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Simulation of a Hailstorm Event over Bangladesh using WRF Model

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ABSTRACT

An attempt is made to simulate a pre-monsoon hailstorm event over Bangladesh using the high-resolution Weather Research and Forecasting (WRF) model. A severe hailstorm event embedded with multi-cell thunderstorm occurred over the North-central region of Bangladesh and adjacent West Bengal state of India on 30 March 2018, which moved towards the South-East direction up to its highest intensity stage during 0900-1030 UTC is selected for the study. The WRF model is used to investigate the dynamical and thermo-dynamical characteristics of the selected hail producing thunderstorm event. The model is run on a double nested domain at 9 and 3 km horizontal resolutions using the Kain-Fritsch (new Eta) cumulus and Mellor-Yamada Nakanishi and Niino Level 2.5 (MYNN2) planetary boundary layer parameterization schemes. The analysis of the accumulated hail, mean sea level pressure, vertical wind shear, vertical (w) component of wind, relative humidity along with low level wind, convective available potential energy (CAPE) and convective inhibition energy (CINE), rainfall (mm) parameters are investigated. Rainfall is compared with that of observed value. The high amount of relative humidity (>90%), CAPE (>3000 JKg^{-1}) and vertical wind shear (>40 ms^{-1}) help to form severe convective storm which vertically developed upto 150 hPa level. In addition, the high value of w component of winds (~0.4 ms^{-1}) helps updraft process which is favorable for hail formation. The present combination of parameterization schemes of model is found suitable to capture the selected hailstorm event reasonably well, but more similar hailstorm events need to be studied to make any final conclusions.

Introduction

Bangladesh experiences a good number of hailstorm events embedded within thunderstorms during the pre-monsoon season. Hailstorms are the severe thunderstorms with the occurrences of hails which develop due to intense localized convection and are characterized by gusty wind (61-150 kmh^{-1}) with spatial scale varying from a few kilometers to a few hundred kilometers with life span of less than 1 hour, but multi-cell storms developed due to organized intense convection may have life span of around several hours travelling over a few hundreds of kilometers (Saha and Quadir, 2016). Hailstorm significantly impacts on the lives and livelihood of the people through casualties and often extensive property damage. Globally, the most intense hailstorms have been documented in the United States, Argentina, Bangladesh and central Africa (Cecil and Blankenship, 2012; Karmaker et al., 2016).

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Several hailstorms are reported on 30 March 2018 of which the hailstorm event occurred over Northern parts of the country during 0600 UTC to 1500 UTC on 30 March 2018 is selected for this study. The selected hailstorm event embedded with multi-cell thunderstorms over the North-central and North-East regions of Bangladesh and nearby territory of India.

This particular case of hailstorms embedded with multi-cell thunderstorm occurred over the North-central region of Bangladesh on 30 March 2018 is selected to conduct the present study using ARW dynamics of WRF model, version 4.0. Application of numerical model in the study of hailstorms is few in Bangladesh. But some works related to thunderstorms occurred over Bangladesh are conducted using the FSU, MM5 and WRF models by many researchers.

Prasad (2006) investigated the environment and synoptic conditions associated with Nor'westers and Tornadoes in Bangladesh using Numerical Weather Prediction (NWP) guidance products mainly derived from FSU model. Akter and Islam (2007) tried to use of MM5 model for weather forecasting related to

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thunderstorms over Bangladesh region and they (Akter and Islam, 2009) further attempted to employ the MM5 model in simulation of MCSs developed in and around Bangladesh. Ahasan et al., (2014) attempted to simulate of a thunderstorm event over Bangladesh using WRF-ARW model and Ahasan et al., (2015) studied the impact of data assimilation in simulation of thunderstorm (Squall line) event over Bangladesh using WRF model, during SAARC STORM Pilot Field Experiment 2011. Das (2010) studied the climatology of thunderstorms over the SAARC region and Das et al., (2015) studied the composite characteristics of Nor'westers based on observations and model simulations. The composite characteristics of Nor'westers based on model simulation and observation has also been studied during SAARC STORM Pilot Field Experiment 2010 (SAARC-STORM, 2011) and SAARC STORM Pilot Field Experiment 2013 (SAARC-STORM, 2013). Most of the above studies are carried out using FSU and MM5 model which are not using by the meteorological community now-a-days. However, though some of the above the works are carried out using WRF model, most of them are related to thunderstorms. But the present study will be highlighted on hailstorms only. Thus, the present study on the numerical simulation of the hailstorm event occurred on 30 March 2018 over the North-central part of Bangladesh using WRF model is very significant. The primary objective of the study is the numerical simulation of the selected hailstorm event occurred over the North-central part of Bangladesh using WRF model. Another objective is to identify and document the favorable dynamical and thermo-dynamical conditions of the selected hailstorm event.

