On the Predictability of the Physical and Dynamical Characteristics of the Troposphere Associated with Early Nor'westers using WRF Model

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ABSTRACT

Attempts are made to simulate the physical and dynamical characteristics of the troposphere associated with a Nor'westers (thunderstorms and hail) occurred at different places on 24 February 2016 in Bangladesh. The WRF model has simulated low pressure over West Bengal and western part of Bangladesh and the low is found to intensify during the formation and occurrence of the nor'wester. Mean sea level pressure is found to decrease by 2.27 hPa from about 0600 UTC to 0900 UTC UTC at Satkhira on 24 February 2016. Low-level circulation and strong south-southwesterly flow of winds have been simulated well by the model. The model has simulated maximum reflectivity of clouds with 50 dBZ and ice water mixing ratio is found to range between 25 and 190 mg/kg and these are simulated by WRF model with sufficient lead time of about 24 hours. Significantly ice water mixing ratio of 110-170 mg kg^{-1} over a greater depth from 700 hPa to 150 hPa has been responsible for enormous hails and ice pellets over Dhaka.

Keywords: *Nor'wester; WRF; Reflectivity and Ice water mixing ratio.*

1. Introduction

Bangladesh is affected by weather disturbances like Nor'westers, tornadoes, tropical cyclones, heavy rainfall and sometimes drought. Of these disturbances, Nor'westers and tornadoes are the severe land-based weather events that occur over the country and neighborhood frequently after the prolonged winter and give first life-giving rains along with severe destruction of properties and loss of lives in Bangladesh (Karmakar, 2005; Das, 2015a; Tyagi, 2000; Sikka and Rao, 2008). The economic losses due to these weather events are also enormous. Nor'westers and tornadoes are violent thunderstorms that affect the country during March through May i.e. the pre-monsoon season. These thunderstorms are called Nor'westers as most of them come from the north and west directions and they are also locally known as the "Kalbaishakhi" (Calamities of the month of Baishakh, April – May).

In some years, nor'westers are also found to occur in late February and early June depending on the early and late withdrawal of winter i.e. northeast monsoon (Karmakar, 2005; Das 2015a). Most of these storms proceed from the northwest although they can come from other directions too. Thunderstorms during this period are produced when the warm, moist air from the Bay of Bengal moving northward meets a cooler air coming from the north that has contrasting thermodynamic characteristics. Tall cumulonimbus (Cb-cloud) clouds are produced, resulting in severe thunderstorms whose fury at times rivals that of tornado. The distribution of the frequency of local severe storms over Bangladesh has been mapped by Karmakar and Quadir (2014a, b). It has been found that the area of maximum frequency of local severe storms is located over Sylhet region extending southwestward up to Dhaka region and having an elongated area extended southward up to Barisal-Khepupara region. The distribution patterns also show that the average number of storms is minimum over northwestern and extreme southeastern parts of the country. The seasonal mean frequency of local severe storms over Bangladesh varies from 40 to 170 having the highest frequency at Sylhet and lowest frequency at Teknaf. They studied different parameters of the troposphere such as mixing ratio, relative humidity, mean mixed layer mixing and precipitable water on the dates of occurrence and non-occurrence of local severe storms. These parameters are found to increase both at the surface and with height on the dates of occurrence of local severe storms.

Thunderstorms are the deepest convective clouds caused by buoyancy forces set up initially by the solar heating of the Earth's surface (Siingh *et al.*, 2010). Suitable synoptic features are important to cause these severe storms. These features are required to be in existence both at the surface and the upper levels. It has been found that the place of occurrence of severe Nor'westers and tornado lies very near to the point of intersection of the axes of low level maximum wind (850 hPa) and upper level jet stream at 250/200 hPa (Dalal *et al*., 2012, Hossain and Karmakar, 1998). Karmakar and Alam (2006) studied the instability of the troposphere associated with thunderstorms/nor'westers over Bangladesh during the pre-monsoon season. According to them, the maximum negative values of different instability such as SI**,** LI, DPI, DII and EI lie over the eastern Madhya Pradesh, Bihar, West Bengal and adjoining Bangladesh indicating the highly unstable area. The negative areas of the indices in combination with the low pressure area over Bihar, West Bengal and adjoining Orissa and Bangladesh as well as the cyclonic circulation up to 3-4 km or above are favorable for the occurrence of Nor'westers in Bangladesh. Normally, nor'westers have been found to occur at the northeastern or eastern part of the area of maximum instability. Other studies related to thunderstorms made by different scientists such as, Das *et al*., 2006, 2015a-d; Das 2010; Houze *et al*., 2017; Dimri *et al*., 2016; Karmakar and Alam (2007), Karmakar and Alam (2011), Karmakar and Quadir (2014a, b); Rasmussen and Houze (2012); Science plan (2005) may be cited. Das *et al.* (2015c) have studied the tornado occurred at Brahmanbaria in Bangladesh in the afternoon of 22 March 2013 using the tropical rainfall measuring mission (TRMM) data, radar observations and model simulations. The maximum reflectivity and the vertical extent of the system found to be about 54.7 dBZ and 15 km, respectively by the Doppler weather radar (DWR) at Agartala, India. The maximum amount of vorticity transferred by directional shear in the storm updraft (helicity) due to convective motion simulated by the model is found to be 1774 m^2 s^{-2}, and the highest value of bulk Richardson number shear that defines the region in which low-level mesocyclogenesis is more and equals to 457.3 m^2 s^{-2}, which is generally supposed to produce rotating storms. The highest vertical velocity simulated by the model is about -28 to 58 m s^{-1}. Karmakar *et al.* (2016) studied the physical and dynamical characteristics of a severe thunderstorm, which had occurred on April 5, 2015 at about 2100 UTC in the southwestern Bangladesh by using WRF Model. 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 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. This research has been undertaken to study the predictability of physical and dynamical characteristics of the troposphere associated with Nor'westers in Bangladesh using WRF Model.

