Simulation of a severe thunderstorm event during the field experiment of STORM programme 2006, using WRF–NMM model

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In the tropics, most of the extreme weather events are convective in nature. Many parts over the Indian region experience thunderstorms at higher frequency during the pre-monsoon months (March–May), when the atmosphere is highly unstable because of high temperatures prevailing at lower levels. During April and May, the eastern and northeastern parts of the country, i.e. Gangetic West Bengal, Jharkhand, Orissa, Bihar, Assam and parts of other northeastern states are affected by higher frequency of severe thunderstorms, locally named as 'Kal-baishakhi' or 'Nor'westers'. Realizing the importance of better understanding and prediction of these severe local storms over east and northeast India and their socio-economic impact, the Department of Science and Technology, Government of India organized a national coordinated programme on 'Severe Thunderstorm Observation and Regional Modelling (STORM)' to be carried out in the pre-monsoon season of 2006–10. Mesoscale models are essential for the accurate prediction of such high-impact weather events. In the present study, an attempt has been made to simulate one thunderstorm event that occurred on 20 May 2006 at Kolkata (22.52°N, 88.37°E) during the field experiment of STORM 2006, using Non-hydrostatic Mesoscale Model (NMM) core of the Weather Research and Forecasting (WRF) system with different initial conditions. This model has been developed by the National Oceanic and Atmospheric Administration/National Centers for Environment Prediction. The model results are validated with STORM field experiment data. The model performed well in capturing stability indices, which act as indicators of severe convective activity along with the thunderstorm-affected parameters as in the observations. The results of these analyses show that the 3 km WRF–NMM has better capability when it comes to thunderstorm simulation. This suggests that high-resolution models have the potential to provide unique and valuable information for severe thunderstorm forecasters.

Keywords: Mesoscale model, stability indices, thunderstorm, vertical velocity, relative humidity.

THUNDERSTORM, resulting from vigorous convective activity, is one of the most spectacular weather phenomena in the atmosphere. A common feature of the weather during the pre-monsoon season (March–May) over the Indo-Gangetic plain and Northeast India is the outburst of severe local convective storms, commonly known as 'Nor'westers' or 'Kal-baishakhi'. Nor'westers are mesoscale convective systems which can develop under the large-scale envelope of the seasonal, low-level trough over the West Bengal–Bihar–Jharkhand belt, with a possible embedded low-pressure area. These severe thunderstorms associated with thunder, squall lines, lightning, torrential rain and hail cause extensive loss in agriculture, damage to property and also loss of life. The casualties reported due to lightning associated with thunderstorms in this region are among the highest in the world. The strong wind produced by the thunderstorm downdraft after coming in contact with the earth's surface spreads out laterally and is referred to as downburst, which is a real threat to aviation. The highest numbers of aviation hazards are reported during the occurrence of these thunderstorms. In India, 72% of tornadoes are associated with Nor'westers. These severe thunderstorms have significant socio-economic impact in the eastern and northeastern parts.

The formation, intensification and propagation of thunderstorms are mostly governed by the synoptic situation and localized thermodynamic conditions of the atmosphere. The microphysical and electrical characteristics are known to significantly affect the formation and intensity of precipitation. A number of studies[1–7] have examined the frequency of occurrence of thunderstorms and precipitation in India. A few attempts have also been made to understand the formation, growth and propagation of thunderstorms and associated features[8,9].

Forecasting thunderstorms is one of the most difficult tasks in weather prediction, due to their rather small spatial and temporal extension and the inherent nonlinearity of their dynamics and physics[10]. Numerical modelling has made substantial advances in the modelling of convective clouds and mesoscale convective systems[11]. In India, studies related to modelling of clouds are scarce, and in particular, intense thunderstorm events[12–14]. They are mainly

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confined to scattered observational investigations using synoptic data, isolated cloud-seeding experiments based on radar, aircraft and satellite observations. In addition, some diagnostic studies on cloud cluster properties, and semi-prognostic studies of cumulus parameterization schemes using single column models have been attempted[15]. Mesoscale models have been developed with flexibility in terms of altering horizontal and vertical resolutions, nesting domains and choosing appropriate options for different physical parameterization schemes. By selecting some important parameters appropriately, these models can be used in a wide range of applications, including thunderstorm forecasting[16].

Stability indices have been a corner stone in the forecasting of convection for many decades and often are used in the research literature as well. Studies on the efficiency of different stability indices for thunderstorm prediction have been made by several authors[17–19]. Advection of warm air in the lower levels and cold air in the upper levels (generally associated with deep troughs in the upper tropospheric westerlies) will increase the conditional instability in the atmosphere and favour outbreak of severe thunderstorms[20–22]. Srinivasan *et al.*[23] have given a detailed account of severe thunderstorms in India and described several case studies. An attempt has been made in the present study to simulate the thunderstorm event that occurred on 20 May 2006 at Kolkata (22.52°N, 88.37°E) during the field experiment of Severe Thunderstorm Observation and Regional Modelling (STORM) programme 2006, using Non-hydrostatic Mesoscale Model (NMM) core of the Weather Research and Forecasting (WRF) system with different initial conditions and validate the model results with STORM field experiment data. This model was developed by the National Oceanic and Atmospheric Administration (NOAA)/National Centers for Environment Prediction (NCEP).

STORM programme and field experiment 2006

The Department of Science and Technology, Government of India organized a national coordinated programme STORM to be carried out in the pre-monsoon seasons of 2006–10, to improve the understanding and prediction of the severe local storms over the east and northeast regions of India, known as 'Kal-baishakhi' or 'Nor'westers' and analyse their socio-economic impact. The focus of the STORM programme was on a comprehensive observational and modelling study on the genesis, evolution and life cycle of intense tropical convective activities over the east and northeast regions of India during pre-monsoon period through meso-network of observations and mesoscale analysis and prediction systems. Extensive observations with modern instruments/sensors, viz. Doppler Weather Radar (DWR), wind-profilers, Automatic Weather Stations (AWS), etc. will be useful in providing a better understanding of the physical, dynamic and thermodynamic characteristics of these thunderstorms.

A field experiment was implemented during 13 April–31 May 2006. In this phase, an outer quadrilateral was formed between Patna, Guwahati, Kolkata, Bhubaneshwar and Ranchi. Apart from the regular network and additional India Meteorological Department (IMD) upper air and surface observations, the Indian Air Force operated three Digi-CORAs (wind/temperature/humidity measuring equipment) at Kalaikunda, Panagarh and Bagdogra. IMD authorized additional radiosonde ascents daily at 06 UTC and 18 UTC during the intensive observation periods (IOPs) at Patna, Ranchi, Bhubaneshwar, Kolkata and Guwahati. The Ministry of Defence facilitated DRDO (Defence Research and Development Organization) facility at Chandipur to make additional meteorological observations and operate their Digi-CORA equipment for upper air sounding. The IMD facilitated hourly/half-an-hourly coverage by DWR at Kolkata and support by other weather radars at Dum Dum, Ranchi, Bhubaneshwar and Paradip every 3 h on a regular basis and hourly during IOPs. The IMD also facilitated the provision of hourly *Kalpana*-1 (INSAT) weather satellite observations during the pilot phase of the experiment. The Indian Air Force reinforced their observation network of Purnea, Panagarh, Barrackpore, Kalaikunda and authorized special pilot balloon ascents. An inner quadrilateral joining Asansol, Murshidabad, Kolkata and Digha was chosen in the outer quadrilateral. In the inner quadrilateral 10 AWS were established by Calcutta University. These became operational from the later stage (after 15 May 2006) of the STORM pilot experiment. Unfortunately, DWR, Kolkata became unserviceable between 26 April and 15 May 2006 and hence, valuable data on the development of convection were not available.

