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ORIGINAL PAPER

Numerical simulation of physical and dynamical characteristics associated with the severe thunderstorm on April 5, 2015 at Kushtia and Jhenaidah

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Abstract The paper deals with the study of the physical and dynamical characteristics of a severe thunderstorm, which had occurred on April 5, 2015, at about 2100 UTC in the southwestern Bangladesh with location around 23.3–23.7N and 89.0–89.4E within the upazilas (sub-districts) of Kumarkhali and Shailkupa under the districts of Kushtia and Jhenaidah, respectively. The thunderstorm was associated with numerous hails of large size. More than 5000 birds which used to live in the bird sanctuary at Shailkupa and 22,011 birds in Chhaglapara Bird Sanctuary of Kumarkhali died as they were hit by the hails. Large hails also damaged crops, houses and forests over the thunderstorm hit areas. The evolution of the thunderstorm is studied by the WRF model, which is initialized using the National Centers for Environmental Prediction Final reanalysis data of 0000 UTC of April 5, 2015. The simulated results provide a basis to study the physical and dynamical characteristics of the thunderstorm, which are generally not identified by the meteorological observations which are too sparse. The model has captured a micro-low over Kumarkhali and its neighborhood, which favored the occurrence of the severe thunderstorm. The model simulated rainfall is about 26 mm near the place of occurrence, which matches well with the area where the reflectivity of hydrometeor is maximum. The convective available potential energy is found to be 1600 J kg^{-1} at 1730 UTC near the place of occurrence of the thunderstorm; this indicates high atmospheric instability over the thunderstorm location for the formation of the thunderstorm. The vertical velocity, convergence, cloud water mixing ratio and the ice water mixing ratio and their vertical extensions are found to be satisfactory and responsible for the occurrence of large hails associated with the thunderstorm.

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Keywords Thunderstorm · CAPE · Vertical velocity · Cloud water mixing ratio and ice water mixing ratio

1 Introduction

Thunderstorm (TS) resulting from vigorous convective activity is one of the most magnificent weather phenomena in the earth's atmosphere. The severe thunderstorms connected with thunder, squalls, hail storm, tornado, lightning and flash flood cause extensive damage and losses to lives and property. A common feature of the weather during the pre-monsoon season over India–Bangladesh region is the outburst of severe local convective storms (Das et al. 1994, 2015a, b, c; Das 2015; Karmakar 2001, 2005; Karmakar and Quadir 2014; Prasad et al. 2014). These thunderstorms are known as Kalbaishakhis or Nor'westers in Bangladesh and surrounding Indian states.

They cause damage to property and crops and even loss of life, particularly over rural areas, sometime running into hundreds of deaths on a single occasion due to destruction caused by squally winds, lightning and occasional tornadoes. Strong heating of landmass during midday initiates convection in preferential meteorological subdivisions of Bihar, Jharkhand, Chhattisgarh, Odisha, Sub-Himalayan West Bengal of India, which move toward the subdivision of Gangetic West Bengal and adjoining Bangladesh and get intensified due to insurgence of the low-level warm moist air mass from the Bay of Bengal. The low-level strong southerly winds from the Bay of Bengal are quite frequent during the pre-monsoon season due to the prevailing extended seasonal low pressure region from Bihar to West Bengal, Bangladesh and even across NE India. The climatology of the synoptic features corresponding to high frequency of thunderstorm occurrence in Bangladesh for the month of May has been investigated by Saha and Quadir (2016), which shows that the frequency of occurrence is high in an environment where the whole tropospheric column exhibits negative anomaly of geopotential height with strong low-level southerly wind which brings warm and moist air from Bay of Bengal to the land areas of Bangladesh and its surroundings. The study of Prasad (2006) using the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40) products showed that southward elongation of an upper-level trough at 300 or 200 hPa level over the Gangetic plains from north India to Bangladesh associated with subtropical jet streams and warm advection in the 850 and cold advection in 300 hPa levels favor the development of thunderstorms.

The sea breeze initiates convective cloud cells which under a favorable environment develop into severe local thunderstorms with occasional tornado cells embedded within the convective organizations and aided by the strong tropospheric wind shear and transport of moisture from the Bay of Bengal (Tyagi et al. 2011a). In general, convection passes through a life cycle of development during the day hours and dissipation in the evening or night hours.

Prominent among the synoptic studies are those by Desai (1950), Koteswaram and Srinivasan (1958), Srinivasan et al. (1973) and Weston (1972), which depict that the pre-monsoon thunderstorms in this region are very tall cumulonimbus (Cb) cloud with tops occasionally reaching a height of 20 km in the vertical, penetrating the tropopause; such strong convections are caused due to the flow of dry continental air on top of the low-level moist air in an environment of high vertical wind shear in the presence of subtropical jet stream (STJS). Saha and Quadir (2016) have shown that the high positive values of low-level vertical wind shear are favorable for the formation of thunderstorms over the Bangladesh region. Prasad (2006) and Ahasan et al. (2014) have found similar findings in the studies. These studies have also shown that the other environmental features, which are important for thunderstorm formation, are the low-level convergence, high convective available potential energy (CAPE) and low Convective Inhibition Energy (CIN).

The thunderstorm activities occur in the environmental condition characterized by high tropospheric instability. Karmakar and Alam (2005a, b) have analyzed a number of instability indices and provided the ranges conducive for formation of thunderstorm. Using the Showalter Index (SI), it was found that the thunderstorms form with SI values between −3 and 3 over the region of eastern India and Bangladesh. Decrease in SI values causes the sharp increase in probability for convection. The Totals–Totals Index (TTI) between 40–45 and K Index (KI) ranging from 35 to 40 indicate high tropospheric instability which is favorable for thunderstorm formation (Jayakrishnan and Babu 2014). Karmakar and Quadir (2014) have shown that the thunderstorms over Bangladesh and surrounding territories of India are formed if the morning time mixing ratio q is high ($q > 16$–$22.4\ \mathrm{g\ kg^{-1}}$) and there exists a high vertical gradient of equivalent potential temperature (EPT) at 0000 UTC in the lower troposphere; the EPT is seen to decrease rapidly with height up to 500 hPa level, and then, it is found to increase depicting the favorable condition for thunderstorm formation.

The studies of thunderstorms over Bangladesh and the Indian region using different numerical weather prediction (NWP) models other than WRF by Das et al. (2006, 2015a, 2016), Basnayake et al. (2010), Litta et al. (2011, 2012) and Tyagi et al. (2011b, 2013) show that the severe convective events are generated by the models with some limitations in the timing and location of the occurrence of thunderstorms. One reason of such discrepancy is identified as the coarse resolution of the initial data.

In the present study, a few aspects of the physical and dynamical characteristics of a severe thunderstorm had occurred on April 5, 2015, at about 2100 UTC in the southwestern Bangladesh with location around 23.3–23.7N and 89.0–89.4E within the upazilas (sub-districts) of Kumarkhali and Shailkupa under the districts of Kushtia and Jhenaidah, respectively. The selected case of thunderstorm was of particular interest as it was associated not only with stormy winds but with numerous hails of large size, and more than 5000 birds of the bird sanctuary at Shailkupa and 22,011 birds in another nearby bird sanctuary at Chhaglapara of Kumarkhali died as they were hit by the hails (Karmakar et al. 2016a, b). Large hails also damaged crops, houses and forests over the thunderstorm hit areas.