2. Thunderstorms under study

The data related to the occurrence of thunderstorms occurred at different places under study have been collected from Bangladesh Meteorological Department (BMD). These are given in Table 1.

Table 1. Thunderstorms under Study

Date	Station	Squall/Gusty wind	Wind Speed m s^{-1}	Direction	Time (UTC)	24 h rainfall (mm)
24-02-2016	Satkhira	Past hail	-	NW	0000	48
	Barisal	Squall	18.01	NW	0010	28
	Dhaka	Gusty, Hail	9.26	NW	0548	8

3. WRF Model and Methodology

The Advanced Research Weather Research and Forecasting model (ARW), version 3.7.1 (Skamarock *et al.*, 2008), which is a three-dimensional, fully compressible, non-hydrostatic. The vertical coordinate is a terrain-following hydrostatic pressure coordinate and the model uses the Runge–Kutta third-order integration scheme. A nested domain with 18, 6 and 2 km horizontal spatial resolution was configured (Figure 1), which is reasonable in capturing the mesoscale cloud clusters. In the present study, 1.0° × 1.0° gridded NCEP FNL (Final) Operational Global Analysis and Global Forecast System (GFS) data has been used as initial and Lateral Boundary Conditions (LBC) for the domain. Main features of the model employed for this study are summarized in Table 2.

Table 2. WRF Model configuration

Model Features	Configurations
Horizontal Resolution	18 km, 6 km and 2 km
Vertical Levels	40
Topography	USGS
Dynamics	
Time Integration	Semi Implicit
Time Steps	20 s
Vertical Differencing	Arakawa’s Energy Conserving Scheme
Time Filtering	Robert’s Method
Horizontal Diffusion	2nd order over Quasi-pressure, surface, scale selective
Physics	
Convection	Kain-Fritsch (new Eta) scheme
PBL	YSU
Cloud Microphysics	WSM6
Surface Layer	Monin-Obukhov
Radiation	RRTM (LW), SW
Gravity Wave Drag	No
Land Surface Processes	Unified NOAH Land Surface Model

4. Results and Discussion

WRF Model has been used in this study to simulate a number of physical and dynamical parameters for thunderstorms/nor’westers occurred at three places in Bangladesh on 24 February 2016. The parameters are rainfall, winds at 950 hPa and 10 m levels, sea level pressure, relative humidity, temperature at 10 m, reflectivity of hydrometeor, vorticity, cloud-water mixing ratio and ice-cloud mixing ratio associated with the Nor’westers under study. Their distributions and vertical cross-section are critically studied and described below.