For the present study of a severe thunderstorm which was reported on 20 May 2006 at 1200 UTC over Kolkata during the field experiment, both AWS and DWR data have been included for validation. This intense convective event produced 52 mm of rainfall over Kolkata. The situation started with a squall passing Dum Dum airport on 20 May 2006 at 1100 UTC, with a maximum speed of 18 ms^{-1}, lasting for a few minutes. Scattered echoes were observed between 0700 and 1400 UTC during analysis of DWR, Kolkata. A few places recorded moderate rainfall over the Gangetic West Bengal (GWB) and isolated rainfall over Orissa, Chattisgarh and Bihar. Dum Dum recorded 5 cm and Alipore 4 cm of rainfall.

For this event, the synoptic chart analysis shows that trough of low pressure lay over Uttar Pradesh (UP) and adjoining Bihar to the north Bay through Jharkhand, GWB. Low-level cyclonic circulation extending up to 0.6 km lay over GWB and adjoining Bangladesh. At 850 hPa, a cyclonic circulation was seen over eastern UP, adjoining Bihar and Jharkhand. A north-south trough lay extending from Sub Himalayan West Bengal (SHWB) to

Table 1. Realized weather phenomenon over Kolkata on 20 May 2006

	Weather phenomenon	Time (IST)	Rainfall amount (mm)	Remarks
20-05-06	Thunderstorm (TS) without rain	1550–1602	052.1	Rainfall reported next morning
	TS with rain	1602–1755		
	Rain with no TS	1755–1810		
	Squall	1633–1635		

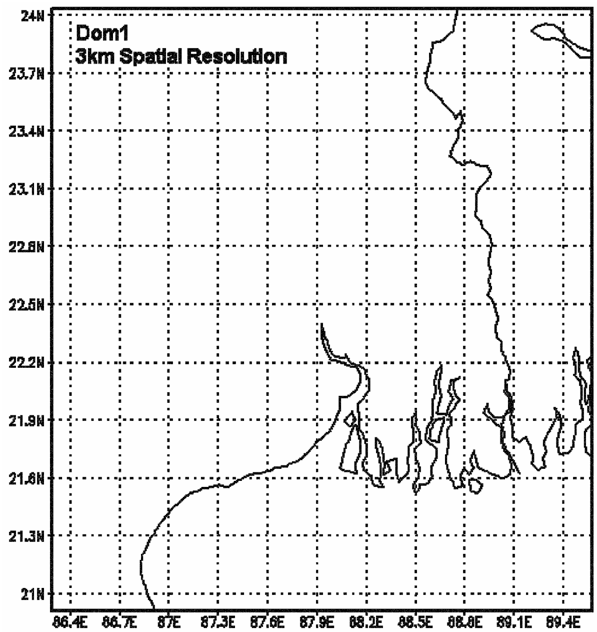

Figure 1. Domain of the WRF–NMM model.

north Bay between 2.1 and 3.6 km. At 500 and 200 hPa, northwesterly winds with speed between 12 and 20 ms^{-1} were observed over the region. *Kalpana* satellite imageries analysis revealed isolated intense convection at 1200 UTC over south GWB, Jharkhand and Orissa[24]. Table 1 shows the realized weather phenomenon over Kolkata on 20 May 2006.

Data and methodology

The WRF–NMM has been credited by its adoption in the NCEP, as its operational mesoscale modelling system for USA in June 2006. Moving over to the WRF–NMM as its operational model, the NCEP has been able to produce weather analyses and forecasts based on a resolution of 0.1°. Recently, the WRF–NMM was also adopted by the National Hurricane Centre, Miami. This state-of-the-art mesoscale model (WRF–NMMV2.2) has been used in this study to perform cloud-resolving simulation of the thunderstorm event over Kolkata on 20 May 2006, with different initial conditions. The WRF–NMM has been used for thunderstorm simulation with horizontal grid resolution of 3 km.

The WRF–NMM is a fully compressible, non-hydrostatic mesoscale model with a hydrostatic option[25]. Its vertical coordinate is a hybrid sigma-pressure coordinate. The grid staggering is the Arakawa E-grid. The model uses a forward–backward scheme for horizontally propagating fast waves, implicit scheme for vertically propagating sound waves, Adams–Bashforth scheme for horizontal advection, and Crank–Nicholson scheme for vertical advection. The same time-step is used for all terms. The dynamics conserves a number of first and second order quantities, including energy and enstrophy[26]. This model supports a variety of capabilities, including real-data simulations, full physics options, non-hydrostatic and hydrostatic (runtime) options, one-way static nesting and applications ranging from metres to thousands of kilometres.

In the present simulation, the model was integrated with multiple initial conditions starting from 19 May 2006 at 0000 UTC, 19 May 2006 at 1200 UTC and 20 May 2006 at 0000 UTC for a period of 48 h (simulation designated as Ex-1), 36 h (simulation designated as Ex-2) and 24 h (simulation designated as Ex-3) respectively, and the robustness of the results was established. A single domain with 3 km horizontal spatial resolution was configured as shown in Figure 1, which is reasonable in capturing the mesoscale cloud clusters. Initial conditions for the 3 km domain were derived from 6 h global final analysis (FNL) at $1.0 \times 1.0°$ grids generated by NCEP's global forecast system. Analysis fields, including temperature, moisture, geopotential height and wind were interpolated to the mesoscale grids by the WRF standard initialization process. These derived fields served as initial conditions for the present experiment.

