for 0300 UTC on July 27, 2005; observed by a) IMD at different stations near Mumbai, and b) TRMM.
2. MATERIALS AND METHODS

2.1 Model

The mesoscale model used in this study is the Advanced Research WRF (ARW) model (version 3.0.1), which has been available since April 2008. The WRF is a limited area, non-hydrostatic primitive equation model, with multiple options for various physical parameterization schemes [11]. This version employs Arakawa C-grid staggering for horizontal grids and a fully compressible system of equations. A terrain following sigma coordinate is used in the vertical grids. The time-split integration uses a third-order Runge–Kutta scheme with a smaller time-step for acoustic and gravity wave modes. In combination with multiple-nest capability, a large number of physics options make the model capable of performing simulations on any scale; limited only by data resolution, quality, and computer resources.

2.2 Experimental Design

The heavy rainfall event over Mumbai on July 26, 2005 was selected for the subject of this study. For this research, three nested domains were configured as shown in Figure 3. The domain of interest was centered on Mumbai (18.56°N, 72.51°E) and contained 27 vertical levels. Domain 1, the outer domain, had 100 × 75 grid points in the horizontal plane with east-west and north-south directions respectively, covering 52.67°E to 92.34°E and 4.11°S to 31.88°N, with a horizontal resolution of 45 km, and with the sub-domain having a 15 km grid spacing with 178 × 133 grid points in the horizontal east-west and north-south directions respectively (set in the ratio of 1:3), covering 60.63°E to 84.38°E and 10.00°N to 26.70°N. The fine-mesh Domain 3, with a 5 km grid spacing, had 208 × 202 grid points (set in the ratio of 1:3), covering 67.87°E to 77.14°E and 14.18°N to 22.70°N.

Figure 3: WRF model domains used in this study.
The different dynamic and physical options used for this study in terms of cumulus parameterization schemes (that is the KF, BMJ and GD schemes) included the WRF single-moment 6-class Graupel (WSM-6) microphysics scheme, used along with the Rapid Radiative Transfer Model (RRTM) scheme for long waves. The Duhia scheme was used for short-wave physics, the Monin-Obukhov scheme for the surface layer, the Noah Land-Surface Model for surface physics and the MRF scheme for treatment of the Planetary Boundary Layer (PBL). Six experiments were carried out with the above domain configurations, as tabulated in Table 1.

The analysis data, with a resolution of 1x1 degrees and taken at 6-hourly intervals, was obtained from the Global Data Assimilation System (GDAS) of the National Weather Service National Center for Environmental Prediction (NCEP), and was used for the preparation of initial and boundary conditions.

This analysis was then interpolated to the WRF-model grid to provide two initial conditions; the first, an initial condition taken at 0000 UTC on July 25 2005, and a second initial condition taken at 0000 UTC on July 26, 2005. The model was run for 54 hours and 30 hours respectively (up to 0600 UTC on July 27, 2005). The model utilizes various terrestrial datasets for terrain, land-use, soil type, soil temperature, vegetation fractions and monthly albedo etc., taken from the WRF user website [12]. To verify the results from the model, TRMM was used. TRMM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA). Its purpose is to monitor tropical and subtropical precipitation and to estimate the associated latent heating. TRMM provides systematic visible, infrared and microwave measurements of rainfall in the tropics, as key inputs to weather and climate research.

Table 1. Design of the experiments.

<table>
<thead>
<tr>
<th></th>
<th>Start-time</th>
<th>End-time</th>
<th>Cumulus Parameterization</th>
<th>Experiment name</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP1</td>
<td>0000 UTC July 25, 2005</td>
<td>0000 UTC July 27, 2005</td>
<td>Modified Kain-Fritsch</td>
<td>EXP25KF</td>
</tr>
<tr>
<td>EXP3</td>
<td>0000 UTC July 25, 2005</td>
<td>0000 UTC July 27, 2005</td>
<td>Grell-Devenyi ensemble</td>
<td>EXP25GD</td>
</tr>
<tr>
<td>EXP4</td>
<td>0000 UTC July 26, 2005</td>
<td>0000 UTC July 27, 2005</td>
<td>Modified Kain-Fritsch</td>
<td>EXP26KF</td>
</tr>
<tr>
<td>EXP5</td>
<td>0000 UTC July 26, 2005</td>
<td>0000 UTC July 27, 2005</td>
<td>Betts-Miller-Janic scheme</td>
<td>EXP26BMJ</td>
</tr>
<tr>
<td>EXP6</td>
<td>0000 UTC July 26, 2005</td>
<td>0000 UTC July 27, 2005</td>
<td>Grell-Devenyi ensemble</td>
<td>EXP26GD</td>
</tr>
</tbody>
</table>
Figure 4. The simulated 850 hPa wind (m/s) along with magnitude, as valid at 1200 UTC on July 26, 2005 from the NCEP and using the different experiments: a) NCEP, b) EXP25KF, c) EXP25BMJ, d) EXP25GD, e) EXP26KF, f) EXP26BMJ, and g) EXP26GD. (Contour levels 3, 6 and 12; winds of 20 and 25 m/s are shaded).