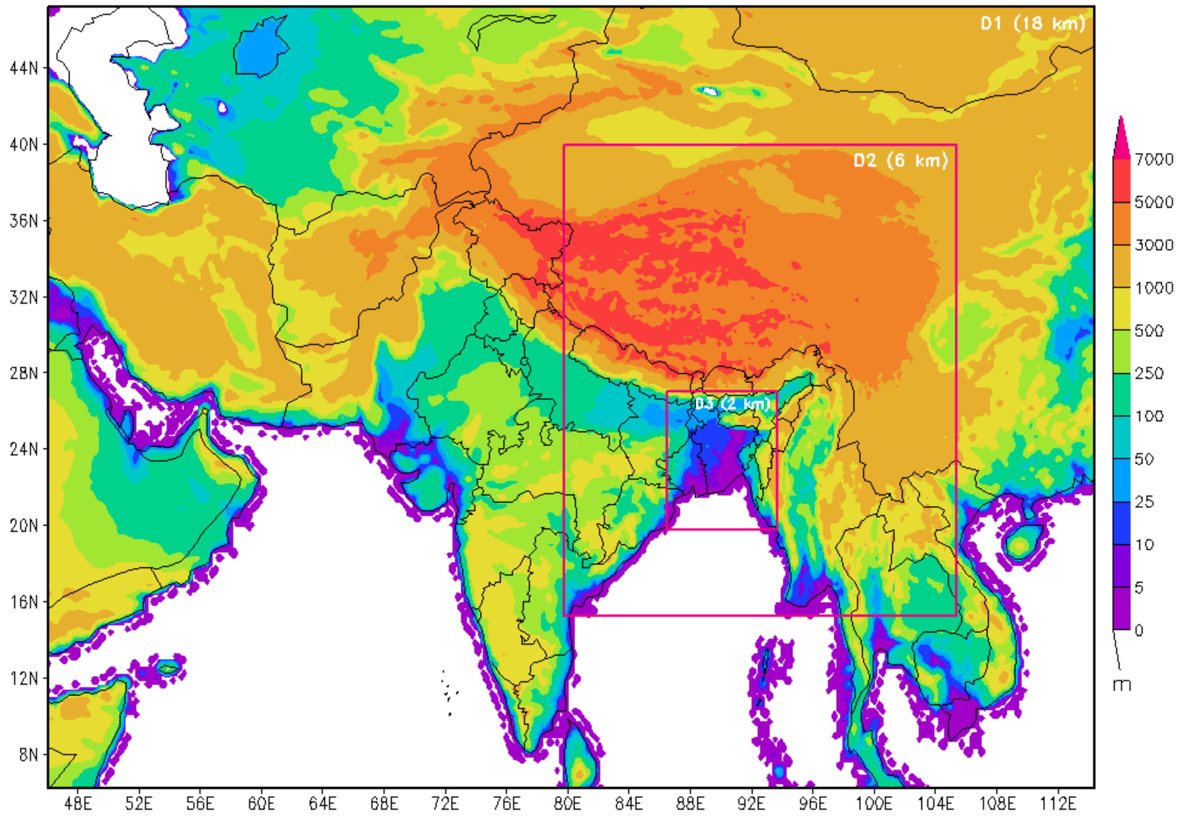

Figure 1: The study domain with the terrain heights at 18-km resolution

4.1 Simulation and TRMM retrieved rainfall, wind speed at 10 m with 950 hPa wind vector and Temperature at 2m

WRF model has simulated three hourly rainfall associated with the Nor'westers under study as shown in Figure 2 (a). During 0000-0300 UTC on 24 February 2016, trace rainfall is simulated in West Bengal and 1-2 mm rainfall over Barisal region of Bangladesh. These rainfall areas are found to shift east-northeast with slight higher rainfall. At 0600

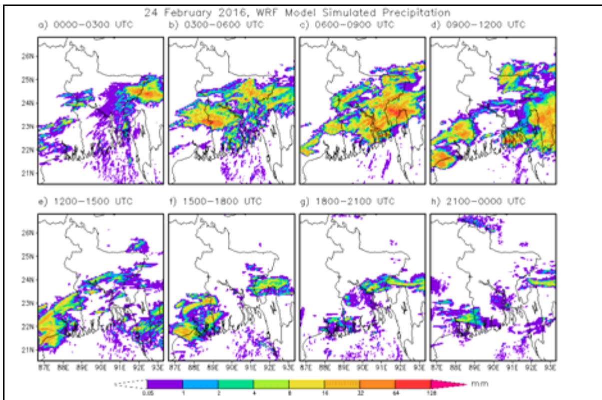

Figure 2 (a): Accumulated 3 hourly rainfall simulated by WRF model

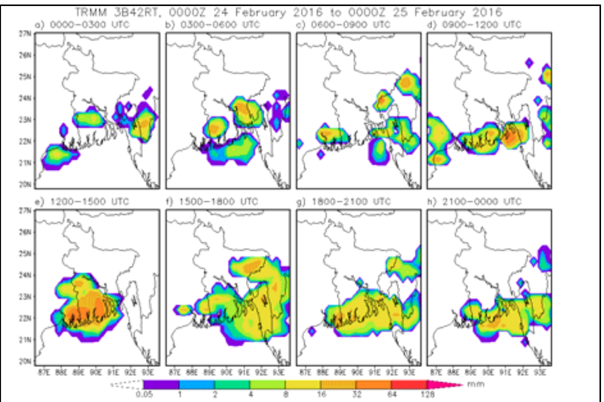

Figure 2 (b): Accumulated 3 hourly rainfall retrieved from TRMM

to 0900 UTC the higher simulated rain is found over the region near Satkhira-Dhaka-Comilla-Agartala with an amount of 16 to 32 mm (Figure 2a). The maximum convection has occurred over Barisal, Dhaka, and Satkhira during 0600-1200 UTC. The convection is seen to extend from Gangetic West Bengal/southwestern Bangladesh up to Comilla-Noakhali-Agartala region. The convection/rainfall area is more prominent in Figure 2a. According to the figure, it is clear that this nor'westers occurred at different places due to the movement of easterly low pressure wave through Orissa-West Bengal-Khulna coast of India-Bangladesh. The convection has propagated towards northeast in between 1500 to 2100 UTC and has become week. The maximum simulated amounts of rainfall near Barisal, Dhaka, Comilla and Satkhira are 10 to 64 mm. The observed and simulated precipitation is also found to differ from each other both in time and spatial distribution. However, the model could simulate the precipitation on the day of Nor'westers.

Three hourly TRMM retrieved rainfall of 24 February 2016 over Bangladesh is presented in the Fig. 2 (b), which shows two patches of rainfall of 16-32 mm during 0300-0600 UTC over Satkhira, Barisal and Dhaka-Comilla regions. The rainfall area is found to expand shifting southwards in the subsequent hours, which are not similar to the model simulated rainfall.

Vector wind at 950 hPa and wind speed at 10 m level are simulated at different synoptic hours on 24 February 2016 and the results are given in Figure 3a. The model simulation wind at 950 hPa shows strong southerly and south-westerly flow over the southwestern and southern parts of the country with a small convergence over West Bengal and adjoining Bangladesh at 0000 UTC. The 950 hPa horizontal wind shows a trough and high wind velocity over the south and south-western part of Bangladesh. There is a strong trough at 950 hPa simulated by the model. A cyclonic circulation is developed over Faridpur-Dhaka region at 0600 UTC, persisting up to 1200 UTC with a strong discontinuity line near Dhaka. This circulation and the line of discontinuity have been responsible for the occurrence of the severe nor'westers over Barisal, Dhaka, Satkhira and other places.

Model simulated wind speed is underestimated over Dhaka. At 0548 UTC, the observed wind speed is 9.26 m s^{-1} (33km/hr). But model simulated highest wind speed over Dhaka is only 7.37 m s^{-1} (27 km/hr) at 0740 UTC, indicating that the model underestimates the wind speed.