The domain covers 86.3°E–89.7°E and 21.0°N–24.0°N. The grids were centred at 88.0°E, 22.5°N with 167×165 grid points. The domain was configured with vertical structure of 38 unequally spaced sigma (non-dimensional pressure) levels. The physical parameterizations used in the study were Geophysical Fluid Dynamics Laboratory for radiation[27], NMM Land surface scheme for land surface, Mellor Yamada Janjic scheme[28] for planetary boundary layer, Ferrier scheme[29] for microphysics, Janjic similarity scheme for surface layer and Grell–Devenyi cloud ensemble scheme[30] for cumulus parameterization. All the above schemes are well tested for WRF–NMM and are

Table 2. WRF–NMM model configuration

Dynamics	Non-hydrostatic
Model domain	21.0–24.0°N, 86.3–89.7°E
Horizontal spatial resolution	3 km
Grid points	167 × 165
Integration time-step	6 s
Map projection	Rotated latitude and longitude
Horizontal grid system	Arakawa E-grid
Vertical coordinate	Terrain-following hybrid (sigma-pressure) vertical coordinate (38 sigma levels)
Radiation parameterization	GFDL/GFDL
Surface layer parameterization	Janjic similarity scheme
Land surface parameterization	NMM Land surface scheme
Cumulus parameterization	Grell–Devenyi ensemble scheme
PBL parameterization	Mellor–Yamada–Janjic
Microphysics	Ferrier (new eta) scheme

Table 3. Critical levels of stability indices

Stability index	Description	Critical level
Lifted index	$T_{500} - T_{\text{parcel}}$	<–3
K index	$(T_{850} - T_{500}) + DT_{850} - (T_{700} - DT_{700})$	>33
Total totals	$(T_{850} - TD_{850}) - 2(T_{500})$	>44
CAPE	$\int_{z=\text{LFC}}^{z=\text{LNB}} g \frac{[\theta_{\text{vp}}(z) - \theta_v(z)]}{\theta_v(z)} \text{d}z$	>1500

used operationally at NCEP. Table 2 shows the model configuration of the present study. The hourly observations of AWS and DWR data over Kolkata were used in this study for model validation.

Results and discussion

According to earlier studies[31,32], the general preconditions for initiation of thunderstorms are conditional instability, a sufficiently deep humid layer in the lower and mid-troposphere and an uplifting mechanism to initiate convection. The formation of thunderstorms is an interaction between these conditions on different scales[31]: 'It is proposed that convective systems depend primarily on large-scale processes for developing a suitable thermodynamic structure, while mesoscale processes act mainly to initiate convection'.

Variation of convection in the atmosphere depends upon dynamic as well as thermodynamic instability indices. A number of stability indices have been devised in order to detect the likely occurrence of thunderstorms. The thunderstorms are likely to develop in regions where the stability indices are at critical levels as shown in Table 3 (http://profhorn.aos.wisc.edu/wxwise/AckermanKnox). An attempt has been made to examine different stability indices from model simulations with different initial conditions. FNL data have been used for the validation of model-simulated stability indices.

Figure 2 *a–d* shows an inter-comparison of FNL data and model-simulated stability indices, namely CAPE, K-index, total totals index and lifted index valid for 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC, with different initial conditions. It can be seen that stability indices of Ex-2 and Ex-3 almost match those of the FNL data, except for CAPE during the thunderstorm hour. CAPE of Ex-3 showed significant increase during the thunderstorm hour and captured 2294 J/kg at 1200 UTC, which is the highest compared to other initial conditions. However, the FNL value is low (965 J/kg) compared to NMM simulation with different initial conditions during the thunderstorm hour. All time-series plots of the K index at different initial conditions indicate favourable values during the thunderstorm hour. Ex-2 and Ex-3 returned the same value (36) of K index at 1200 UTC, which is almost close to the FNL data (38). The K index of Ex-1 was 34, which is less compared to the FNL data at 1200 UTC.

The total totals index of Ex-2 and Ex-3 was equivalent to that of the FNL data (45) at 1200 UTC, which is a favourable value for thunderstorm occurrence. The total totals index of Ex-1 was 42, which is less compared to the critical value for the thunderstorm occurrence and FNL data. There was no considerable variation between Ex-1, Ex-2 and Ex-3 resulted lifted index and FNL data during the thunderstorm hour. The lifted index of Ex-1, Ex-2 and Ex-3 was –5, which is close to the FNL data (–4). The CAPE, total totals and K index of Ex-2 and Ex-3 showed significant increase and lifted index showed significant decrease during the thunderstorm hour. Comparing all the stability indices of Ex-2 and Ex-3 with the FNL data, we conclude that the model has captured well the overall pattern. The skew-*t* plot of Ex-3 at 1200 UTC of 20 May 2006 over Kolkata is shown in Figure 3. The plot shows that the atmosphere was convectively unstable at 1200 UTC. Examination of all the model-simulated stability indices clearly indicated that the model captured well the instability of the atmosphere at 1200 UTC for the occurrence

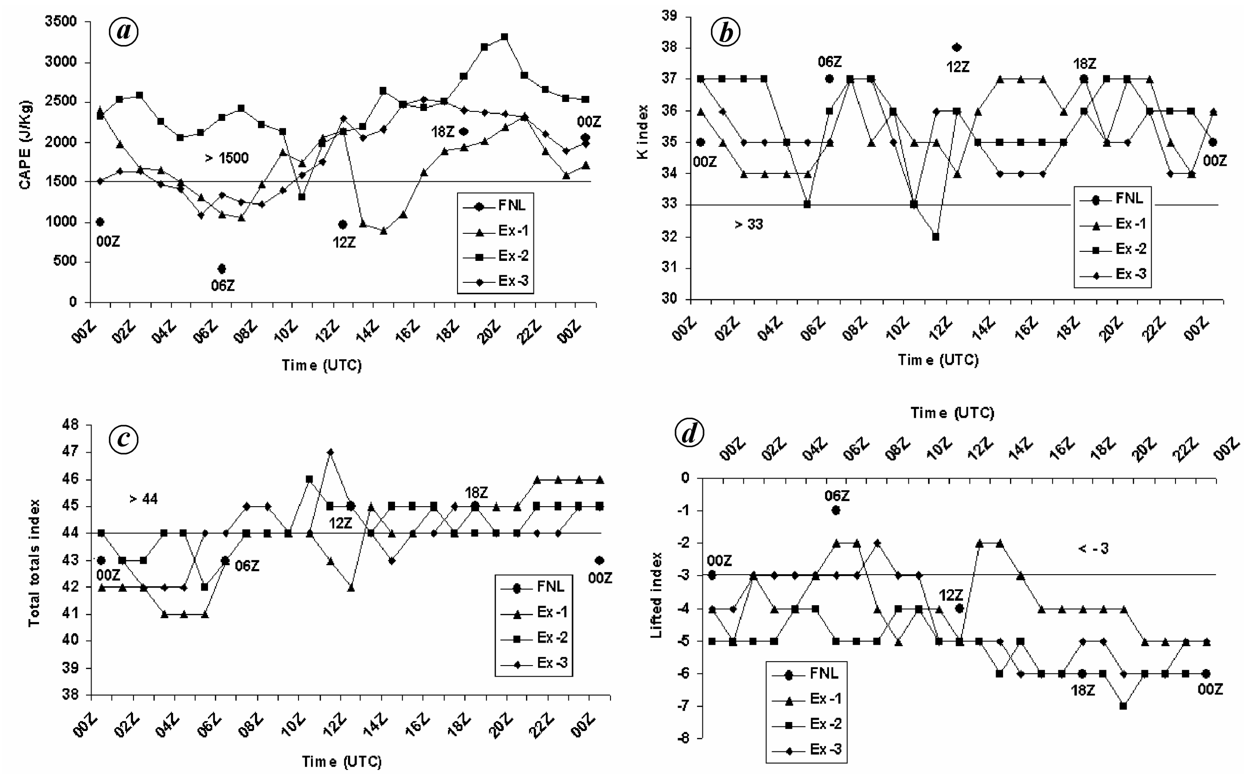

Figure 2. Inter-comparison of FNL data and model-simulated stability indices with different initial conditions over Kolkata valid for 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC. ***a***, CAPE (J/kg); ***b***, K index; ***c***, Total totals index, and ***d***, Lifted index.