2 Prevailing synoptic conditions and data used

The synoptic features during, prior and post-occurrence of the event under investigation are shown in the IR imageries (Fig. 1) from the Indian National Satellite System (INSAT). The time intervals of the images are not uniform and vary from 1.5 to 5 h due to unavailability of the images for some hours. From the image of 0630 UTC, it is seen through the distribution of clouds that a low pressure area extends over east Uttar Pradesh, Bihar, northern West Bengal, Meghalaya, Assam and northern Bangladesh, when two small convective cloud covers are found over western Bangladesh and adjacent West Bengal which further developed into relatively large convective system as seen in the imageries of

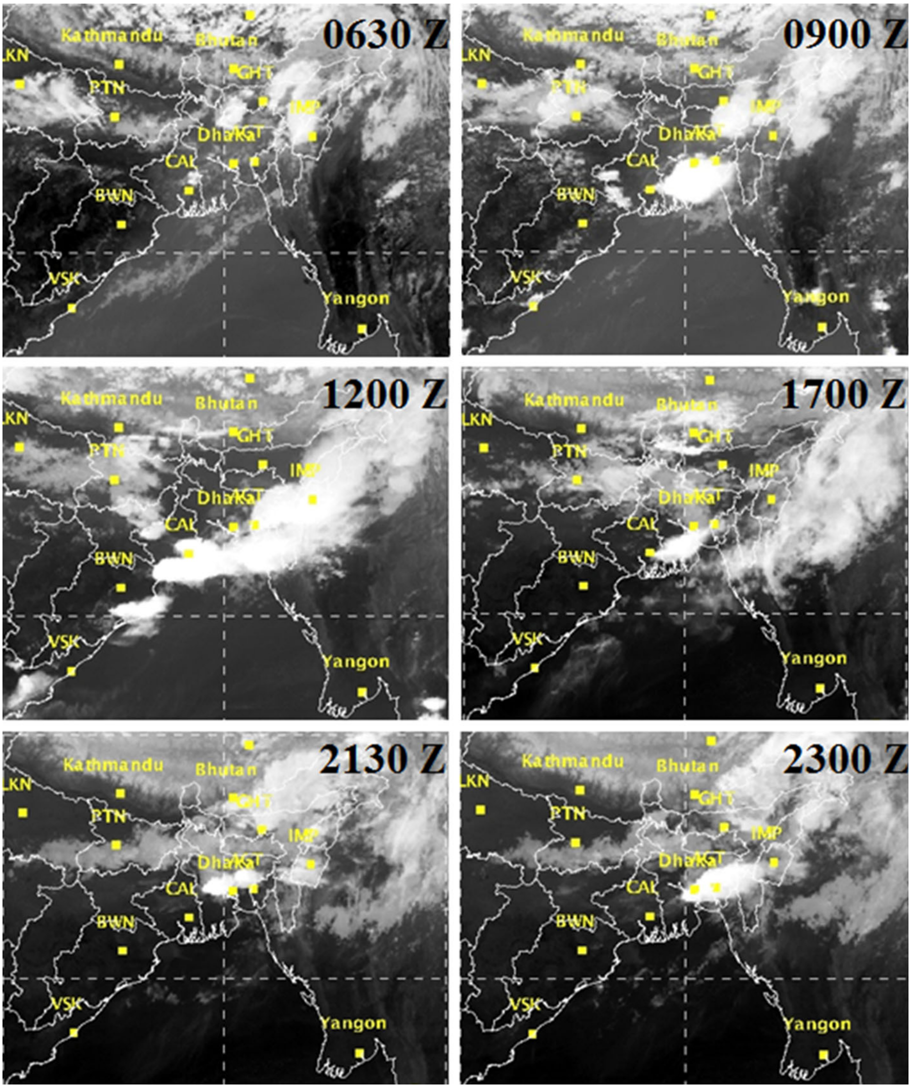

Fig. 1 Infrared imageries from INSAT on April 5, 2015

0900 and 1200 UTC. The convective cloud masses are found to be oriented from southwest to northeast over Bangladesh and its adjacent territories. At 1700 UTC a convective system prevailed over southwestern Bangladesh. The satellite image of 2130 UTC (1730–2100 UTC images are not available) shows that the convective cell is located in the anticipated place at the left edge of the cloud with anvil spreading toward the east. The thunderstorm had occurred from this cloud cell at around that time. The image of 2300 UTC shows that the cloud system was slightly in the west. The locations of the meteorological stations of Bangladesh Meteorological Department (BMD) near the place of occurrence and the affected upazilas are given with latitude and longitude as given in Table 1. The affected upazilas such as Kumarkhali and Shailkupa are in the districts of Kushtia and Jhenaidah.

Table 1 Location of the nearby meteorological stations of Bangladesh Meteorological Department (BMD) and the approximate location of the villages of the affected upazilas (sub-districts)

Location of the BMD stations	Lat. (°)	Long. (°)
Ishurdi	24.1333N	89.0500E
Jessore	23.1833N	89.1667E
Chuadanga	23.6500N	88.8167E
Thunderstorm affected areas		
Village: Chhaglapara, Dhalnagar; Union: Chandpur; Upazila: Kumarkhali; District: Kushtia	23.3–23.6N	89.0–89.2E
Village: Moukuri and Patharbare; Union: Sharutia; Upazila: Shailkupa; District: Jhenaidah	23.5–23.7N	89.2–89.4E

The nearby meteorological station of BMD is Jessore situated at a distance of about 40 km south of the thunderstorm location; the station Chuadanga is located at a distance of around 30 km to the west and Ishurdi is 60 km to the north from the place of occurrence of the thunderstorm. The meteorological records between 2100 UTC of April 5, 2015, and 0000 UTC of April 6, 2015, at the nearest stations Jessore and Chuadanga showed that there was 00 mm rainfall in these stations and the wind was calm at Jessore and around 2 m s^{-1} at Chuadanga. At Ishurdi, 2 mm of rainfall was observed and the wind was calm. This indicates that the thunderstorm was a much localized one and its activity did not extend up to the nearby stations.

The sea level pressure chart of 0000 UTC derived from FNL gridded dataset (not shown here) demonstrates low pressure zone prevailed over Bihar and adjoining area extending its trough to western part of Bangladesh, while the seasonal low pressure zone passes over Odisha and extends up to the head Bay of Bengal. In the gradient level, the southwesterly wind blows over Bangladesh and northeastern India which advects moisture to the lands from the Bay of Bengal and provides favorable environment for thunderstorm activities. In the study, the following data are used for initializing the NWP model and interpreting the results:

1. Data from the National Centers for Environmental Prediction (NCEP) Final (FNL) Global Analyses at 1.0° × 1.0° grids for 0000 UTC are used for initialization of the model. The lateral boundary conditions (LBC) of the domain are updated at every 6 h interval using the NCEP FNL data.
2. Rawinsonde data and skew-T plot over Dhaka at 0000 UTC and 1200 UTC on April 5–6, 2015, were obtained from the University of Wyoming to study the instability parameters.
3. Satellite-derived precipitation data from Tropical Rainfall Measuring Mission (TRMM)-3B42RT are used for interpreting the model result.