Data Used and Methodology

Data used to run the WRF model and validation of model output, Case description, Model setup and Methodology are described in the following section:

Data

The United States Geological Survey (USGS) Global datasets with 30 sec horizontal resolutions are used to create terrain/topography and vegetation/land-use field. The NCEP-FNL Global Data Assimilation System (GDAS) data with 1°×1° horizontal and 6 hours temporal resolution are used as the initial and lateral boundary condition.

The daily observed rainfall data is collected from Bangladesh Meteorological Department (BMD) to compare or validate the model derived rainfall. The TRMM Multisatellite Precipitation Analysis (TMPA) with 3-hr temporal resolution and 0.25°×0.25° spatial resolution data are also used for validation of model simulated rainfall. The cloud image collected from INSAT meteorological satellite is also used to observe the signature of the storm activities.

Case Description

As observed in INSAT 3D satellite images, the thunderstorm started to develop at 0000 UTC, 30 March 2018 with three small cumulus clouds over the nearby West Bengal region of India to the North-Western part of Bangladesh which made remarkable development with the progress of time and moved towards the South-East direction. As observed in the INSAT 3D satellite images, the thunderstorms had 3 distinct cells at 1000 UTC of which 2 cells have the width of over 100 km each and the third one had the width of over 50 km. The highest intensity of the thunderstorm cells are observed at 1000 UTC. As reported in the newspaper, the hailstorm coupled with rain and gusty winds damages crops and houses, and at least six peoples are died in different regions of Bangladesh. The INSAT-3D meteorological satellite cloud image at 1000 UTC of 30 March 2018 is shown in Figure 1. A very well-defined hail producing multi-cell convective storm/ thunderstorm over the North-central part of Bangladesh is clearly observed in the cloud image at 1000 UTC on 30 March 2018.

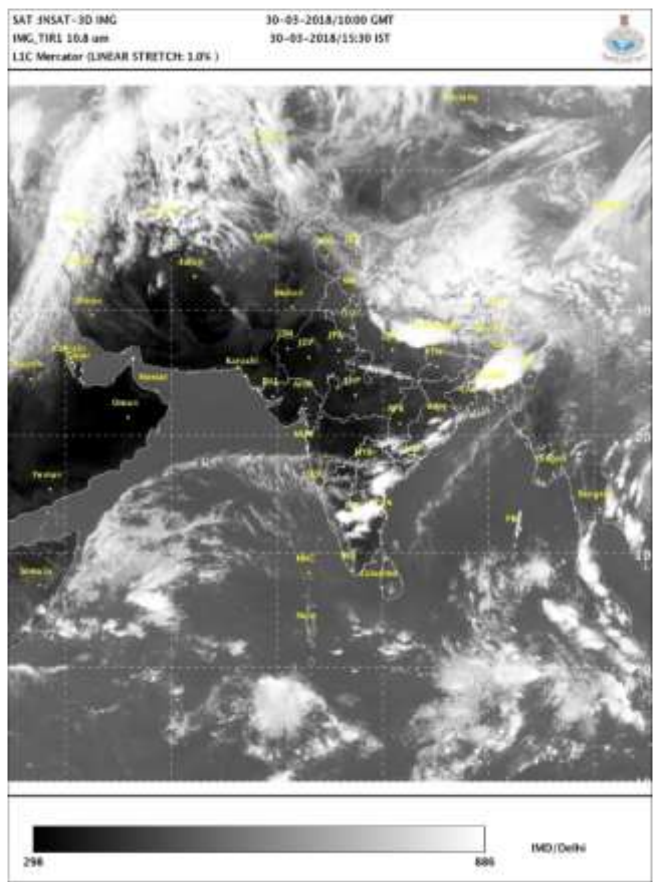

Figure 1: The INSAT-3D meteorological satellite cloud image at 1000 UTC of 30 March 2018

Table 1: Bangladesh Meteorological Department (BMD) observed 24-hr accumulated rainfall, wind speed and direction on 30 March 2018