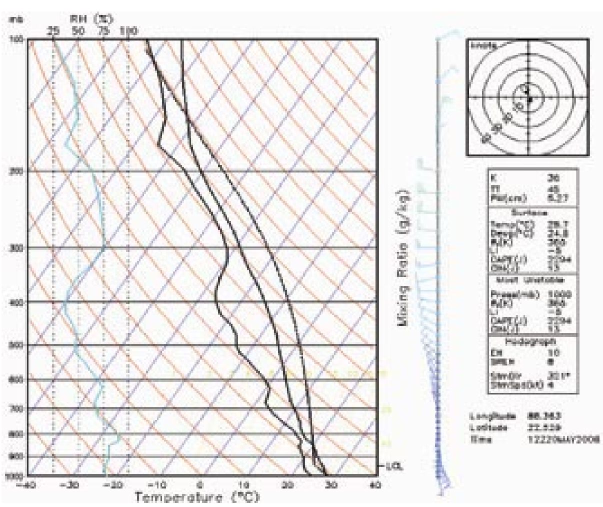

Figure 3. Skew-*t* plot of Ex-3 at 1200 UTC of 20 May 2006 over Kolkata.

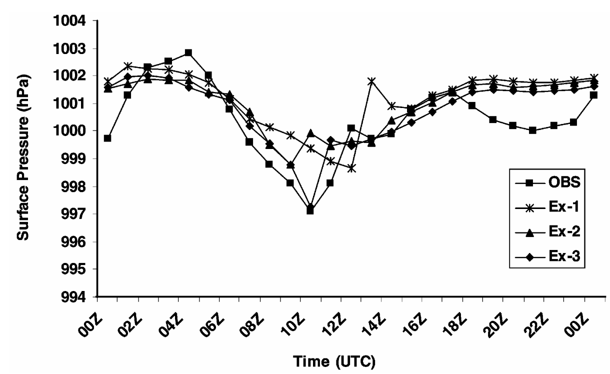

Figure 4. Inter-comparison of observed and model-simulated surface pressure (hPa) with different initial conditions over Kolkata valid for 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC.

of a severe thunderstorm. Thus the thermodynamic structure over Kolkata became conducive for a thunderstorm occurrence on the evening of 20 May 2006.

The storm initiation and development was examined by the analysis of surface pressure, surface temperature, relative humidity, accumulated rainfall and surface wind speed. Surface pressure and temperature are useful parameters in determining the likelihood occurrence of a thunderstorm. Figure 4 shows the hourly variation of model-simulated surface pressure at different initial conditions with the observed values over Kolkata (AWS data from Kolkata), from 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC. Ex-3 captured well the diurnal variation of surface pressure with a sudden rise from 997.3 to 999.4 hPa at 1100 UTC, which is 1 h prior to the observed time, with a rise from 998 to 1000 hPa. Ex-2 captured the rise from 998.8 to 999.9 hPa at 1000 UTC. Ex-1 captured the rise from 998.6 to 1001.7 hPa at 1300 UTC, which is 1 h later than the observed rise. The time series plots of Ex-1 and Ex-3 match well with the observation. Sudden pressure rise during a storm is a characteristic feature of a thunderstorm[33], which is captured well by the WRF–NMM. Similar is the case with the diurnal variation of surface temperature (Figure 5), where Ex-3 captured the variation with a drop in temperature at 1100 UTC from 33.5°C to 27°C, 1 h before the time of the thunderstorm, which could be attributed to the cooling of the surface temperature due to precipitation by the thunderstorm system. Ex-2 captured the temperature drop at 1000 UTC from 33.3°C to 26.5°C, while Ex-1 at 1300 UTC from 32°C to 23°C. The observed temperature showed a sudden drop from 33 to 22°C at 1200 UTC. Ex-1 captured well the time and intensity compared to the observation.

Relative humidity at the surface level has also been taken into account, as it is an essential factor for intense convection. Storm days require a sufficiently humid and deep layer in the lower and middle atmosphere[32]. Figure 6

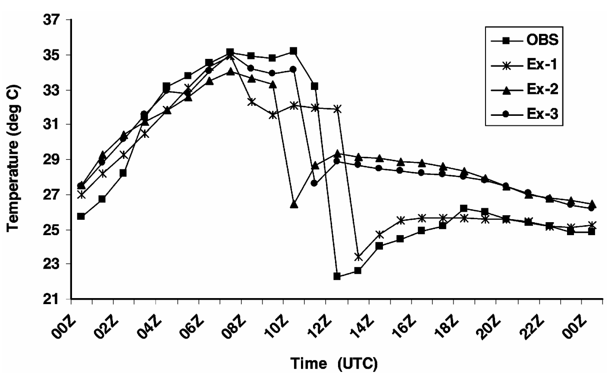

Figure 5. Same as Figure 4, but for surface temperature (°C).

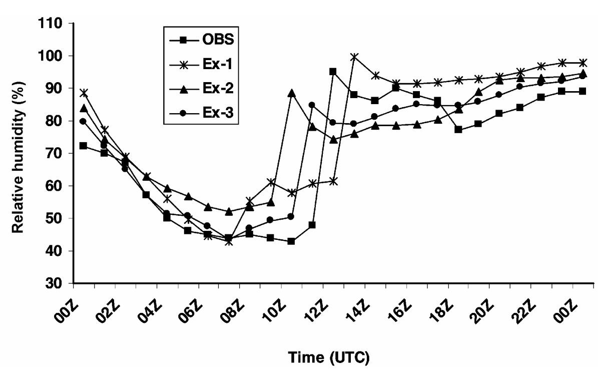

Figure 6. Same as Figure 4, but for relative humidity (%).