Figure 5. The simulated 300 hPa wind (m/s) along with its magnitude, as valid at 1200 UTC on July 26, 2005 from the NCEP and using the different experiments: a) NCEP, b) EXP25KF, c) EXP25BMJ, d) EXP25GD, e) EXP26KF, f) EXP26BMJ, and g) EXP26GD (Contour levels 3, 6 and 9; winds of 12, 15 and 20 m/s are shaded).
3. RESULTS AND DISCUSSION

3.1 Upper and Lower-level Wind

The simulated 850-hPa winds valid at 1200 UTC on July 26, 2005 over the Indian subcontinent, and from the different experiments, are presented in Figure 4. All the experiments predicted strong westerly or northwesterly winds over the western coast of India, with a maximum speed of 20 m/s. The experiment EXP26GD simulated winds of a magnitude 20 m/s over Mumbai (Figure 4g), whereas in all the other simulations, winds of a magnitude 12-15 m/s were predicted in this region. All of the schemes showed the presence of a strong cyclonic circulation over Orissa and the eastern part of Madhya Pradesh, though the centre of the low was simulated a bit further east as compared to the analyses. It is clear from the figure that all the experiments underestimated the winds in the Arabian Sea, where a strong westerly flow with a maximum speed of 20 m/s can be seen in the NCEP, not visible in the simulated results. Figure 5 shows the simulated 300-hPa winds valid at 1200 UTC on July 26, 2005, using the different experiments. All experiments simulated the upper level easterly or northeasterly flow reasonably well, with a speed of approximately 9 m/s over Mumbai. One interesting feature is that the EXP25GD simulated 300-hPa winds of a magnitude of 15 m/s over the Arabian Sea near Mumbai. On the whole, both the upper and lower level winds were simulated well using the model.

3.2 Thermal Structure and Moisture Fields

Figure 6 shows the NCEP and the simulated 850 hPa temperatures valid at 1200 UTC on July 26, 2005, from all the experiments. The simulated 850 hPa temperature from all the experiments aligns well with the NCEP. Figure 6 shows the NCEP and the simulated 850 hPa temperatures valid at 1200 UTC on July 26, 2005, using the different experiments: a) NCEP, b) EXP25KF, c) EXP25BMJ, d) EXP25GD, e) EXP26KF, f) EXP26BMJ, and g) EXP26GD. (Contour level 1.5).

Figure 6. The simulated 850 hPa temperature (K) as valid at 1200 UTC July 26, 2005 taken from the NCEP and using the different experiments: a) NCEP, b) EXP25KF, c) EXP25BMJ, d) EXP25GD, e) EXP26KF, f) EXP26BMJ, and g) EXP26GD. (Contour level 1.5).
the observed figure. It can be seen that the structure of the isotherms is almost the same in all the experiments, except for some small-scale features simulated in synoptic resolution (45 Km) experiments (Figure 6b-g). The simulated 300 hPa temperatures valid for 1200 UTC on July 26, 2005 (Figure 7) also show warmer isotherms in the upper level when compared with the NCEP analysis. Figure 8 represents the simulated latitude-height, cross-section of relative humidity from the different experiments around Mumbai.

**Figure 7.** Simulated 300 hPa temperature (K), as valid at 1200 UTC July 26, 2005 taken from the NCEP and using the different experiments: a) NCEP, b) EXP25KF, c) EXP25BMJ, d) EXP25GD, e) EXP26KF, f) EXP26BMJ, and g) EXP26GD. (Contour level 1).