3 Numerical model setup

The study uses the Advanced Research Weather Research and Forecasting (ARW) model version 3.7.1 (Skamarock et al. 2008) for simulating the selected case of thunderstorm. The ARW is a three-dimensional, fully compressible, non-hydrostatic model. The vertical coordinate is a terrain-following hydrostatic pressure coordinate and the model uses the Runge–Kutta third-order scheme for time integration of the prognostic equations. The domain configuration consists of a three-way nested domain with 18, 6 and 2 km horizontal resolutions for outermost, inner and innermost domains, respectively (Fig. 2), which is capable of capturing the mesoscale processes. Data from the NCEP 6 h FNL Global Analyses at 1.0° × 1.0° grids are used for initializing the model. The FNL data are also used for feeding the lateral boundary of the domain. The model uses the YSU PBL scheme and WSM6 microphysics scheme (Hong and Lim 2006) for simulation of the thunderstorm event following Das et al. (2015c, d) and Litta et al. (2011). The summary of the features and configurations of the WRF model used in the present study are given in Table 2. The model is run for 40 vertical levels with USGS envelop topography. In the

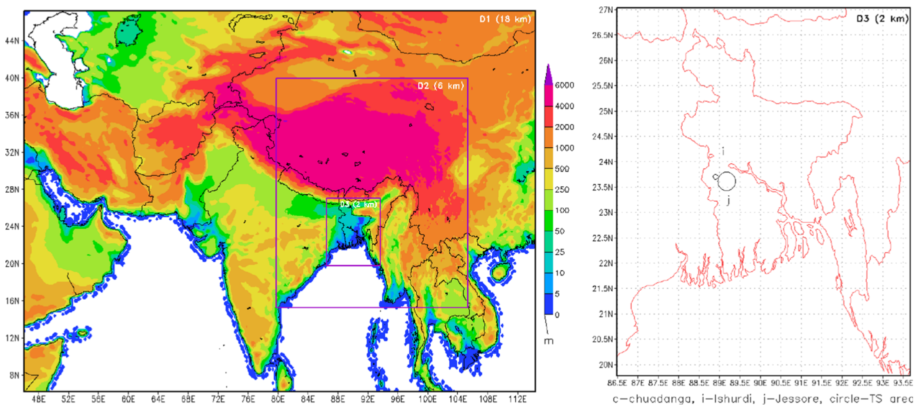

Fig. 2 Three-way nested WRF model domains with resolutions of 18, 6 and 2 km used for the study. The shade represents topography. The occurrence of thunderstorms locations (*circle*) and nearest meteorological observatories (*c*, *i*, *j*) showed in the right panel of the figure

Table 2 Summary of the WRF model

Model features	Configurations
Horizontal resolution	18, 6 and 2 km
Vertical levels	40
Topography	USGS
Dynamics	
Time integration	Semi-implicit
Time steps	100 s
Vertical differencing	Arakawa's energy conserving scheme
Time filtering	Robert's method
Horizontal diffusion	Second order over quasi-pressure, surface, scale selective
Physics	
Convection	Kain–Fritsch (Kain 2004) in domain 1 and 2 and no cumulus scheme in domain 3
PBL	YSU scheme
Cloud microphysics	WSM6 Hong and Lim (2006)
Surface layer	Monin-Obukhov
Radiation	LW (RRTM), SW (Dudhia)
Gravity wave drag	No
Land surface processes	Unified NOAH land surface model

model, the semi-implicit time integration with time step of 100 is used. The Arakawa staggered C grid is used for horizontal differencing. As a vertical differencing, Arakawa's Energy Conserving Scheme and the Robert's method for time filtering are used in the model. For taking care of sub-grid scale cumulus convection, Kain–Fritsch scheme is used in domains 1 and 2, and domain 3 is without cumulus scheme. The model is run for 24 h for the episode; the starting time of run is 0000 UTC of April 5, 2015. The model results are considered from the innermost domain for analyzing the desired meteorological characteristics (Das et al. 2015a).

4 Results and discussion

The model was run for 24 h with initial fields of 0000 UTC. According to the model, the thunderstorm was formed at around 1730 UTC over the area around 23.3°N–23.7°N and 89.0°E–89.4°E while in reality it occurred at about 2100 UTC over the same area. The model results show the formation at around 3.5 h earlier than the actual time of occurrence.

4.1 Statistical analysis of the meteorological parameters and justification of the domains

Some comparative statistical analyses of different parameters simulated by the model with the 3 hourly observed meteorological parameters at nearby stations are made for different domains and the results are given in Table 3. It is seen that the domain 3 results with horizontal resolution of 2 km are better than those in other two domains with lower resolutions of 18 and 6 km, respectively. The root mean square error (RMSE) of sea level pressure (SLP) at Chuadanga is 1.72 hPa for domain 3. The correlation coefficient of the model simulated SLP and observed SLP is 0.60 at Chuadanga in domain 3, the results for other domains are comparable with those for domain 3. It may be mentioned that at Chuadanga there is 00 mm rainfall. However, the results for domain 3 are used as the thunderstorm system was highly localized; and it is assumed that because of the high resolution of the innermost domain it has better simulated the local level dynamic and thermodynamic features of the thunderstorm.

Table 3 Statistical analysis of the meteorological parameters for the nearest BMD observatory Chuadanga

Statistical analysis	Meteorological parameters	Domain 1	Domain 2	Domain 3
Mean absolute error (MAE)	Sea level pressure (SLP)	1.38	1.32	1.30
	Relative humidity (RH)	16.44	16.42	16.72
	Rainfall	11.35	13.83	9.27
Root mean square error (RMSE)	SLP	1.80	1.74	1.72
	RH	18.51	18.45	18.66
	Rainfall	15.24	18.55	12.43
Correlation coefficient (CC)	SLP	0.60	0.60	0.60
	RH	0.82	0.81	0.83

4.2 The dynamic features

4.2.1 Sea level pressure, geopotential and temperature

Sea level pressure The sea level pressure (SLP) has been simulated over Bangladesh at half hourly interval on April 5, 2015, and its distribution is studied. The spatial distribution of SLP at 1430 and 1730 UTC are given in Fig. 3a, b as an example. It is found that there is always a low pressure system over West Bengal and adjoining Bangladesh with a strong trough extended across western Bangladesh with some diurnal variation in magnitude. Figure 3b shows that the sea level pressure is relatively lower over west-southwestern part of Bangladesh at 1730 UTC on April 5, 2015, having a micro-low of 1004 hPa near the place of occurrence of thunderstorm as indicated by a circle in the figure. This trough of low pressure with embedded micro-low is promising and responsible for the occurrence of the severe thunderstorm.

Geopotential The distribution of geopotential (Fig. 3c, d) shows that a low geopotential zone extends from West Bengal toward southwest Bangladesh with relatively minimum geopotential of 500 and 650 $m^2\ s^{-2}$ at 1000 hPa level at 1430 and 1730 UTC, respectively, near Kumarkhali and then it increases drastically showing very strong geopotential gradient from west to east.

Temperature The spatial distribution of model generated low-level temperature at 950 hPa level for 1430 and 1730 UTC are shown in Fig. 3e, f. The figures show that a warm zone is advancing from west toward the location of the thunderstorm and at 1730 UTC the cold and warm zones interfaced near that location with a temperature contrast of about 4 °C.

The above distribution of local scale thermal, geopotential in the lower level and the trough of low pressure including micro-low produce satisfactory conditions for formation of the thunderstorm.