Station Name	Type	Wind Speed (kph)	Wind Direction	Time (UTC)	Rainfall (mm)
Sylhet	Squall	78	Westerly	0950-1020	23
Mymensingh	Squall	59	Northwesterly	0950-1020	10
Mymensingh	Squall	59	Easterly	2230-2300	10

Model Setup and Methodology

The ARW dynamics solver of the WRF model (here-in-after WRF-ARW) is used in this study (Skamarock, 2008). The model is run on a double nested domain at 9 and 3 km horizontal resolutions suing the Kain-Fritsch (new Eta) cumulus (Kain, 2004) and Mellor-Yamada Nakanishi and Niino Level 2.5 (MYNN2) planetary boundary layer parameterization schemes (Mellor and Yamada, 1974). Figure 2 shows the model experiment setup with double nested domain for present study. Others schemes are used in this study are the Milbrant 2-moment for separate categories of hail and graupel with double-moment cloud, rain, ice, snow, graupel and hail for cloud microphysics (Milbrandt and Yau, 2005), Rapid Radiative Transfer Model (RRTM) for long wave (Mlawer et al., 1997) and Dudhia for short wave radiation scheme (Dudhia, 1989) etc. The above combination of cumulus and planetary boundary layer parameterization schemes along with other physics and dynamics of WRF model is found suitable in hailstorm study (Sultana, 2021). The physics and dynamics used in this study are presented in Table-1. The model is run for 24 hours using the initial and lateral boundary condition at 0000 UTC of 30 March 2018.

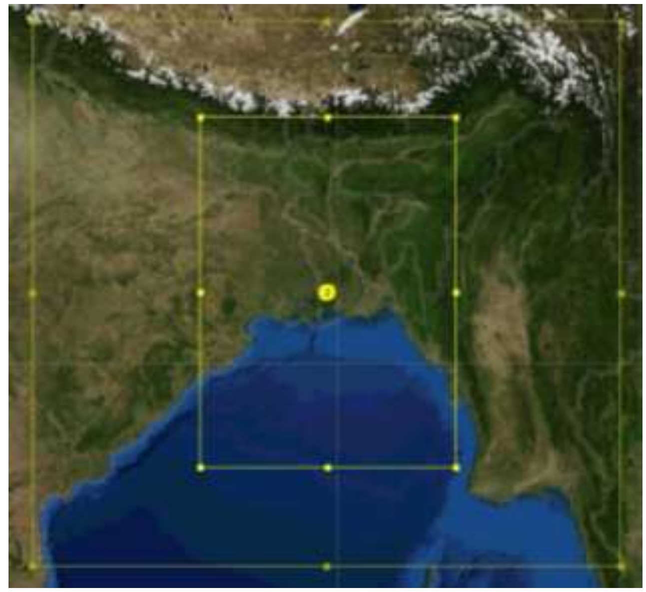

Figure 2: Nested domain for NWP study

The accumulated hail, mean sea level pressure, vertical wind shear of the u component of wind, w component of wind, relative humidity along with low level wind, CAPE and CINE and rainfall are analyzed. The model simulated above parameters are investigated to study the selected case and model simulated rainfall is compared with that of BMD observed and TRMM estimated.

The selected severe hailstorm event embedded with multi-cell thunderstorms occurred over the North, North-West part of Bangladesh and nearby territory of India on 30 March 2018 which moved towards the South-East direction with its highest development during 0900-1030 UTC. Thus, the model simulated and derived meteorological parameters at 1000 UTC are used in this study to explain the synoptic conditions favorable for formation of the selected hailstorm over Bangladesh.

Table 2: The physics and dynamics used in this study

Physics	
Cumulus scheme	Kain-Fritsch (new Eta) (Kain, 2004)
Planetary Boundary Layer	Mellor-Yamada Nakanishi and Niino Level 2.5 (MYNN2) (Mellor and Yamada, 1974)
Surface Layer Option	Monin-Obukhov sheme
Microphysics	Milbrant 2-moment (Milbrandt and Yau, 2005)
Radiation	Rapid Radiative Transfer Model (RRTM) for long wave (Mlawer et al., 1997) and Dudhia for short wave radiation scheme (Dudhia, 1989)
Land Surface Processes	Unified Noah Land Surface Model
Dynamics	
Time Integration	3rd order Runge-Kutta
Vertical Differencing	Arakawa's Energy Conserving Scheme
Time Filtering	Robert's Method
Horizontal Diffusion	2nd order over Quasi-pressure, surface, scale selective
Spatial difference scheme	6th order centered difference
Horizontal grid	Arakawa C-grid