### 3.3 Rainfall

Figure 9 shows the simulated 24 hour cumulative rainfall over Mumbai from the TRMM and the different experiments, valid at 0300 UTC on July 27, 2005. It can be observed that the maximum rainfall simulated from the EXP25KF, EXP25BMJ and EXP25GD (Figure 9b, c and d) was 48, 64 and 32 cm respectively, while the TRMM shows a maximum total rainfall of 32 cm at the same time.

The maximum rainfall from the experiments EXP25BMJ and EXP25KF were very accurate when compared with the observed position, though the position of EXP25KF was a little south of the observed
Figure 8. The latitude-height cross-section of relative humidity (%), as valid at 1200 UTC on July 26, 2005, taken from the NCEP and using the different experiments: a) NCEP, b) EXP25KF, c) EXP25BMJ, d) EXP25GD, e) EXP26KF, f) EXP26BMJ, and g) EXP26GD. (Contour level 5).

location. This level of maximum rainfall decreased drastically with the experiments EXP26KF, EXP26BMJ and EXP26GD, with simulated rainfall amounts of only 16 cm (Figure 9d, e and f).

The particular location of the heavy precipitation around Mumbai was very well simulated with the EXP25BMJ simulation, though the magnitude of rainfall was less than the actual observation. Though all the experiments simulated a maximum rainfall comparable to the TRMM rainfall around Mumbai, the actual observed rainfall from the IMD showed a much higher rainfall when compared to the TRMM rainfall. The rainfall recorded by IMD is a point measurement, while the resolution in the TRMM rainfall is 0.25° both for scan and for pixel, and this could be one of reasons for their differences in magnitude. Though TRMM rainfall is a merged, derived product from both IR and microwave measurements, sometimes TRMM underestimates rainfall near the surface, due to warm clouds.

The simulated 6-hourly cumulative rainfall from the most detailed resolution (innermost domain: 5 km resolution) experiments EXP25KF, EXP26KF, EXP25BMJ, EXP26BMJ, EXP25GD, and EXP26GD were analyzed and a qualitative comparison with the TRMM merged rainfall was carried out. The simulated 6-hourly cumulative rainfall from the EXP25KF, EXP26KF, EXP25BMJ, EXP26BMJ, EXP25GD and EXP26GD
Figure 9. Simulated 24-hour cumulative rainfall (cm) from the TRMM and other experiments - 0300 UTC July 27, 2005: a) TRMM, b) EXP25KF, c) EXP25BMJ, d) EXP25GD, e) EXP26KF, f) EXP26BMJ, and g) EXP26GD (Contour levels 1, 2, 4, 8, 16, 32, 48, 64 and 80).

Figure 10. Six-hourly accumulated rainfall (cm) from the TRMM: July 25, 2005 a) 0600 UTC, b) 1200 UTC, c) 1800 UTC July 26, 2005; d) 0000 UTC, e) 0600 UTC, f) 1200 UTC, and h) 0000 UTC July 27, 2005 respectively. (Contour levels 1, 2, 4, 8, 16, 32, and 48).
Figure 11. Simulated 6-hourly cumulative rainfall (cm) valid at 0600 UTC July 26, 2005 to 0000 UTC July 27, 2005 from EXP25KF and EXP26KF (Contour levels 1, 2, 4, 8, 16, 32, and 48).

Figure 12. Simulated 6-hourly cumulative rainfall (cm) valid at 0600 UTC July 26, 2005 to 0000 UTC July 27, 2005 from EXP25BMJ and EXP26BMJ (Contour levels 1, 2, 4, 8, 16, 32, and 48).
Figure 13. Simulated 6-hourly cumulative rainfall (cm) valid at 0600 UTC July 26, 2005 to 0000 UTC July 27, 2005 from EXP25GD and EXP26GD (Contour levels 1, 2, 4, 8, 16, 32, and 48).