4.2.2 Low-level horizontal wind and vertical velocity

Low-level horizontal wind The spatial distribution of the low-level wind vector at 950 hPa levels is shown in Fig. 4a, b for 1000 and 1730 UTC, respectively. From Fig. 4a, it is seen that the strong southerly wind blows from the Bay of Bengal that advects huge moisture to the land from the sea. Strong south-southwesterly winds blow to the area of Shailkupa and Kumarkhali where a strong east-northeasterly winds blow from the other side forming a local zone of convergence or discontinuity line at 1000 UTC (Karmakar 2005). This provides progressive environment for convection to take place. The low wind speed over this area is compensated by setting up of the vertical winds resulting to the updraft of the air parcels and causing cumulus convection. Figure 4b shows that a localized anticyclonic circulation has developed to the southern part of the same zone signifying that a downdraft is occurring at that time and a zone of convergence still prevails to the north of divergent zone. This signifies that the system is characterized by the evolution of local wind system. The appearance of low-level divergence in the southern part at 1730 UTC infers that the developed thunderstorm has reached to maturity stage when rainfall is supposed to take place.

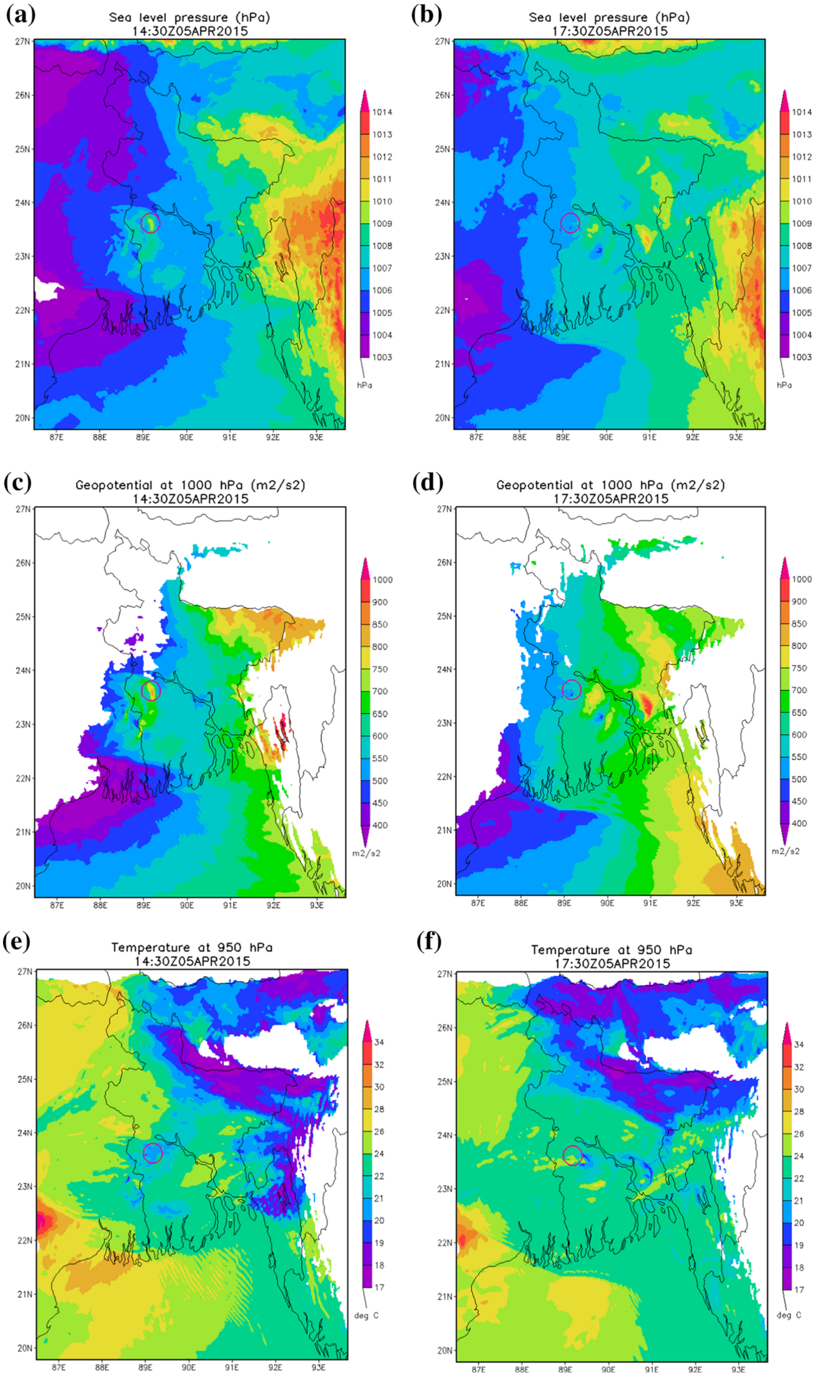

Fig. 3 **a**, **b** Model simulated SLP, **c**, **d** 1000 hPa geopotential and **e**, **f** 950 hPa temperature at 1430 and 1730 UTC on April 5, 2015

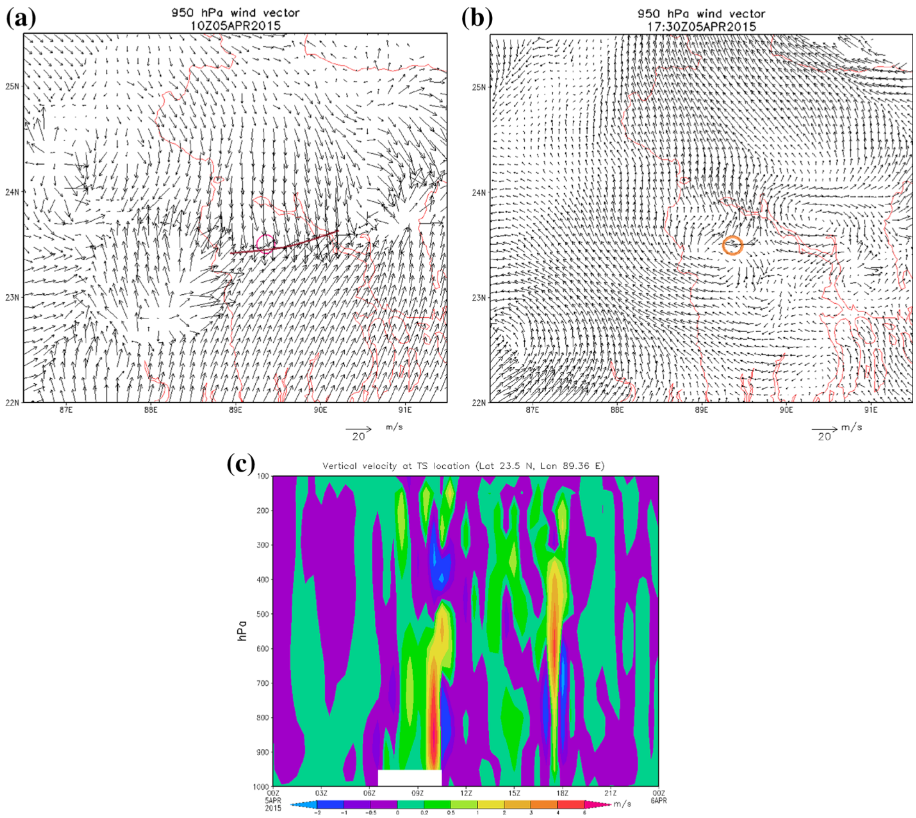

Fig. 4 **a**, **b** Model simulated wind vector at 950 hPa and *bold line* indicating discontinuity line and **c** time–pressure cross section of vertical velocity at the location of TS

Vertical velocity It is well recognized that the thunderstorms are formed due to convection caused by the updraft of lighter air parcel. The convection occurs through a life cycle—cumulus stage, mature stage and dissipating stage. In the cumulus stage, the updraft of air causes the convective cells to develop and in the other stages entrainment of air from the environment takes place. In the mature stage, the rain occurs and a large part of the cell has a downdraft which characterizes the rain area (Byers and Braham 1949). According to Byers and Braham (1949), the updraft continues in a portion of the cell in the low and intermediate levels and in all parts of the top levels, while in the dissipating stage, downdrafts take place all over the cell, although weak updraft is present in the upper parts.