Results and Discussion

The model simulated parameters of the hailstorm are well analyzed and discussed in the following section:

Accumulated Hail

Model simulated accumulated hail (mm) for the inner domain during 0700~1400 UTC on 30 March 2018 is shown in Figure 3. It is observed that model is capable of capturing the accumulated hail for the study area of Bangladesh. But model fairly underestimates the amount of accumulated hail. Model simulates the accumulated hail in the order of 1-2 mm.

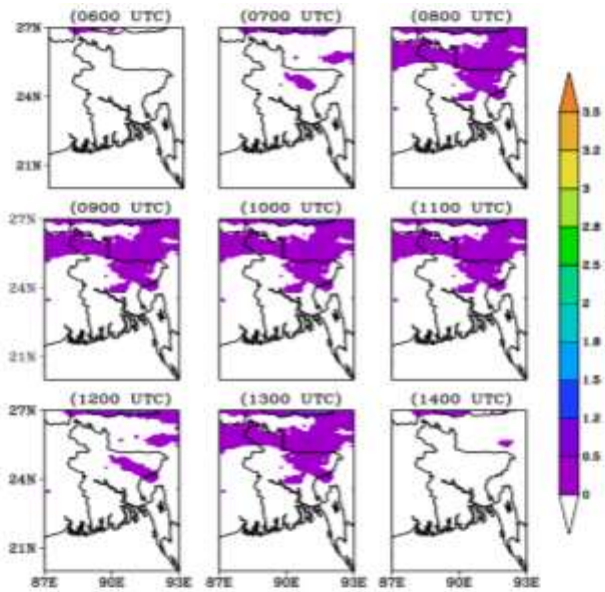

Figure 3: Model simulated accumulated hail (mm/hour) for the inner domain during 0600 UTC to 1400 UTC on 30 March 2018

Mean Sea Level Pressure

Model simulated mean sea level pressure (hPa) at (a) 0600 UTC, (b) 0900 hPa, (c) 1200 UTC and (d) 1500 UTC of 30 March 2018 are shown in Figure 4(a-d). In the figures, a trough of low pressure, with the core of lowest pressure in the order on 1006-1008 hPa, is found to be extended along the Gangetic plain of the West Bengal of India to Bangladesh. This situation is one of the favorable conditions for genesis and progress of a hailstorm producing thunderstorm over Bangladesh (Prasad, 2006). Thus, the formation of a low pressure over the Gangetic plain of West Bengal of India and intrude towards Bangladesh through the middle of the country is the prerequisite for genesis of thunderstorm activities which leads to produce hails (Prasad, 2006).

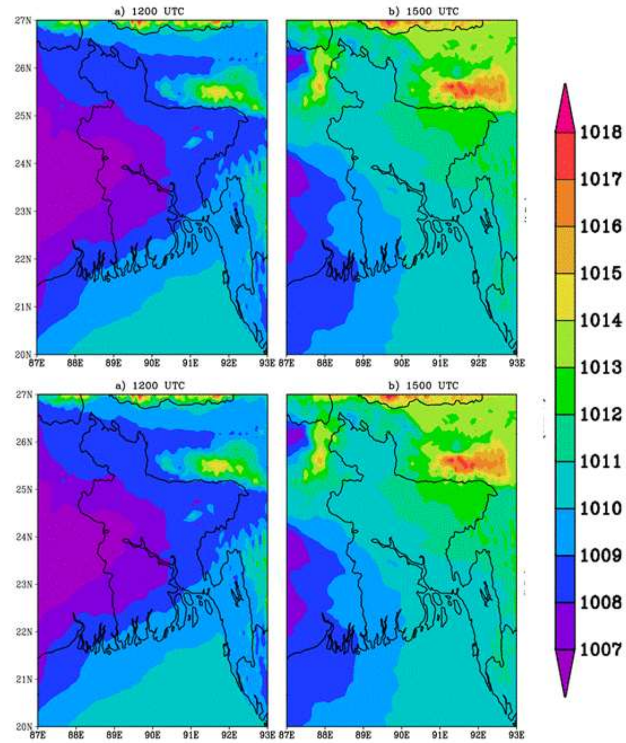

Figure 4(a-d): Model simulated mean sea level pressure (hPa) at (a) 0600 UTC, (b) 0900 hPa, (c) 1200 UTC and (d) 1500 UTC of 30 March 2018