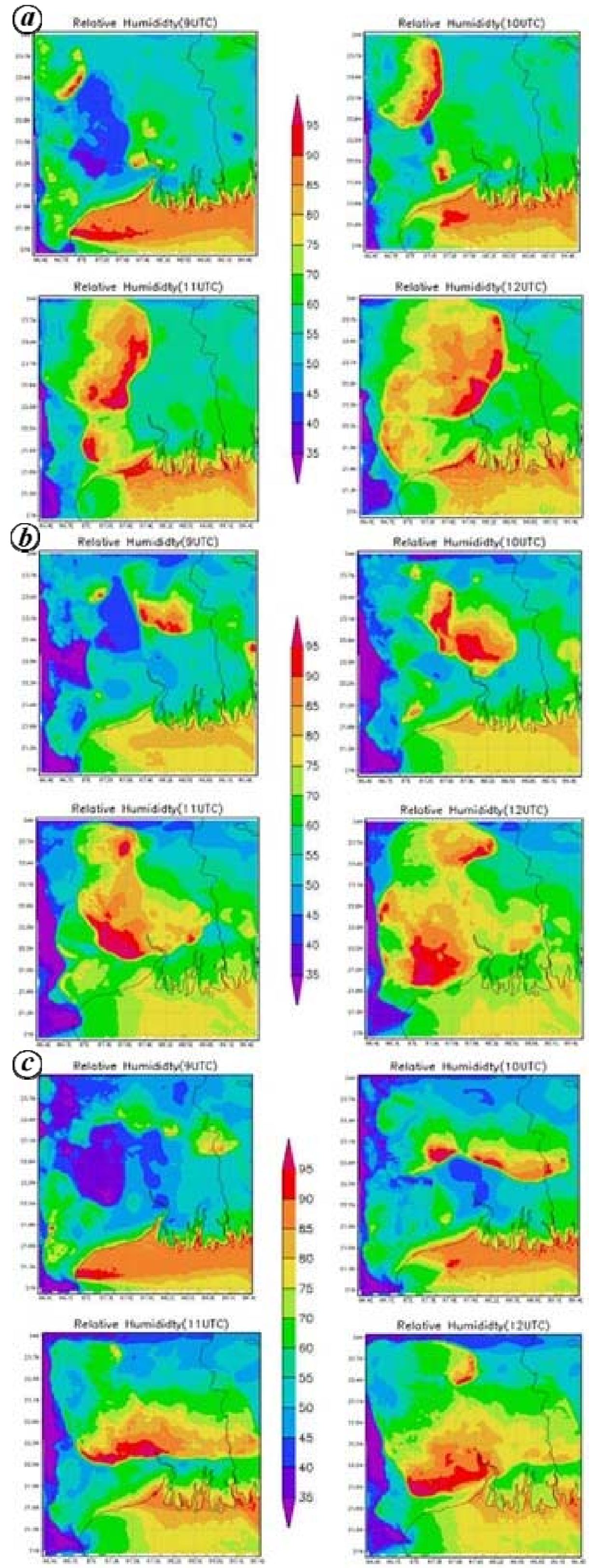

Figure 7. Spatial distribution of relative humidity (%) from (***a***) Ex-1, (***b***) Ex-2 and (***c***) Ex-3 valid on 20 May 2006 at 0900, 1000, 1100 and 1200 UTC.

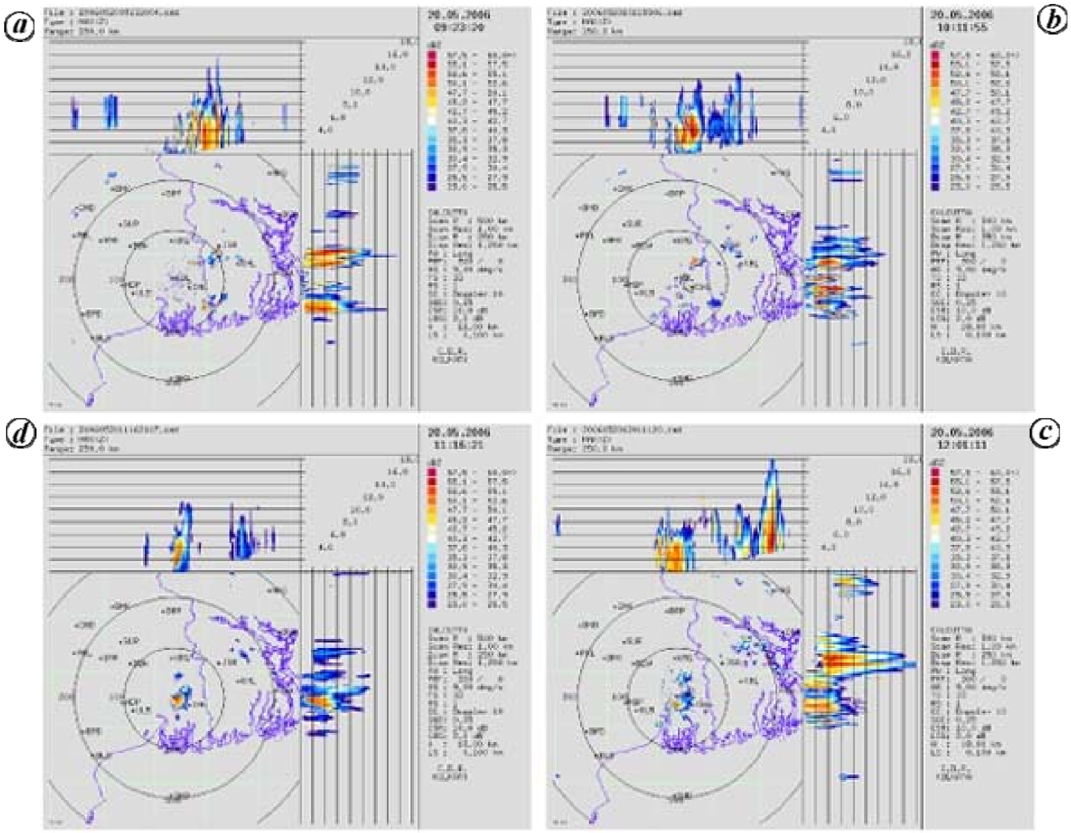

Figure 8. Kolkata DWR pictures on 20 May 2006 valid at (***a***) 0900 UTC, (***b***) 1000 UTC, (***c***) 1100 UTC and (***d***) 1200 UTC.

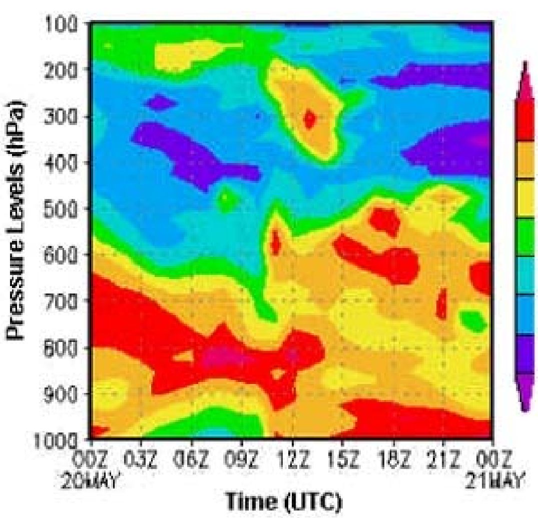

Figure 9. Time–height cross-section of relative humidity (%) from Ex-3 over Kolkata valid for 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC.

shows the inter-comparison of observed and model-simulated relative humidity using different initial conditions over Kolkata valid for 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC. The observed relative humidity values peaked from 48 to 95% at 1200 UTC, whereas Ex-3 showed a sharp rise from around 50 to 85% at 1100 UTC, which is 1 h prior to the thunderstorm occurrence. Ex-2 showed a sudden rise from 55 to 88% at 1000 UTC, whereas Ex-1 showed a peak from 61.5 to 99.6% at 1300 UTC. The model-simulated spatial distribution of relative humidity with different initial conditions at the surface level from 0900 to 1200 UTC is shown in Figure 7 *a–c*. From Figure 7 *c*, which shows the results of Ex-3, we can see that a squall line was initiated at 0900 UTC from the east of Kolkata, which gradually moved towards Kolkata at 1000 UTC and intensified at 1100 UTC as in DWR pictures (Figure 8). However, Figure 7 *a*, which shows the spatial distribution of Ex-1, shows that the squall line was initiated at 0900 UTC to the west of Kolkata and gradually moved towards Kolkata during the next few hours. The movement of the system in Ex-1 was opposite to that observed (Figure 8). Figure 8 shows the DWR pictures of Kolkata from 0900 to 1200 UTC. The squall line movement in the DWR pictures matches well with Ex-3. Ex-2 also matches, but a 2 h time lag exists. Figure 9 shows time–height cross-section of relative humidity of Ex-3 over Kolkata. It shows a considerable amount of moisture (more than

80%) present at the lower and middle levels. Relative humidity remained high from the time of genesis of the thunderstorm to the time of precipitation. This is a favourable condition for thunderstorm formation. By examining the vertical, temporal and spatial distribution of relative humidity, it can be concluded that there is enough moisture present in the lower and middle levels of the atmosphere during the thunderstorm hour.