Figure 4c shows the vertical time section of vertical velocity for near TS simulated location which depicts the evolution of the thunderstorms. It is seen that the whole tropospheric column experiences updrafts alternated by downdrafts until 1730 UTC when an organized narrow vertical zone of updraft is observed which extends vertically up to the 100 hPa level, characterizing the cumulus convective stage of the thunderstorm. The vertical upwards wind is found to have speed varying from 0.2 to 6.7 m s^{-1}, vertical velocity being maximum at 1030 UTC from 950 to 480 hPa and at 1730 UTC from 960 to 200 hPa. During the period 1800–1900 UTC, a downdraft is observed from lower to upper level and updraft above, which characterizes the mature stage. From 1930 to 2000 UTC, a shallow downdraft occurs in the lower level extending up to a height of 900 hPa, while the updraft prevails in the layer between 900 and 100 hPa level and then downdraft is found to begin extending from surface to about 650 hPa overlain by updrafts upwards. This situation may be considered as the beginning of the dissipation stage. Thereafter, the whole column is characterized by downdraft up to 250 hPa level beyond which weak updraft is observed. The model results describe well the findings of the classical work of Byers and Braham (1949).

4.2.3 Vorticity and divergence

The geographic distribution of the vorticity at 1430 and 1730 UTC are shown in Fig. 5a, b. It is found that positive vorticity dominates over the thunderstorm area at both 1430 UTC and 1730 UTC, the vorticity being of the order of $150 \times 10^{-5}\ s^{-1}$. The similar characteristics are observed in case of the distribution of divergence for the same levels. At 1430 UTC, the thunderstorm area is covered by dominant convergence over the place of occurrence and is surrounded by divergence (Fig. 5c) and the same is found to dominate at 1730 UTC which matches with the interpretation of the horizontal wind distribution and evolution of the vertical wind fields. The convergence is found to be of the order of -10 to $-20 \times 10^{-4}\ s^{-1}$ at 1730 UTC (Fig. 5d).

4.3 Thermodynamic features

4.3.1 Low-level relative humidity (RH), cloud water mixing ratio and ice water mixing ratio

Relative humidity (RH) The distributions of relative humidity (RH, %) at 950 hPa level at 1000 and 1730 UTC are shown in Fig. 6a, b. Figure 6a shows a southwest–northeast-oriented strip of high RH across the place of occurrence with dry zones in south and north at 1000 UTC. At 1730 UTC, it is seen that the RH has substantially decreased leaving a narrow wet zone with dry zones to its north and south (Fig. 6b). This situation is very conducive for a strong thunderstorm formation. The concentration of high RH follows the patterns of wind distribution and the zone of wind convergence (Fig. 4a, b). The area of the selected thunderstorm is covered by a small patch of relatively high humidity, which is advected by the southwesterly flow (Fig. 4a). The surrounding areas to the north, east and west appears to be dry. Such situation with highly localized concentration of high RH provides strong atmospheric instability that favors the cumulus convective processes leading to severe thunderstorm. According to Karmakar and Quadir (2014), the mixing ratio >16–$22.4\ g\ kg^{-1}$ and RH $> 85\%$ in the morning time favors the TS formation in the late hours of the day over Bangladesh and surrounding territories of India.

Cloud water mixing ratio and ice water mixing ratio The vertical time section of the cloud water mixing ratio and ice water mixing ratio for the area of the thunderstorm are shown in Fig. 6c, d. According to this distribution, the cloud water mixing ratio extends over the vertical domain and its depth gradually increases with maximum depth of 400 hPa at 1400–1530 UTC and extends from 800–250 hPa at about 1730 UTC with maximum value of cloud water mixing ratio of $1140\ mg\ m^{-3}$ between 700 and 600 hPa (Fig. 6c). The cloud water is fully diminished after 1800 UTC. This infers that the activities of this thunderstorm cell have the life cycle of around 5 h. The height time section of the ice water

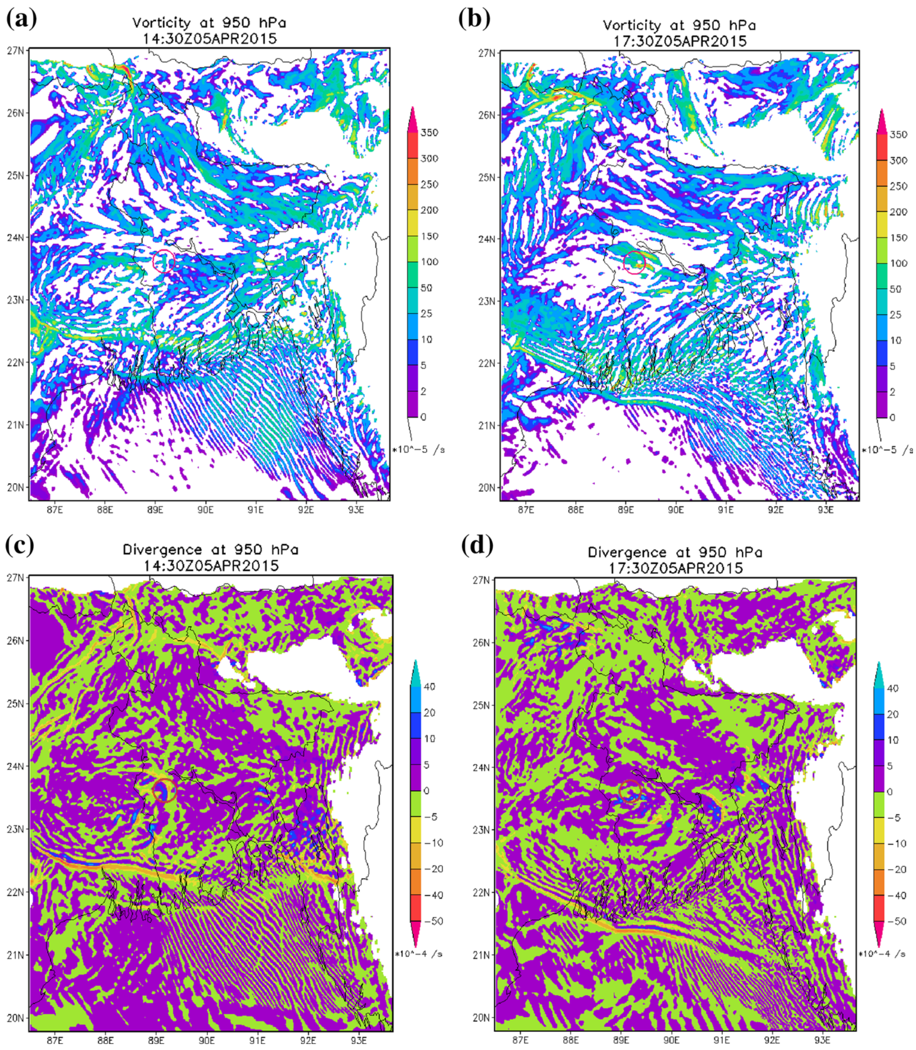

Fig. 5 Model simulated 950 hPa **a**, **b** vorticity and **c**, **b** divergence at 1430 and 1730 UTC on April 5, 2015

mixing ratio is shown in Fig. 6d for the same location. The distribution of ice water column at different times from 1030 to 1830 UTC indicates 3 episodes of high ice concentration indicating the same number of heavy showers of hails. The figure reveals that the vertical distribution of the ice water mixing ratio higher than 140 mg kg^{-1} extends from 580 to 250 hPa. Very high values of mixing ratio in the range 30–158 mg kg^{-1} are seen at different heights varying from 650 to 200 hPa. Figure 6c, d depicts that the base of the cloud water mixing ratio starts at around 800 hPa at its highest development and the top extends to 250 hPa, while the base of the ice water distribution is at around 650 hPa and the top exceeds 200 hPa level at 1730 UTC.