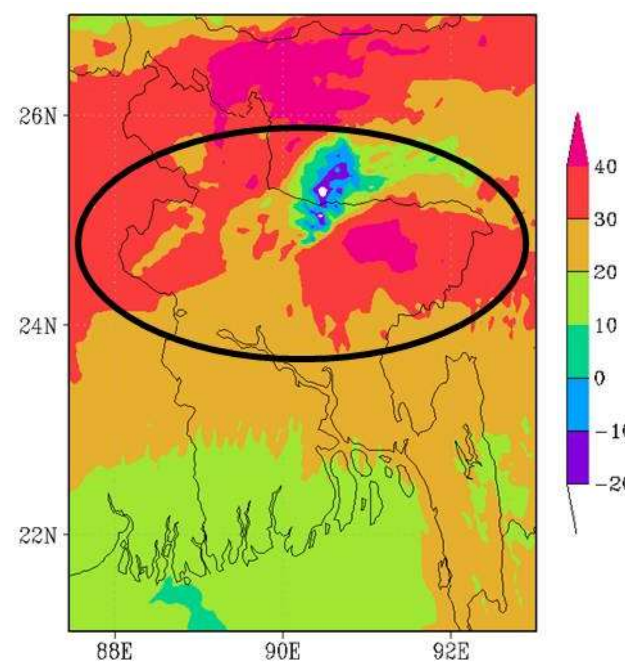

Figure 5: Model derived vertical wind shear (ms^{-1}) of the u component of wind between 925~500 hPa level at 1000 UTC on 30 March 2018

Vertical Wind Shear of the U Component of Wind

The model derived vertical wind shear (ms^{-1}) of the u component of wind between 925~500 hPa levels at 1000 UTC on 30 March 2018 is shown in Figure 5. In the figure, the high vertical wind shear in the order of ~30-40 ms^{-1} is observed over the North-East part of the country at 1000 UTC on 30 March 2018. As observed in the cloud image, the thunderstorms are situated at the same region at 1000 UTC on 30 March 2018 where model simulated highest vertical wind shear in the order of ~40 ms^{-1}. This high value of vertical wind shear might be favorable for the genesis of cumulonimbus clouds, which ultimately leads to multicell thunderstorms as well as supercell thunderstorms (Holton, 2004). Some previous study suggests that, in addition to high updraft speed, the vertical airflow could be equally important for hail formation and hail growth.

Vertical Component (W) of Wind

The model simulated w component (vertical component) of wind for 500 hPa level at 1000 UTC of 30 March 2018 is shown in Figure 6(a) and the vertical profile of the atmosphere across 24.5°N latitude (location of hailstorm) at 1000 UTC of 30 March 2018 is presented in Figure 6(b). Positive high values of w component of wind represent the location of updraft region (green-pink tone) and negative values of the w represent the location of down draft region (light-deep blue) in both the figures. The updraft and down draft cells are located close to each other and are randomly distributed exhibiting the multicell formation within the relatively large area. Figure 6(a) shows that the high values of w component of winds is in the order of 0.4 ms^{-1} over the North-central part of the country. The vertical profile of w exhibits three convective cells of which second one along 89°E is prominent [Figure 6(b)].

Relative Humidity Along with Low Level (925 hPa) Wind

Model simulated relative humidity (%) along with low level wind for 925 hPa level at 0600 UTC of 30 March 2018 (a) and the vertical profile of the relative humidity (%) across 24.5°N latitude (location of hailstorms) at 0600 UTC of 30 March 2018 (b) are presented in Figure 7(a-b). An axis of more relative humidity in the order of ~>90% from the South-East to the North-West direction through the middle of the country is seen in Figure 7(a). The Southerly winds continuously pumping the moisture from the Bay of Bengal towards the Bangladesh. A dry line also observed over the North-West part of the country which helps to form of storms along the Southern side of the dry line.

In the vertical profile of the relative humidity along 24.5°N latitude (location of hailstorm), it is observed that the relative humidity in the order of ~ >90% is confined between 800-200 hPa level of the atmosphere [Figure 7(b)]. The areas of comparatively more humidity indicate the updraft regions and the areas of comparatively less humidity indicate the down draft regions. It is observed that the vertical height of the storms reaches above 200 hPa level which indicates that severity of the storms.