experiments, valid at 0600 UTC, 1200 UTC and 1800 UTC on July 26, 2005, and 0000 UTC on July 27, 2006, are shown in Figures 11, 12 and 13 respectively. The structure and pattern of the simulated rainfall using the initial condition 0000 UTC on July 25, 2005 closely resembled the TRMM observation, while the initial conditions at 0000 UTC on July 26, 2005 did not simulate the observed pattern of rainfall accurately across all the experiments. The structure of rainfall in the EXP25GD simulation was more accurate when compared to EXP25KF and EXP25BMJ, where the centre of maximum was shifted slightly northward (over Mumbai). This might be due to the interaction of the detailed resolution with Domain 1 and Domain 2 in the nested experiment, where the error from the 45 and 15 km resolution transferred to the 5 km innermost domain during the model integration. At 1200 UTC on July 26, 2005 (Figures 11b, 13b), both EXP25KF and EXP25GD realistically simulated a localized area of heavy precipitation around southern Mumbai. The quantum of rainfall predicted by both experiments (EXP25KF and EXP25GD), around 16 cm, was more realistic than the 4 cm for EXP25BMJ. The EXP26KF, EXP26BMJ and EXP26GD experiments also simulated unrealistic rainfall along the Western Ghats both at 1200 UTC and 1800 UTC on July 26, 2005 (Figure 11f, 12f and 12f). At 1800 UTC on July 26, 2005, the EXP25BMJ experiment simulated rainfall of around 16 cm. The experiments EXP25KF, EXP25BMJ and EXP25GD simulated a localized area of heavy rainfall around Mumbai at 0000 UTC on July 27, 2005, with the magnitude ranging from 16-24 cm, and the TRMM also showed rainfall of around
16 cm at 0000 UTC on July 27, 2005 over Mumbai. While the simulation using the BMJ scheme showed a very heavy precipitation zone in both the EXP25BMJ (Figure 12d) and EXP26BMJ experiments (Figure 12h), EXP26KF (Figure 11d) also simulated a localized area of heavy rainfall around Mumbai. However, the centre of maximum rainfall for EXP25GD (Figure 13d), EXP26GD (Figure 13h) and EXP26KF (Figure 11h) were shifted slightly southward, eastward and southward respectively. One of the major limitations of all the simulations was that none of the schemes, either at the coarser or the finer domains, were able to simulate the observed rainfall over the northwestern part of India.

4. CONCLUSIONS

A qualitative assessment of the simulation of a heavy rainfall event on July 26, 2005 over Mumbai, India was attempted with WRF model version 3.0.1 at three nested domain configurations, with horizontal resolutions of 45, 15 and 5 km respectively, using the KF, BMJ and GD schemes. The sensitivity of the two different initial conditions: 0000 UTC on July 25, 2005 and 0000 UTC on July 26, 2005 were also evaluated in this study. The large-scale circulation features in all the simulations, including moisture and temperature patterns, both at upper and lower levels, closely resembled the NCEP analyses, and though the localized heavy precipitation around Mumbai was captured for both initial conditions, it was captured particularly well for 0000 UTC on July 25, 2005. The experiment EXP25BMJ simulated the observed rainfall structure around Mumbai; however, the simulated rainfall in the EXP25KF and EXP25GD experiments was reasonably accurate as well, though the rainfall was shifted slightly southeast from the actual position. All the experiments underestimated the rainfall, when 0000 UTC on July 26, 2005 was used as the initial condition. It may be that from running a simulation period of less than 24 hours, this initial condition had an error in precipitation quantity and position at periods +06, +12, +18 hour (0600, 1200, 1800 UTC on July 26, 2005). The BMJ scheme outperformed the KF and GD schemes, while the results from the last version showed that GD outperformed the BMJ scheme in the same case [8]. Thus, all model users should decide on the suitable physical parameters before utilizing an updated version of any of the models.

The BMJ scheme was derived from the Betts-Miller convective adjustment scheme [13]. In this scheme, the deep convection profiles and the relaxation time are variable and depend on the cloud efficiency; a non-dimensional parameter that characterizes the convective regime. Cloud efficiency depends on the entropy change, precipitation and the mean temperature of the cloud, as well as the shallow convection moisture profile which is derived from the requirement that the entropy change be small and non-negative. This scheme may also be refined for higher horizontal resolutions, primarily through modifications of the triggering mechanism. Thus it can be concluded that the above factor was one of the main reasons responsible for the high vertical instability in the atmosphere around Mumbai on this extreme event day.

This is a very preliminary attempt to use the WRF model (version 3.0.1), and it is recommended that further testing using more case studies, as well as an improved version of the model plus the incorporation of different satellite data and Doppler Radar data, through use of the WRF data assimilation system, is carried out. Although the above conclusions are based on a very limited number of experiments, this study provides some insights for WRF model users in the
tropics and may prompt the modeling community to pursue and evaluate real-time quantitative precipitation forecasting.

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