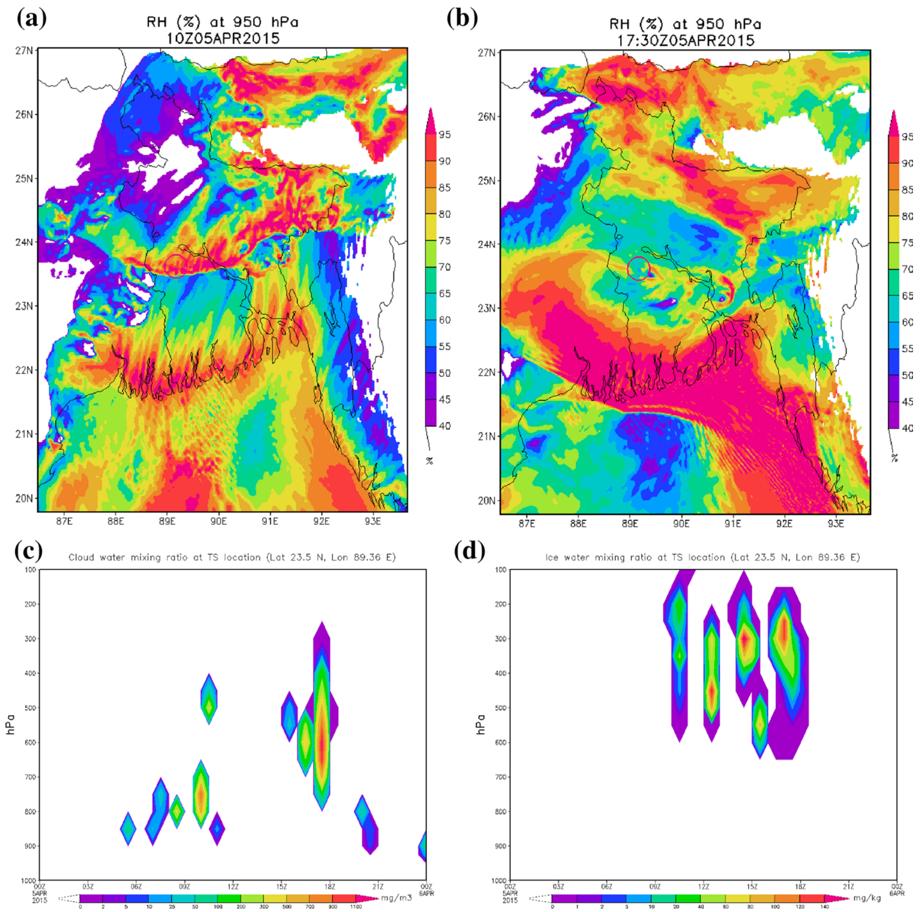

Fig. 6 **a**, **b** Model simulated 950 hPa RH at 1000 and 1730 UTC, **c** time–pressure cross section of cloud water at the location of TS and **d** same as (**c**) but for ice water mixing ratio

4.3.2 Precipitation and reflectivity

Precipitation The 3 h accumulated precipitation from 1500 to 1800 UTC as obtained from the model is shown in Fig. 7a, which shows that the model has generated rainfall over an east–west-oriented area representing the thunderstorm event. It shows about 26 mm rainfall near the place of occurrence of the thunderstorm. Rainfall has also occurred over central and eastern parts of the country, indicating that the model has captured the rain well. The 3 h composite rainfall for 2100 UTC on April 5, 2015—0000 UTC on April 6, 2015, as obtained from TRMM shows that the rainfall occurred over the eastern part of the area of the thunderstorm. There is a difference of about 3.5 h between the times of simulated thunderstorm and the one which actually happened, the former being preceded (Fig. 7b). This figure shows the rainfall over the area east of the place of occurrence of the thunderstorm event and the whole eastern Bangladesh with an amount of 22–46 mm.

Reflectivity The radar reflectivity from the Kolkata Doppler Weather Radar (DWR) station is shown in Fig. 7c, d, which indicates that the radar reflectance for the