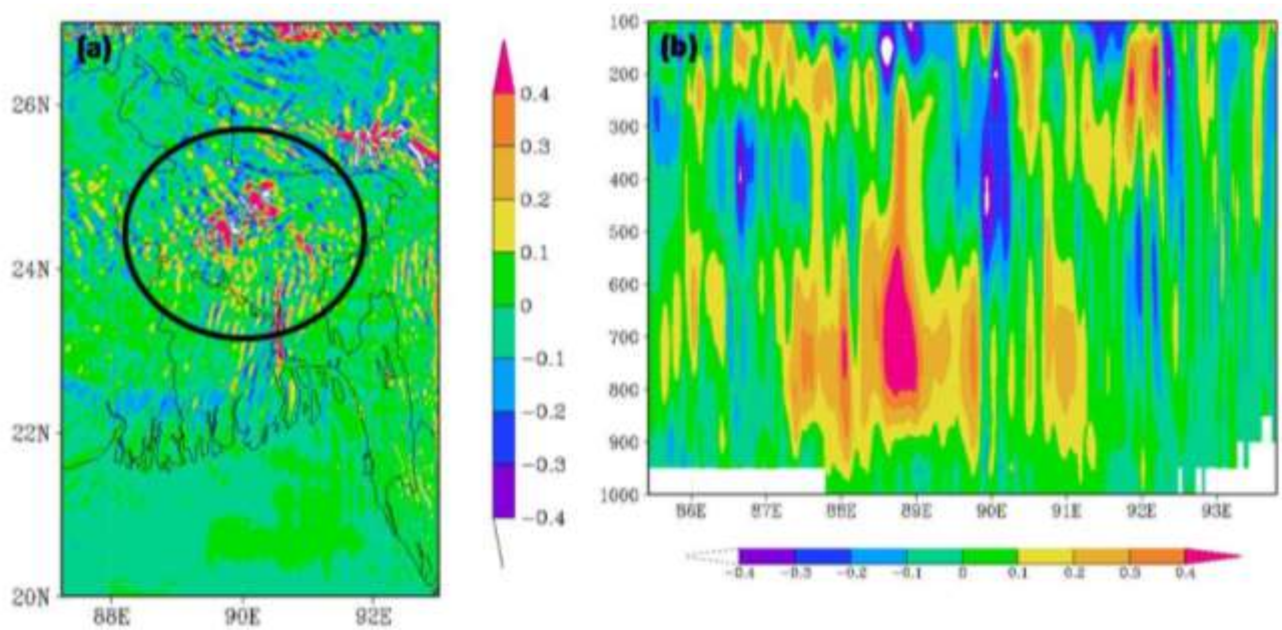

Figure 6(a-b): (a) Model simulated w component (vertical component) of wind (ms^{-1}) for 500 hPa level at 1000 UTC of 30 March 2018 and (b) the vertical profile of the atmosphere across 24.5°N latitude (location of hailstorm) at 1000 UTC of 30 March 2018