The temperature is more over the northwestern part of Bangladesh at 0600 to 0900 UTC. Normally, temperature >29 ºC is favorable for the occurrence of thunderstorms/nor'westers (Reynolds, 2008). On 24 February 2016, the diagram shows higher temperature of about >300 K over West Bengal, extending to

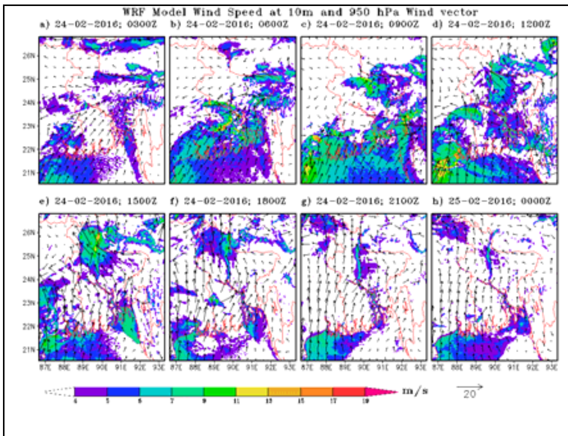

Figure 3 (a): WRF model simulated vector wind at 950 hPa and wind speed at 10 m

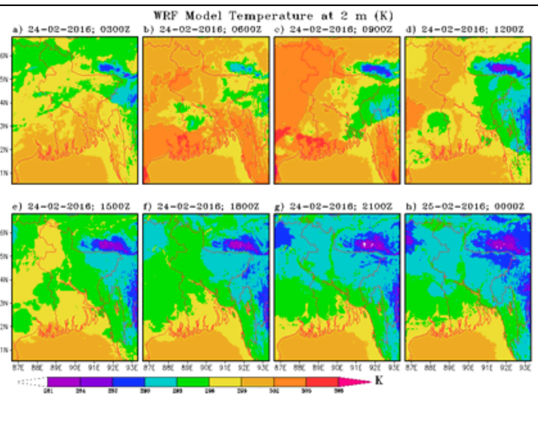

Figure 3 (b): WRF model simulated temperature at 2m

Bangladesh through northwestern and southwestern parts of the country with a colder region along the central Bangladesh at 0600 and 0900 UTC (Figure 3b). At 0300 UTC, the temperature at Satkhira, Barisal and coastal region is found higher than rest of Bangladesh and found to increase in the subsequent hours,

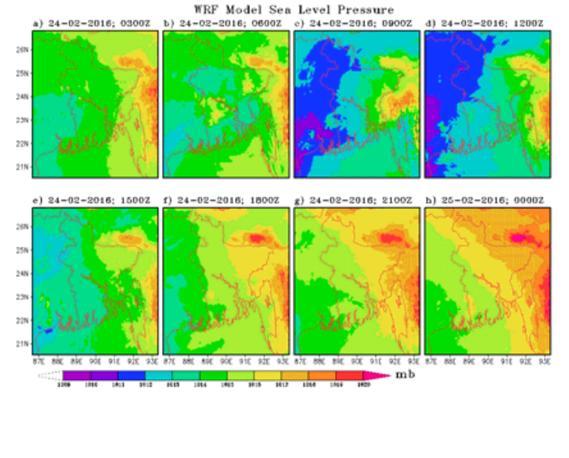

Figure 4(a): WRF model simulated Sea Level Pressure (SLP)

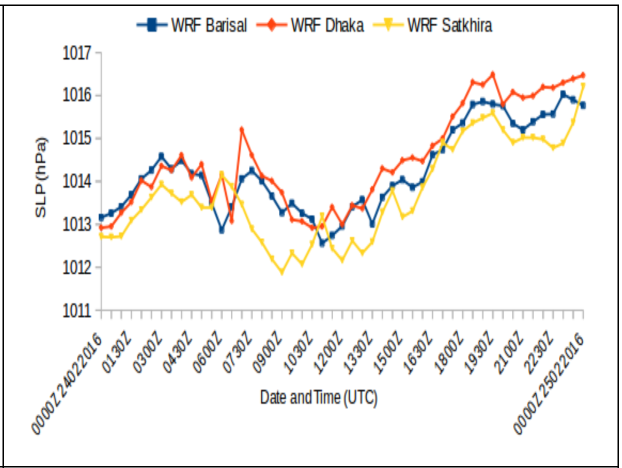

Figure 4(b): Diurnal variation of model simulated SLP at Barisal, Dhaka and Satkhira

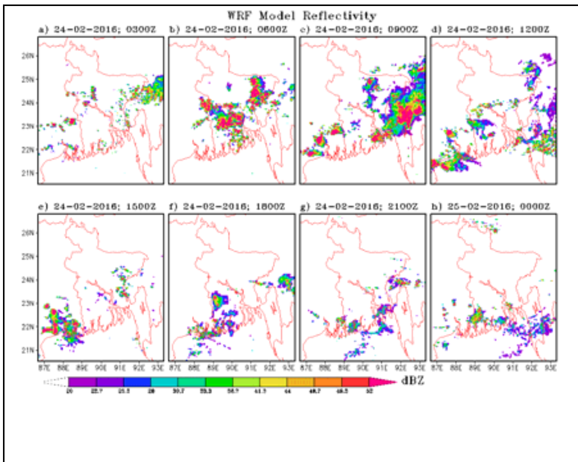

Figure 4(c): WRF model simulated reflectivity (dBZ)

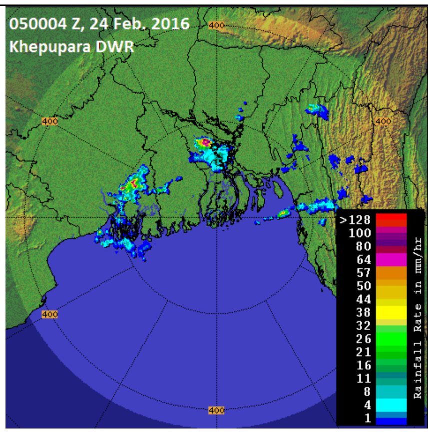

Figure 4(d): DWR derived rain rate in Khepupara Radar on 24 February 2016

when the nor'wester occurred at Satkhira and Barisal. During 0600 to 0900 UTC, the temperature ranges between 300 to 305 K (27-32ºC) at most places in Bangladesh including Dhaka and the maximum temperature of >306 K lies over the southern part of Bangladesh. This temperature over the country has been favorable of the generation of convection in the atmosphere.