Figure 10 shows a comparison of observed and model-simulated accumulated progressive rainfall with different initial conditions at Kolkata. Ex-3 was able to capture 29 mm of rainfall at 1100 UTC, which is less compared to the actual observation (52 mm). Ex-2 was only able to simulate 22 mm at 1000 UTC, which is less. The total accumulated rainfall of Ex-1 was 36.6 mm. However, the rainfall amount during the thunderstorm hour was only 16.6 mm. The model-simulated spatial distribution of hourly rainfall under different initial conditions at surface level from 0900 to 1200 UTC is shown in Figure 11 *a*–*c*. The spatial pattern of hourly rainfall was the same as the pattern of relative humidity. From Figure 11 *b* and *c*, we can clearly see that the squall line was initiated at 0900 UTC from the east of Kolkata and gradually moved towards Kolkata. However, Figure 11 *a* shows that the squall line was initiated at 0900 UTC from the west of Kolkata and gradually moved towards Kolkata during the following hours. The direction of the squall line movement in Ex-1 was opposite to that observed, as in the case of relative humidity. The rainfall amount was also less compared to Ex-2 and Ex-3.

The model-simulated spatial distribution of moisture convergence under different initial conditions at 850 hPa from 0900 to 1200 UTC is shown in Figure 12 *a*–*c*. Figure 12 *c* illustrates moisture convergence of Ex-3, which proved to be better in the simulation of all the parameters discussed earlier. This shows maximum convergence (convergence is positive and divergence is negative) to the east of Kolkata at about 1000 UTC, which is consistent with the weather report that a squall line started to

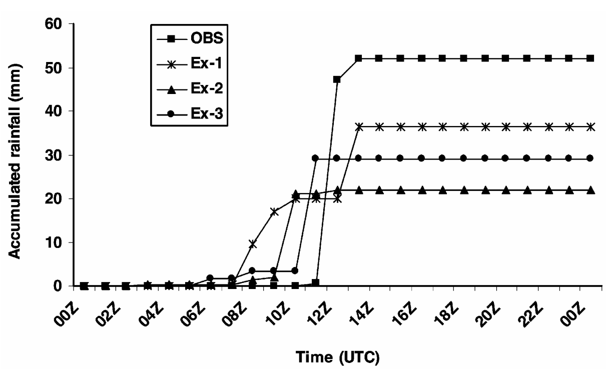

Figure 10. Inter-comparison of observed and model-simulated diurnal variation of accumulated rainfall (mm) with different initial conditions over Kolkata valid for 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC.

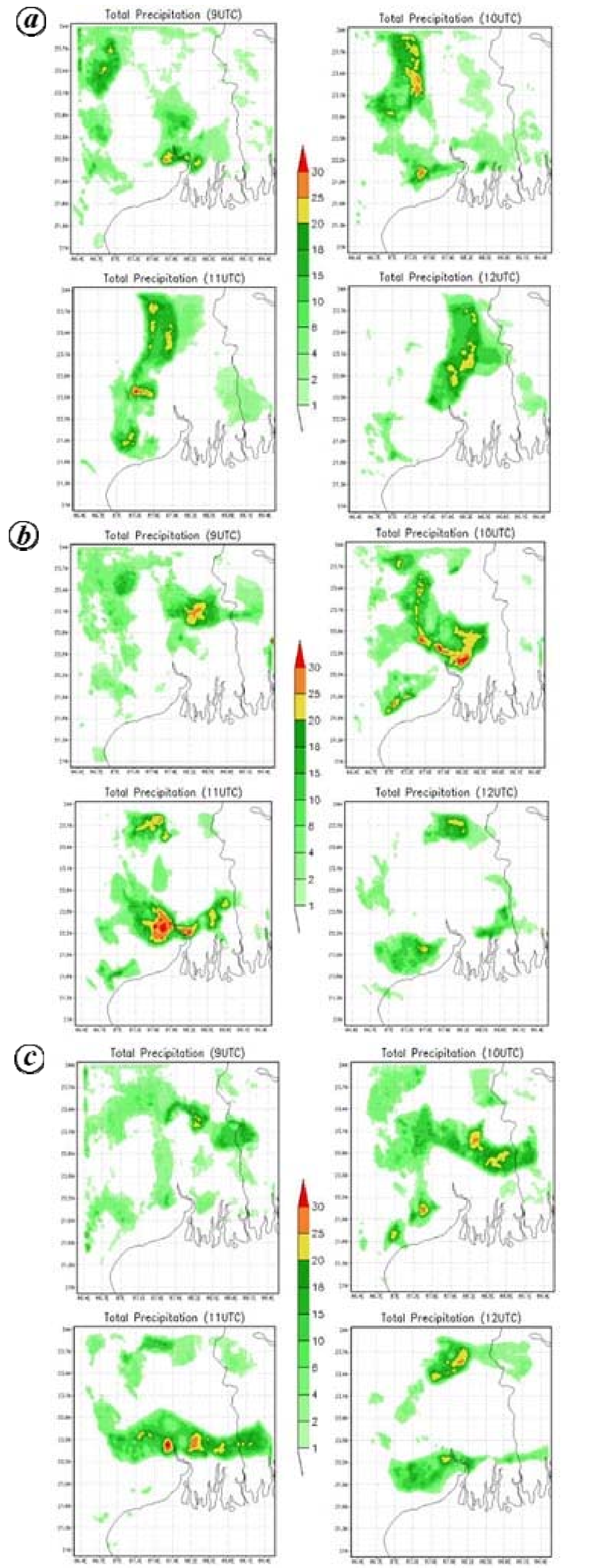

Figure 11. Spatial distribution of hourly rainfall (%) from (***a***) Ex-1, (***b***) Ex-2 and (***c***) Ex-3 valid on 20 May 2006 at 0900, 1000, 1100 and 1200 UTC.