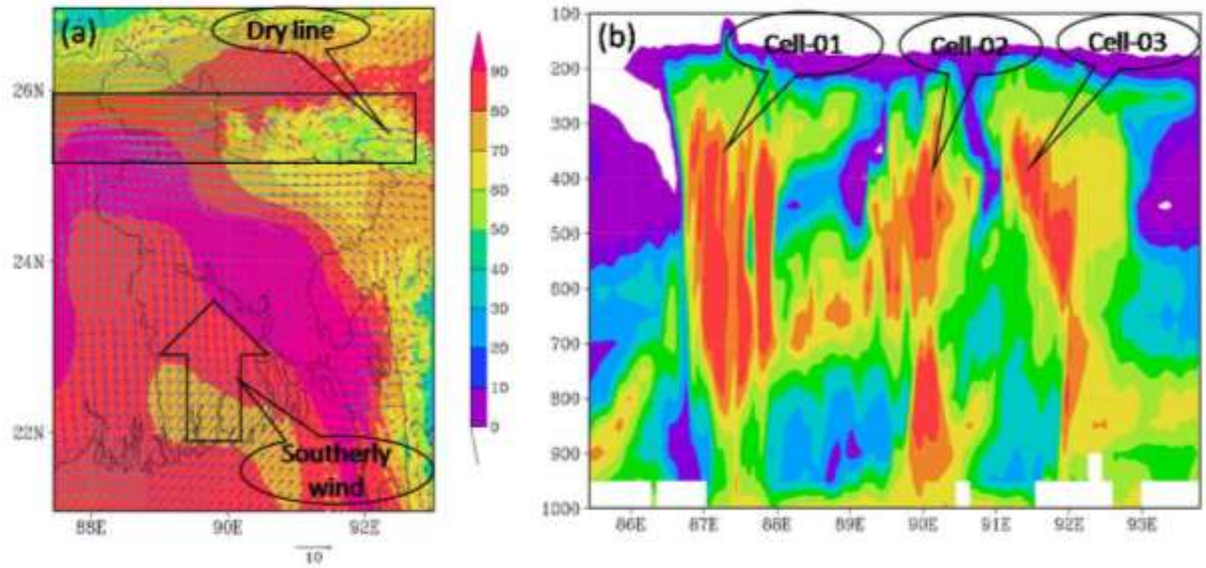

Figure 7(a-b): Model simulated relative humidity (%) along with low level wind for 925 hPa level at 0600 UTC of 30 March 2018 (a) and the vertical profile of the relative humidity (%) across 24.5°N latitude (location of hailstorm) at 1000 UTC of 30 March 2018 (b)

CAPE and CINE

Figure 8 shows the model simulated Convective Available Potential Energy (CAPE) and Convective Inhibition Energy (CINE) over Bangladesh at 1000 UTC of 30 March 2018. The CAPE and CINE, these two instability indices of the atmosphere are very important to measure the all kinds of convective storms. From the figures, it is observed that most of the area of the country are characterized by high values of CAPE (>3000 JKg^{-1}) and very low values of CINE (<50 Jkg^{-1}). Both the values of CAPE and CINE indicate the signature of the possibility to initiate of severe convection thermodynamically over the region.

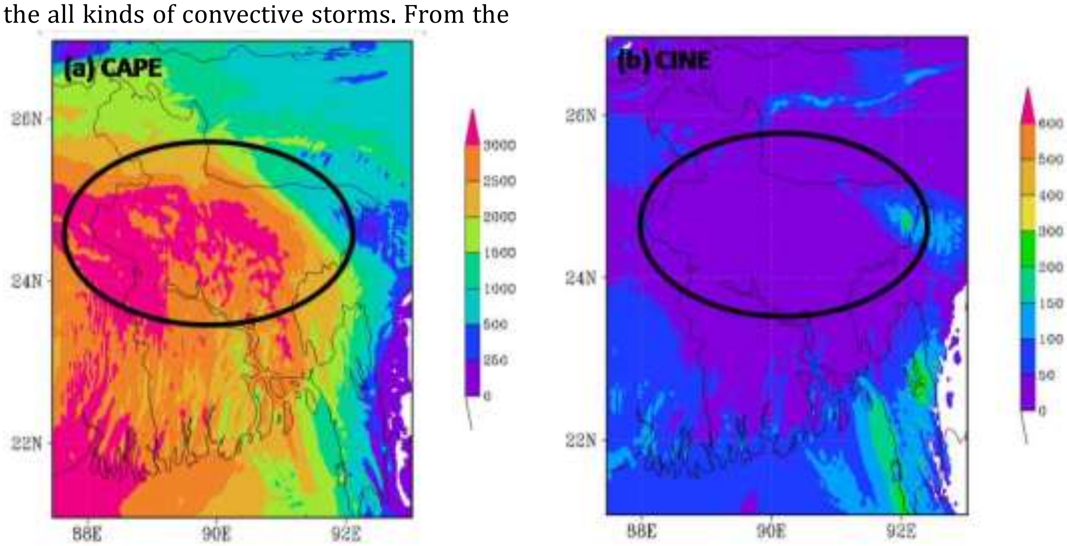

Figure 8: Model simulated Convective Available Potential Energy (CAPE) and Convective Inhibition Energy (CINE) over Bangladesh at 1000 UTC of 30 March 2018

Rainfall

The daily accumulated model simulated rainfall for 30 March 2018 is shown in Figure 9(a). The model simulated daily accumulated rainfall is compared with that of BMD observed rainfall and TRMM estimated rainfall [9(b-c)]. From the figures, it is found that the spatial distribution of model simulated rainfall is very similar with the TRMM rainfall though the model underestimates the TRMM rainfall. In both the figures 9(a) and 9(c), the rainfall is confined over the North-central part of the country. In BMD observed rainfall, the rainfall is confined over the Northern and Northwestern part of the county. However, rainfall is available in the North-central part of the county in all three figures. The dissimilarity between model simulated rainfall and BMD observed rainfall may be due to less observed stations over the North and North-East of the country which are not enough to captured rainfall of such highly localized convective storms.