4.2 *Evolution of sea level pressure (SLP) and maximum reflectivity (dBZ)*

Figure 4a shows the spatial distribution of SLP with time on the date of occurrence of nor'westers on 24 February 2016. At 0300 UTC, there is a low pressure area with 1013-1014 hPa over West Bengal and major part of Bangladesh. The area of this low is reduced and found to lay over West Bengal and southwestern Bangladesh extended to Barisal-Dhaka region at 0600 UTC. At this time the minimum pressure is found to be 1013 hPa over southwestern Bangladesh with a trough extending to Dhaka and the nor'wester occurred here at about 0548 UTC. The atmospheric pressure is decreased further to less than 1011 hPa at 0900 UTC; but at 1200 UTC the model simulated the low over the north-west and western parts of Bangladesh.

After 1200 UTC, sea level pressure is found to increase over the same area.

The diurnal variation of model simulated sea level pressure at Barisal, Dhaka and Satkhira is shown in Figure 4b. At Barisal, the diurnal variation of sea level pressure shows that the SLP is 1014.58 hPa at 0300 UTC and 1012.87 at 0600 UTC, giving a pressure drop of 1.71 hPa. At Dhaka, the sea level pressure is found 1014.61 at 0400 UTC; it decreases to 1013.08 at 0630 UTC. The pressure at Dhaka is increased rapidly to 1015.2 hPa 0700 UTC with a pressure drop of about 1.53 hPa during 0400-0630 UTC and the nor'wester occurred at Dhaka during period. The rapid increase in pressure indicates passing of the nor'wester. At Satkhira, the figure shows that the pressure is minimum at 0030 UTC with a value of 1012.7 hPa when the nor'wester occurred there. The sea level pressure is then started increasing and becomes 1014.15 hPa at 0600 UTC. Then it decreases from 0600 UTC to 0900 UTC with a pressure drop of 2.27 hPa for the second time at Satkhira. This lowest pressure is attained about 9 hours after the occurrence of the nor'westers.

The reflectivity of hydrometeor in the atmosphere is simulated at different synoptic hours on 24 February 2016 (Figure 4c). It is seen that the reflectivity becomes maximum and distinct at 0600 to 1200 UTC on 24 February 2016 over the places of occurrence. It shows clearly the higher reflectivity of about 50 dBZ near Barisal, Dhaka, Satkhira and adjoining area at about 0600 UTC. The reflectivity becomes more prominent at about 1200 UTC but the area of reflectivity is shifted southeast-east over a larger area. The value of reflectivity is more than 50 dBZ.

Figure 4(d) shows DWR derived rain rate of Khepupara station at 050004 UTC over Barisal, Satkhira and Dhaka and is compatible with the model simulated reflectivity at 0600 UTC, showing precipitation at the places of occurrence of nor'westers.

4.3. Relative humidity simulated by WRF model

The distribution of relative humidity at 2 m simulated by WRF model over Bangladesh is shown in Figure 5a at every three hour on 24 February 2016. Dry and moist zones are seen in the figure. There are clear intersections of dry and moist lines near Barisal, Dhaka and Satkhira at 0600 and 0900 UTC, where nor'westers are reported to occur. At 0300 to 0600 UTC model simulated relative humidity at 2m showed the range of 80-95% over eastern and southern parts of Bangladesh and this high relative humidity is conducive for strong convection.

Figures 5(b-d) shows time cross-section of relative humidity simulated by WRF model at Barisal, Dhaka and Satkhira respectively.

At Barisal, the vertical cross-section of RH shows high relative humidity (about 95%) near the surface up to 900 hPa in the morning on 24 February 2016 (Figure 5b). In the morning, there is a drying condition with less humidity at 900-600 hPa. Then the RH starts increasing and extending through a window to upper troposphere (200 hPa). The RH at 200 hPa spreads with time like and anvil indicating icing condition there. At Dhaka, the vertical cross-section of RH shows high relative humidity (about 95%) near the surface up to 900 hPa in the morning on 24 February 2016 (Figure 5c). The RH is seen to extend upward gradually and during 0500-0800 UTC an atmospheric window is found through which moisture has extended to 250-200 hPa and spread with time like a distinct anvil. This upper air moisture indicates significant and enormous icing in the Cb-cloud of the nor'wester over Dhaka. The vertical time cross-section of relative humidity simulated by WRF model at Satkhira on 24 February 2016 is shown in Figure 5d, which shows that the troposphere is dry with 0-10% humidity in the layer 550 hPa-300 hPa except between 0600-1200 UTC when moisture is seen to rise up to about 200 hPa, the Nor'wester being occurred at many places at that time. The relative humidity is 50-95% in the layer 780-650 hPa or more during 0000-0600UTC and more than 95% in the layer 880-750 hPa during 0700-1300 UTC. Between 0700 UTC and 1200 UTC, there are two atmospheric windows through which moisture is seen to rise up to 200 hPa and spread like an anvil at about 1200 UTC on 24 February 2016. In the lower troposphere, the relative humidity is less (40-80%) because the air remains relatively drier in February (end of winter season) and the vertical cross-section indicates that the moisture is convected/transported in the middle and upper troposphere and was conducive for the formation of the nor'wester at the end of winter season 2106.