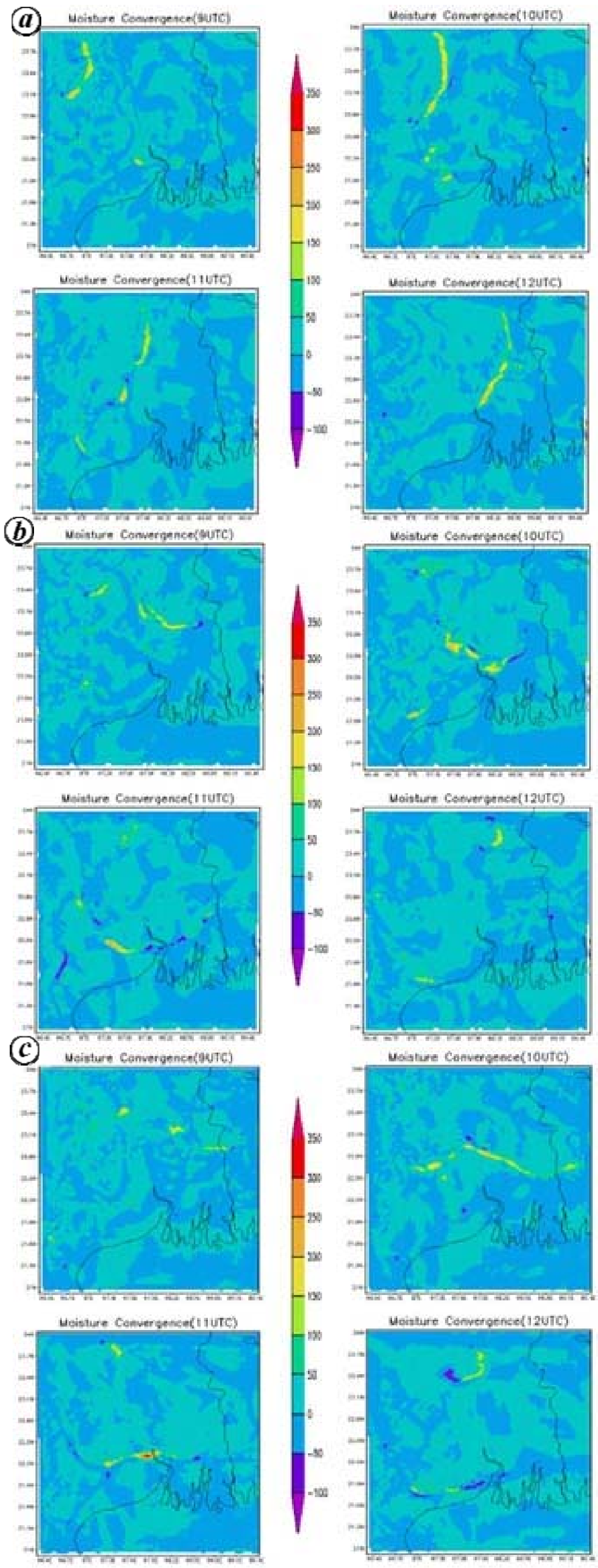

Figure 12. Spatial distribution of moisture convergence (s^{-1}) from (***a***) Ex-1, (***b***) Ex-2 and (***c***) Ex-3 on 20 May 2006 valid at 0900, 1000, 1100 and 1200 UTC.

the east of Kolkata and slowly moved towards Kolkata. Thus the maximum moisture convergence is in agreement with the weather report. Figure 12 *b* shows moisture convergence of Ex-2, which is also in agreement with the weather report with a time lag of 2 h. Figure 12 *a* displays the moisture convergence of Ex-1, which is not in agreement with the weather report because it started to the west of Kolkata. The time series of observed and model-simulated surface wind speeds under different initial conditions is given in Figure 13. The observed surface wind speed was maximum at 1200 UTC, whereas Ex-2 and Ex-3 resulted in wind speed maximum at 1000 UTC. Therefore, the wind speed maximum simulated by Ex-2 and Ex-3 is consistent with the simulated time of the storm, which is comparatively less than that observed. The simulated wind speed of Ex-3 was less compared to other model simulations and observations. The spatial plots of model-simulated surface wind speed from 0900 to 1200 UTC with different initial conditions are presented in Figure 14 *a–c*. From Figure 14 *c*, we see that a squall line was initiated at 0900 UTC, which gradually moved towards Kolkata at 1000 UTC. The squall line passed over Kolkata at 1100 UTC with a maximum speed of 16 ms^{-1}, which is close to the observed value (18 ms^{-1}) reported by IMD. But Ex-2 showed that the squall line passed over Kolkata at 1000 UTC, which is 2 h prior to the observation. Ex-3 failed to capture the direction of squall line movement, as in the case of the other thunderstorm-affected parameters.

Prediction of the dominant convective mode is based on the assessment of magnitude of vertical motion which is needed to initiate convection[34]. Figure 15 shows the time–height cross-section of model-simulated pressure vertical velocity with different initial conditions over Kolkata valid for 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC. If a strong updraft and downdraft can co-exist side by side without mutual inference, a severe thunderstorm is likely to develop[35]. Figure 15 *a*, which is the output of Ex-1, shows strong updraft at 1300 UTC

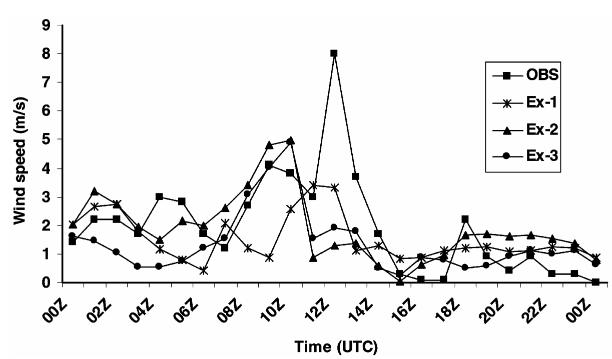

Figure 13. Inter-comparison of observed and model-simulated diurnal variation of surface wind speed (ms^{-1}) with different initial conditions over Kolkata valid for 20 May 2006 at 0000 UTC to 21 May 2006 at 0000 UTC.