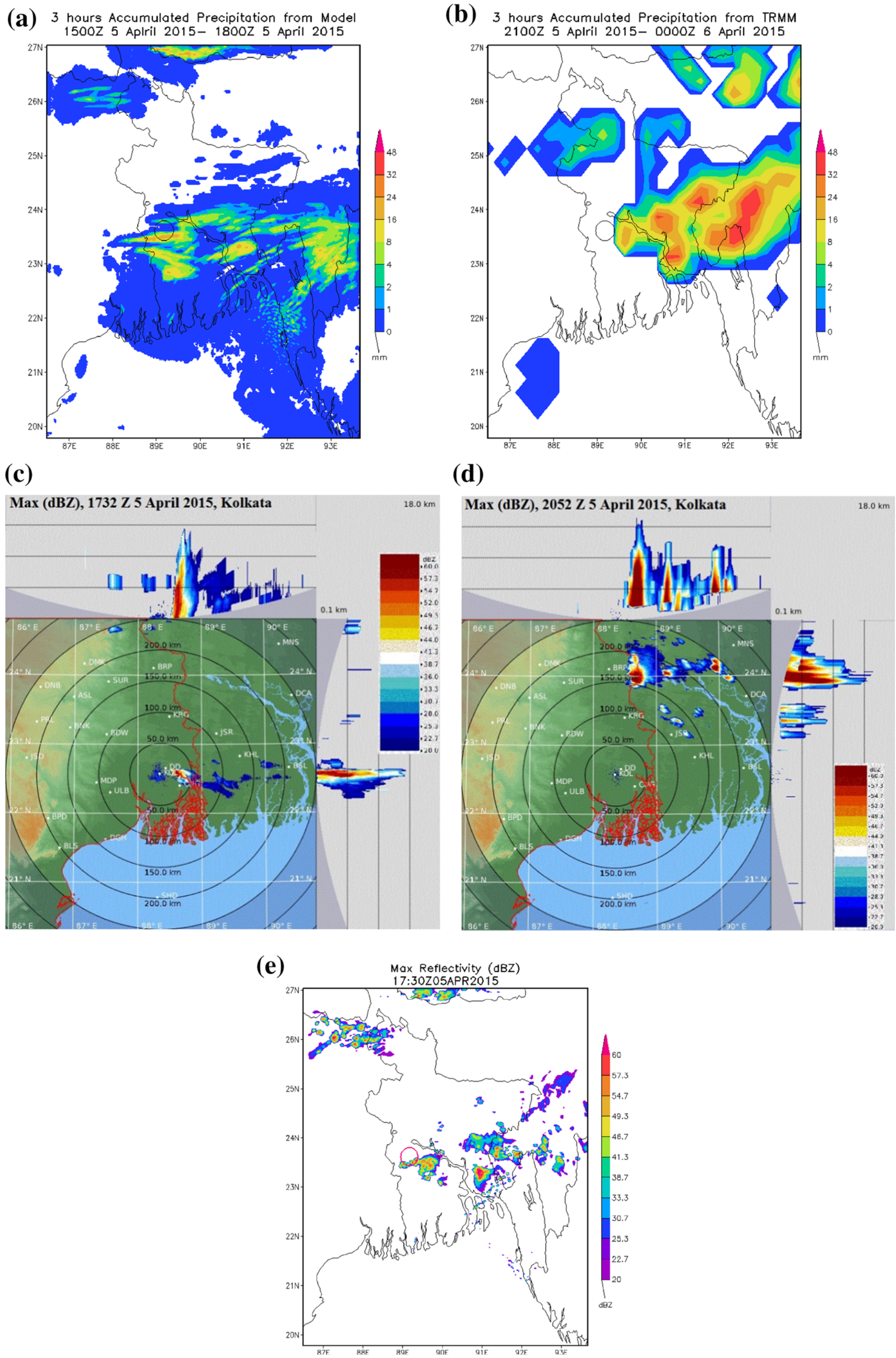

Fig. 7 **a** Model simulated 3 hourly accumulated rainfall during 1500–1800 UTC on April 5, 2015, **b** TRMM retrieved 3 hourly rainfall during 2100 UTC of April 5, 2015, to 0000 UTC of April 6, 2015, **c**, **d** Kolkata DWR-derived reflectivity and **e** model simulated reflectivity

thunderstorm is of the same magnitude as that simulated by the model (Fig. 7e). The reflectivity of hydrometeor in the atmosphere has been simulated at different synoptic hours on April 5, 2015. Analysis has shown that the reflectivity becomes maximum and distinct at 1730 UTC on April 5, 2015, over the place of occurrence as shown in Fig. 7e. The value of reflectivity is more than 60 dBZ, which indicates severe convection and heavy precipitation. Kolkata DWR reflectivity at 1732 UTC shows that the convection persisted over the area covering Kolkata and nearby region (Fig. 7c). The radar observation at Kolkata at 2052 UTC confirms the reflectivity of 60 dBZ as shown in Fig. 7d at the place of occurrence of the thunderstorm. The reflectivity of 60 dBZ is equivalent to rainfall rate of 205 mm h^{-1} according to the Marshall–Palmer formula (1948):

$$R(\text{mm/h}) = \left(\frac{10^{(\text{dBZ}/10)}}{200}\right)^{\frac{5}{8}}$$

It may be mentioned that the reflectivity of hydrometeor is maximum over the area of simulated maximum rainfall.

4.3.3 Thermodynamic charts and convective available potential energy (CAPE)

Thermodynamic charts Different instability parameters are computed from the thermodynamic chart prepared from rawinsonde data over Dhaka and the results are given in Table 4. At 0000 UTC on April 5, 2015, 8 instability parameters out of 9 at Dhaka were found to be favorable for convection to occur. However, the CAPE was unfavorable for convection. The Showalter Index (SI), Cross Total Index (CTI), Vertical Total Index (VTI), Totals–Totals Index (TTI) and SWEAT Index (SWI) were favorable for the occurrence of severe thunderstorms as per the criteria developed by Karmakar and Alam (2006, 2007a, b, 2011), and Tyagi et al. (2011b). At 1200 UTC, instability of the troposphere was found to have been slightly reduced, which might be due to the occurrence of thunderstorm in between 0000 and 1200 UTC. CAPE started increasing with the progress of the day up to 0000 UTC on April 6, 2015, and CIN became more favorable at 1200

Table 4 Observed instability parameters and precipitable water over Dhaka on April 5–6, 2015

Parameters	April 5, 2015		April 6, 2015	
	0000 UTC	1200 UTC	0000 UTC	1200 UTC
Showalter Index	−3.01	0.46	−3.09	3.24
Lifted Index	1.62	−1.47	−5.28	0.74
SWEAT Index	421.81	391.28	270.60	185.98
K Index	35.10	30.81	40.90	29.50
Cross Total Index	23.90	20.20	24.30	17.50
Vertical Total Index	26.90	24.30	25.10	23.50
Totals–Totals Index	50.80	44.50	49.40	41.00
CAPE (J kg^{-1})	00	311.09	2172.44	00
CIN (J kg^{-1})	00	−94.34	−26.16	00
Lifted condensation level	900.72 hPa	918.05 hPa	955.42 hPa	871.23 hPa
Precipitable water (mm)	39.86	47.52	58.39	39.89

UTC. The values of Lifted Condensation Level (LCL) are 900.72, 918.05 and 955.42 hPa at 0000 UTC, 1200 UTC on 5 April and 0000 UTC on April 6, 2015, respectively, indicating descending of LCL with the progress of time. The precipitable water content of the troposphere is found to increase from 0000 UTC on 5 April to 0000 UTC on April 6, 2015, and this indicates that there has been more influx of precipitable water in the troposphere.

The WRF model simulated different instability parameters and precipitable water on April 5, 2015, are given in Table 5. The table indicates that the instability parameters at 1730 UTC at the model predicted location of convection significantly favors the occurrence of thunderstorms on April 5, 2015. There was adequate precipitable water, i.e., 45.1 mm at the location for initiating the convective activity.

Skew diagrams are prepared with the help of NCEP FNL reanalysis data and WRF model results for 0600 UTC over the place of occurrence of the thunderstorm and are shown in Fig. 8a, b, respectively. Figure 8a shows a large positive area from 770 hPa level to about 185 hPa level. This positive area is proportional to the CAPE and indicates a significant instability of the troposphere, which is favorable for the occurrence of a thunderstorm. The model simulated diagram (Fig. 8b) also shows a large positive area from 820 to 175 hPa levels and the negative area is considerably smaller than the positive area, indicating unstable condition at 0600 UTC. As a result, the instability parameters as well as other parameters as indicated in the both side of the diagrams are larger in the diagram prepared from FNL data and WRF model (Fig. 8a, b). The LCL is about 830 hPa in Fig. 8a and 845 hPa in Fig. 8b; the value 845 hPa is of slightly lower height (i.e., descending of LCL) and is more favorable for thunderstorm to occur. LI of −10 and CAPE of 3096 J kg^{-1} indicate highly unstable troposphere as shown in Fig. 8b.

Convective available potential energy (CAPE) The WRF model has simulated CAPE at different times and the spatial distributions of CAPE over Bangladesh and adjoining areas are shown in Fig. 8c. At 0800 UTC, the value of CAPE is ≥3000 J kg^{-1} and at 1730 it is about 1600 J kg^{-1} near the place of occurrence (Fig. 8c, e). CAPE is found to be less than 500 J kg^{-1} at 1430 UTC (Fig. 8d), which may be attributed to the occurrence of rain when

Table 5 Model simulated different instability parameters and precipitable water at the model predicted location of convection at 1730 UTC on April 5, 2015

Parameters	Model simulated values	Threshold value
Showalter Index	–	≤−3 °C (Karmakar and Alam 2006)
Lifted Index	−1	≤0 °C (Karmakar and Alam 2006)
SWEAT Index	–	≥200 (Karmakar and Alam 2006)
K Index	41	≥34 °C (Karmakar and Alam 2006)
Cross Total Index	–	≥16 °C (Karmakar and Alam 2006)
Vertical Total Index	–	≥24 °C (Karmakar and Alam 2006)
Totals–Totals Index	51	≥40 °C (Karmakar and Alam 2006)
CAPE (J kg^{-1})	1527	>1000 J kg^{-1} (Tyagi et al. 2011b)
CIN (J kg^{-1})	1	–
Lifted condensation level	975 hPa	<880 hPa (Das et al. 2015a)
Precipitable water (mm)	45.1	–