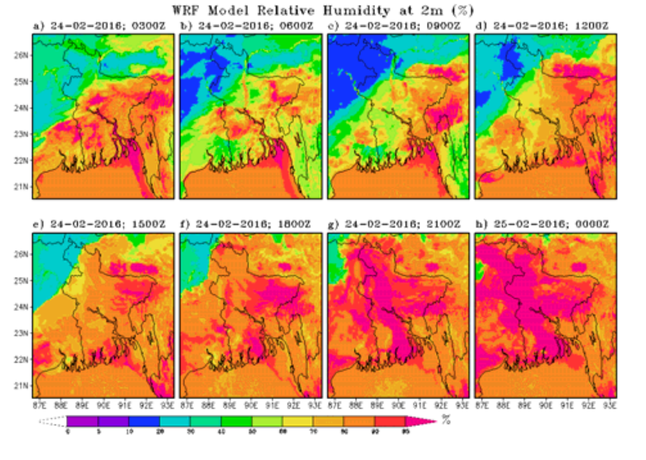

Figure 5(a): WRF model simulated relative humidity (%) over Bangladesh and adjoining area

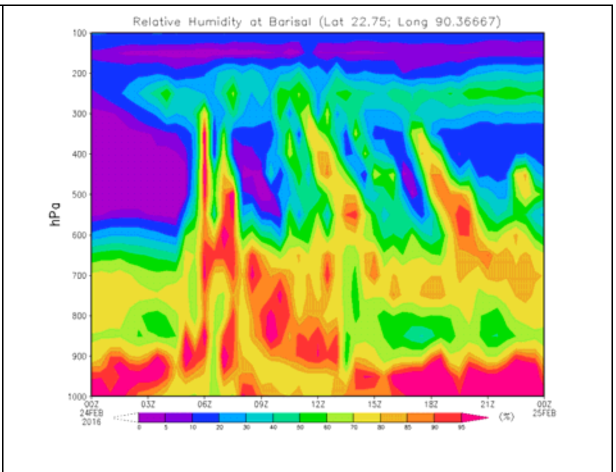

Figure 5 (b):Vertical time cross-section of RH (%) simulated by WRF model at Barisal

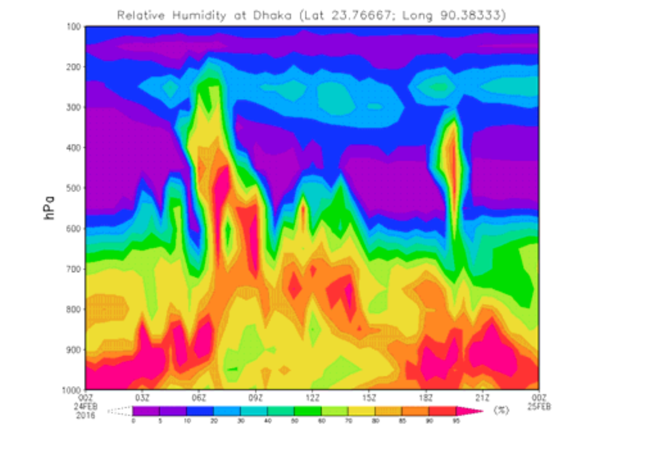

Figure 5 (c):Vertical time cross-section of RH (%) simulated by WRF model at Dhaka

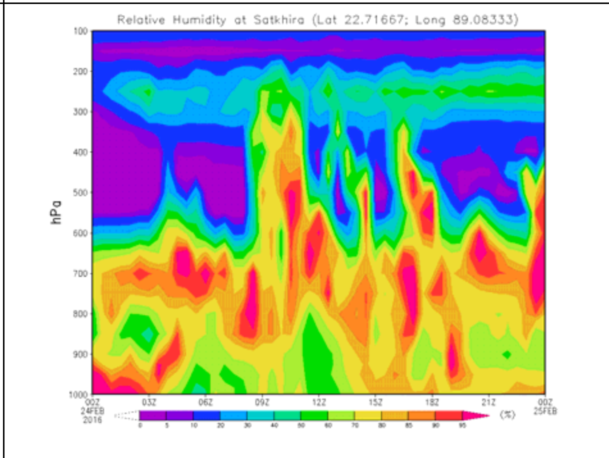

Figure 5 (d):Vertical time cross-section of RH (%) simulated by WRF model at Satkhira

Figure 5(e): Numerous hails on 24 February 2016 (*Source*: BDNews24.com, 24 February 2016)

Before the occurrence of the nor'westers, RH at the surface becomes less and drying condition is found to exist around 850 hPa. Practically, numerous hails and ice pellets occurred over Dhaka at around 0600 UTC on 24 February 2016 (Figure 5e). These findings are well matched the study made by Karmakar *et al.* (2016).