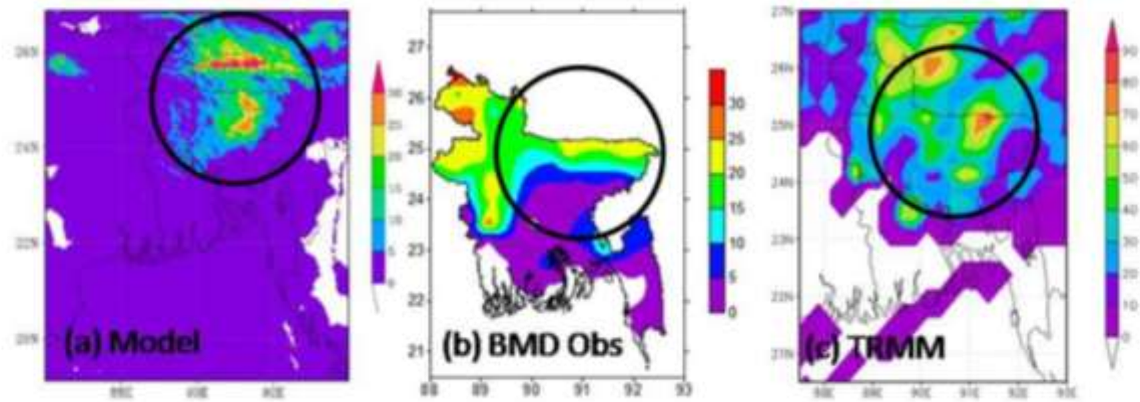

Figure 9(a-c): Daily accumulated rainfall (mm) of model simulated (a), BMD observed (b) and TRMM estimated (c) on 30 March 2018

Conclusions

Based on the above model simulated and derived parameters for the selected hailstorm event occurred on 30 March 2018 over Bangladesh, the following conclusions may be drawn:

i. The model is capable to capture the area of hail activity over the study area, but it is found that the model underestimated the amount of hail.

ii. The mean sea level pressure shows a trough extending along the Gangetic plain of West Bengal of India to Bangladesh with a core region of lowest pressure within the range of 1006-1008 hPa.

iii. The model simulated highest vertical wind shear in the order of ~40 ms^{-1} over the study area favored the genesis of cumulonimbus clouds (Holton, 2004), which ultimately leaded to form multi-cells thunderstorms with supercell development.

iv. The high value of vertical component of wind w is observed in the order of 0.4 ms^{-1} over the North-central part of the country, which are associated with downdraft cell adjacent to the updraft cell. The size of the closed updraft and downdraft cells is roughly estimated as 10-15 km. In the vertical profile of the w component of winds, three convective clusters are observed of which second one along 89°E is prominent.

v. An axis of high relative humidity in the order of ~>90% is found to extend from the South-East to the North-West direction through the middle of the country. The Southerly winds were found to continuously pump the moisture from the Bay of Bengal towards the lands of Bangladesh. A dry line also observed over the North-West part of the country which helps to the form of thunderstorm along the Southern side of the dry line. In the vertical profile of the relative humidity along 24.5°N latitude (location of hailstorm), it is observed that the relative humidity in the order of ~ >90% is confined between 800-200 hPa level of the atmosphere [Figure 7(b)].

vi. Most of the areas of the country are characterized by high values of CAPE (>3000 JKg^{-1}) and very low values of CINE (<50 Jkg^{-1}) which provide the favorable condition for initiation of the strong convections (Quadir, 2020).

vii. Model simulated rainfall matches well with the TRMM and BMD observed rainfall. Some temporal and spatial biases are observed in the simulation. It is found that the hail areas are found to be detected well in the model though the amount was highly under estimated.

Though the present combination of cumulus and planetary boundary layer schemes of WRF model is capable enough to capture the studied hailstorm event in reasonably well, but more similar hailstorm events need to be studied to make any final conclusions.

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