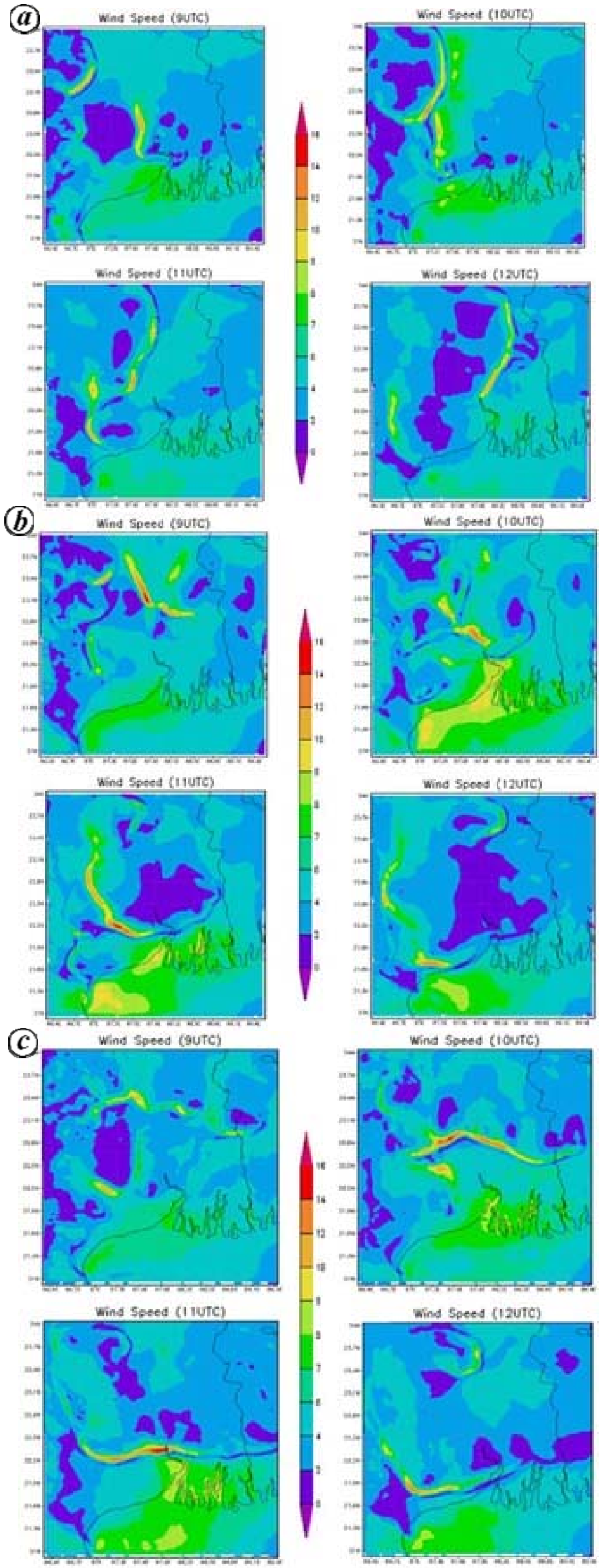

Figure 14. Spatial distribution of surface wind speed (ms^{-1}) from (***a***) Ex-1, (***b***) Ex-2 and (***c***) Ex-3 on 20 May 2006 valid at 0900, 1000, 1100 and 1200 UTC.

with a magnitude of –2 Pa/s and downdraft at 1400 UTC in the order of 0.6 Pa/s during the model predicted time. From Figure 15 *b*, which is the output of Ex-2, we can see a strong downdraft at 1000 UTC with a value more than 1.2 Pa/s. But the updraft was weak at 0900 UTC, with a value of –0.3 Pa/s. Figure 15 *c*, which is the result of Ex-3, clearly shows the updraft and downdraft. From Figure 15 *c* it can be seen that the updraft occurred at 1100 UTC, with magnitude –1.8 Pa/s and downdraft occurred around 1200 UTC with magnitude 0.6 Pa/s. The pressure vertical velocity plots of Ex-1 and Ex-3 showed the updraft and downdraft during thunderstorm formation and occurrence, which is an important phenomenon related to thunderstorm lifecycle. The trends shown by various meteorological fields of Ex-3 are in good agreement with each other and consistent with the dynamic and thermodynamic properties of the atmosphere for the occurrence of a severe thunderstorm. Ex-2 well captures all the meteorological parameters with 2 h time lag. Ex-1 failed to capture the direction of squall line movement. It may also be noted that all the characteristic properties of the genesis, occurrence and lifecycle of the severe thunderstorm were well simulated by Ex-3.

Conclusion

The thunderstorm of 20 May 2006 over Kolkata was simulated using WRF–NMM with different initial conditions to resolve mesoscale signature of the atmosphere and establish the robustness of the results. The high-resolution model is able to broadly reproduce several features of the thunderstorm event, such as spatial pattern and temporal variability.

Ex-3 had well simulated the thunderstorm initiation in terms of pressure vertical velocity, stability indices and moisture convergence. Simulation of the stability indices was good, with values indicating higher instability for the thunderstorm to occur. The model simulated well the updraft and downdraft during the thunderstorm formation and occurrence. The model also simulated high moisture convergence over Kolkata during thunderstorms hours.

Ex-3 performed well in simulating all the thunderstorm-affected parameters, namely surface pressure, surface temperature, relative humidity, accumulated rainfall and surface wind speed, which are useful for the occurrence and intensity of the severe thunderstorm, though 1 h time lag was found to exist.

From the spatial plots of relative humidity, wind speed, hourly rainfall and moisture convergence of Ex-3, we see that a squall line was initiated at 0900 UTC, which gradually moved towards Kolkata at 1000 UTC and intensified at 1100 UTC. The model has also captured well the squall line movement.

Overall, Ex-3 simulated well the intense convective activity, though 1 h time lag existed and rainfall amount was

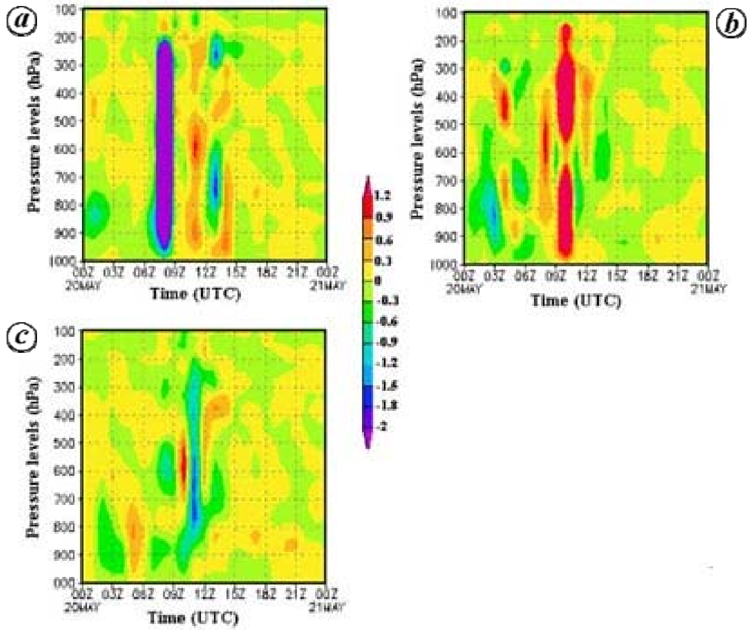

Figure 15. Model-simulated time–height cross-section of pressure vertical velocity (Pa/s) with different initial conditions at Kolkata on 20 May 2006: (***a***) Ex-1, (***b***) Ex-2 and (***c***) Ex-3.

less intensified. This was the only intense case during the field experiment 2006, where both AWS and DWR data were available for validation. In future, more numerical experiments can be conducted on thunderstorms with STORM field experiment (2007–10) data. Thus we conclude that the 3 km WRF–NMM performed well in genesis, intensification and decay of severe thunderstorm. This suggests that high-resolution models have the potential to provide unique and valuable information for severe thunderstorm forecasters.

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ACKNOWLEDGEMENTS. We thank the Department of Science and Technology, New Delhi for providing financial support. We also thank IMD, Calcutta University, the Indian Air Force, Army and Navy for providing data. Thanks are also due to the three reviewers for their constructive comments and useful suggestions.

Received 17 September 2007; revised accepted 21 May 2008