Figures 6 (b-d) gives the vertical time cross-section of the vertical velocity over Barisal, Dhaka and Satkhira respectively. Figure 6b for Barisal shows the vertical extension of vertical

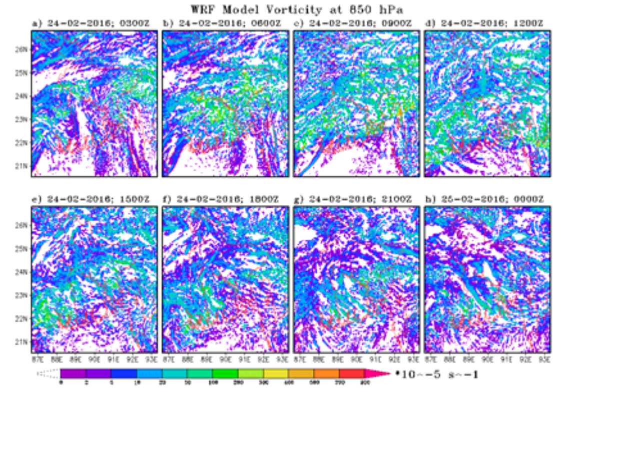

Figure 6(a): WRF model simulated vorticity at 850 hPa over Bangladesh on 24 February 2016

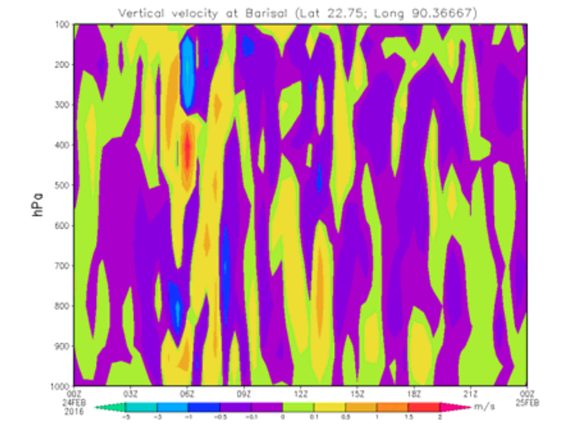

Figure 6(b): Vertical time cross-section of vertical velocity simulated by WRF model at Barisal on 24 February 2016

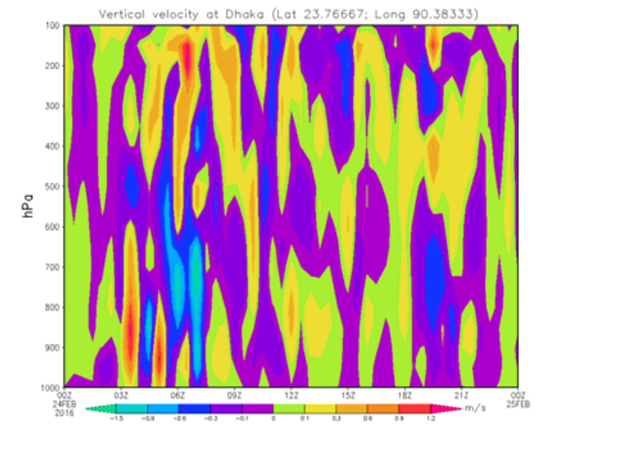

Figure 6(c): Vertical time cross-section of vertical velocity simulated by WRF model at Dhaka on 24 February 2016

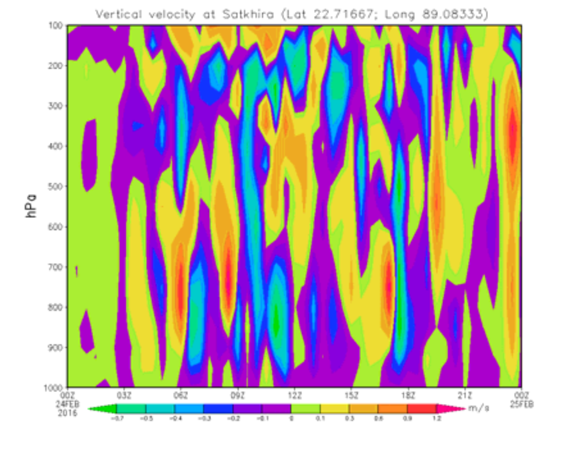

Figure 6(d): Vertical time cross-section of vertical velocity simulated by WRF model at Satkhira on 24 February 2016

4.4 Vorticity at 850 hPa and vertical time cross-section of vertical velocity

On 24 February 2016, it is seen that the vorticity is positive over Bangladesh throughout the whole day as shown in Figure 6a. The vorticity is .found to increase slightly at 0600 UTC onwards. There is a zone of higher vorticity extended from southwestern Bangladesh to northeast up to Comilla from 0600 UTC to 1500 UTC. The value is about 300-400×10^{-5} s^{-1} at 1200 UTC. This positive surface vorticity was responsible for the occurrence of the nor'wester on 24 February 2016.

velocity from 1000 to 100 hPa during 0430-0730 UTC, having the maximum updraft of 2ms^{-1}. There are interruption of updrafts and downdrafts in the troposphere too. Figure 6c shows the vertical-time cross-section of vertical velocity over Dhaka on the same day. Strong vertical velocity of 1.2 m/s is found to exist from 1000 to 600 hPa level at about 0330 UTC and from 1000 hPa to 750 hPa at around 0430-0450 UTC, when the nor'wester occurred over Dhaka on 24 February 2016. Figure 6d shows that there are pockets of negative and positive vertical velocity at Satkhira throughout the whole day on 24