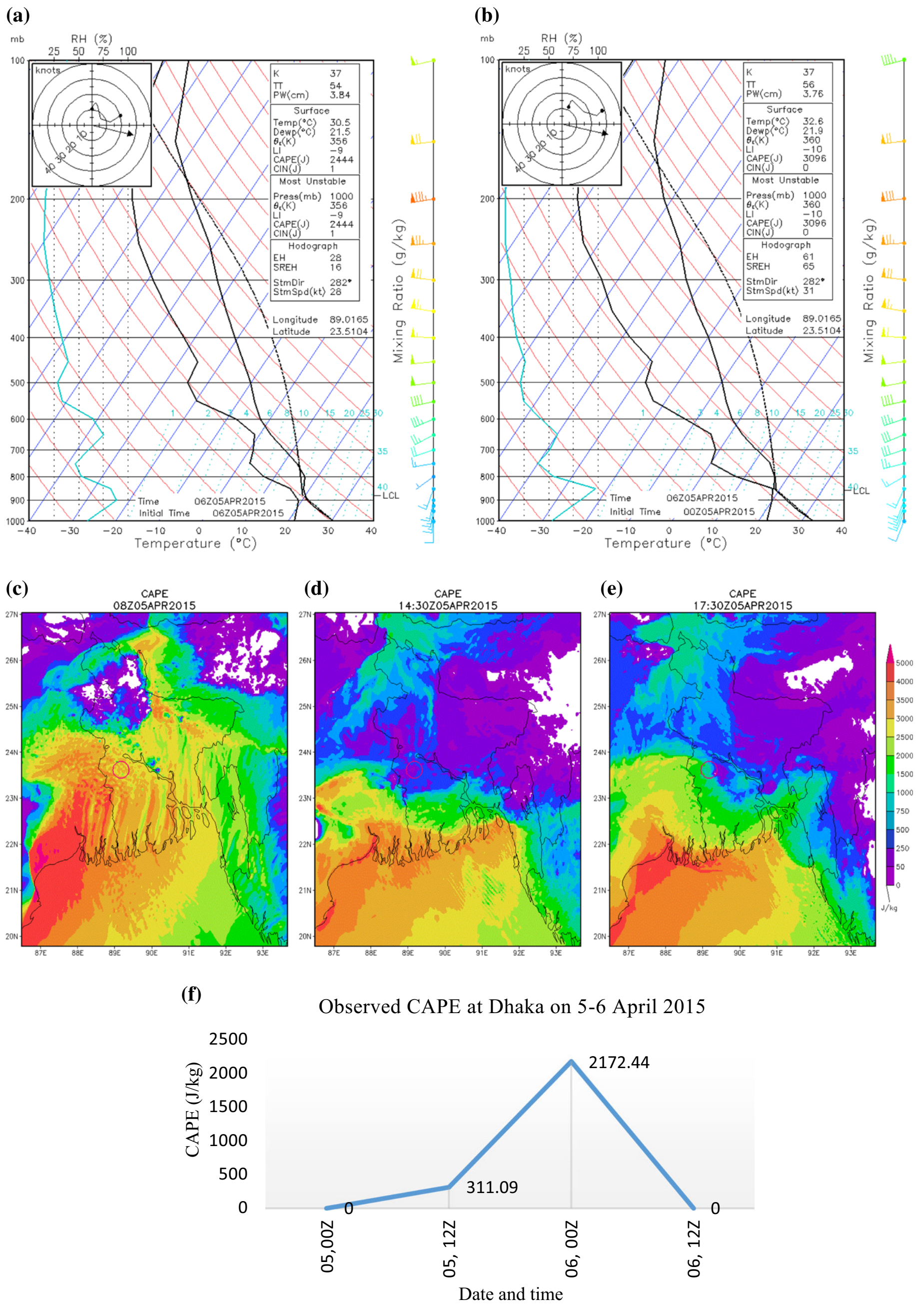

Fig. 8 Skew-T plot **a** from NCEP FNL data, **b** from model at 0600 UTC, **c**–**e** spatial distribution of model simulated CAPE on April 5, 2015, and **f** interpolation of observed CAPE at Dhaka

energy is dissipated, and again CAPE is built up at 1730 UTC causing the thunderstorm to occur.

Observed value of CAPE at 0000 UTC on April 5, 2015, is 0 which is at Dhaka. Dhaka is nearly 200–250 km east from the location of thunderstorm occurrence. This is the only upper air observation which we have. But if the CAPE values obtained from the thermodynamic diagram at Dhaka are plotted on a graph and the result is interpolated, the CAPE value at 2100 UTC becomes about 1700 J kg^{-1} (Fig. 8f), which is nearer the model simulated value.

5 Conclusions

On the basis of the present study, the following conclusions can be drawn:

1. The model simulated results provide a basis to study the microphysical and dynamical characteristics of the thunderstorms, which generally not available in the data from meteorological stations. The model has captured almost all the characteristics of the severe thunderstorm of April 5, 2015, which was generated at around 1730 UTC. The model produced the thunderstorm which apparently formed at around 1730 UTC, i.e., almost 3.5 h earlier than it actually happened.
2. The model results show that a low pressure zone prevails over Bihar and adjoining area extending its trough to western part of Bangladesh. The model simulated a micro-low near the place of occurrence of the thunderstorm, which is advantageous for the occurrence of the severe thunderstorm.
3. The model simulated strong south-southwesterly winds blowing to the area of Shailkupa and Kumarkhali and strong east-northeasterly winds blowing from the other side formed a local zone of convergence, which provides a favorable condition for the formation of the thunderstorm.
4. The simulated vertical upward motion is found to have speed varying from 0.2 to 6.7 m s^{-1} on April 5, 2015, having strong updrafts at 1030 UTC from 950 to 480 hPa and at 1730 UTC form 960 to 200 hPa. The simulated vorticity and convergence (divergence) are found to match with distribution and evolution of vertical wind fields.
5. The simulated relative humidity distribution shows high moisture flux to the area of interest prior to and during the occurrence of thunderstorm.
6. The cloud water mixing ratio extends over 800–250 hPa at 1730 UTC with maximum value of 1140 mg m^{-3} at 700–600 hPa near the place of occurrence of the thunderstorm. The distribution of ice water column at different times from 1030 to 1730 UTC indicates 3 episodes of high ice concentration within the vertical column 700–200 hPa which infers the presence of high concentration of hails in the vertical column. The strongest column extends from 650 to 200 hPa at 1730 UTC.
7. The model has well captured the rain and reflectivity of hydrometeor close to the place of occurrence of the event. The value of reflectivity is found to be more than 60 dBZ both in the model result and observation at Kolkata DWR, indicating severe convection and heavy precipitation. The model results show 26 mm of rain over the same area where the reflectivity of hydrometeor is maximum.
8. The instability parameters obtained from rawinsonde observation at Dhaka at 0000 UTC indicated favorable condition in the morning on April 5, 2015, which reduced slightly at 1200 UTC. The positive area in the Skew-T diagram constructed from NCEP FNL data is found to extend from 770 to 185 hPa which demonstrated a CAPE of 2444 J kg^{-1}. The simulated CAPE is found to be about 1600 J kg^{-1} at 1730 UTC near the place of occurrence of the thunderstorm. The precipitable water content of the

troposphere is found to be 37.6–38.4 mm in case of both FNL data and model simulation.

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