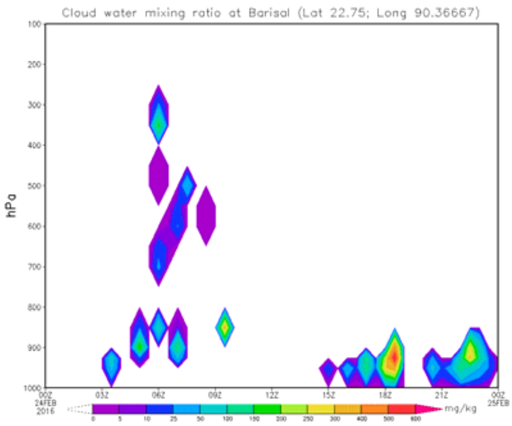

Figure 7(a): Vertical time cross-section of cloud water mixing ratio simulated by WRF model at Barisal on 24 February 2016

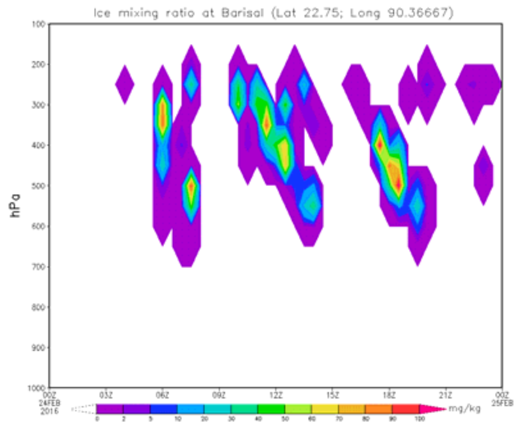

Figure 8(a): Vertical time cross-section of ice water mixing ratio simulated by WRF model at Barisal on 24 February 2016

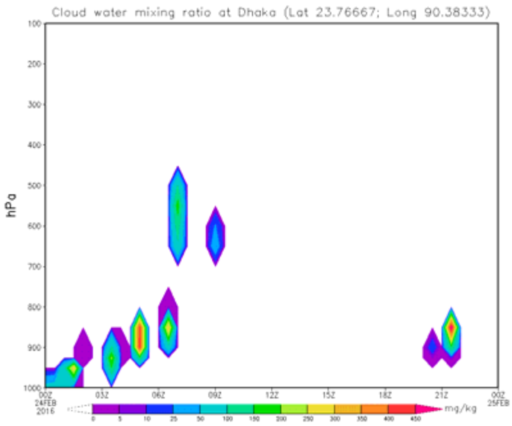

Figure 7(b): Vertical time cross-section of cloud water mixing ratio simulated by WRF model at Dhaka on 24 February 2016

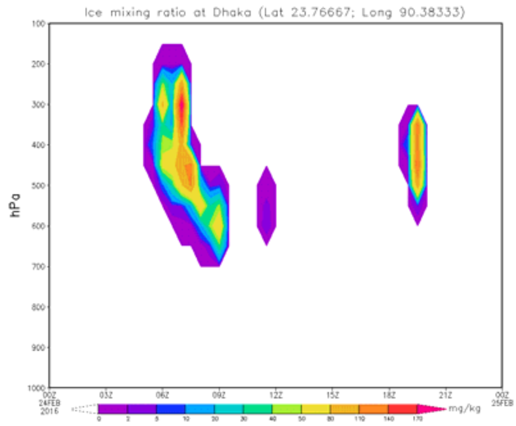

Figure 8(b): Vertical time cross-section of ice water mixing ratio simulated by WRF model at Dhaka on 24 February 2016

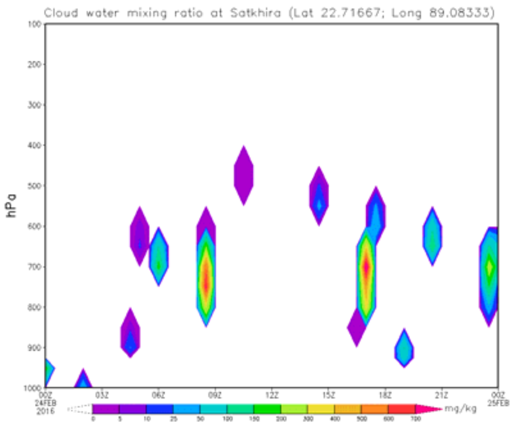

Figure 7(c): Vertical time cross-section of cloud water mixing ratio simulated by WRF model at Satkhira on 24 February 2016

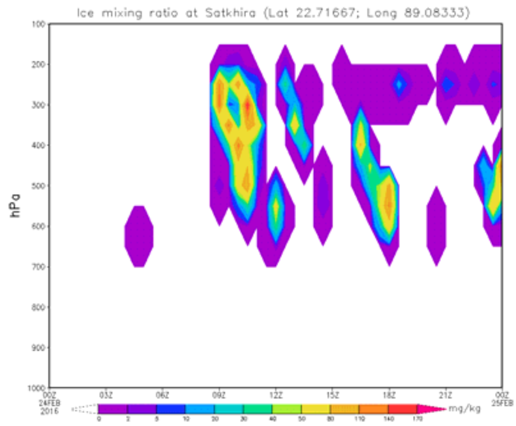

Figure 8(c): Vertical time cross-section of ice water mixing ratio simulated by WRF model at Satkhira on 24 February 2016

February 2016. During 0000-0300 UTC, the vertical velocity of about 0.1-0.2 m/s was dominant from surface to about 230 hPa level, when the nor'wester occurred at Satkhira.

Between 0600 UTC and 1700 UTC, the positive vertical velocity is dominant at different heights up to about 250 hPa or more. The maximum vertical velocity is of the order of 1-4 ms^{-1}. This indicates that updrafts and downdrafts were present in the atmosphere over Satkhira during occurrence of the nor'wester and this vertical velocity is possible to be predicted well with lead time of more than 8-12 hours. These findings are similar with results of Karmakar *et al*. (2016).

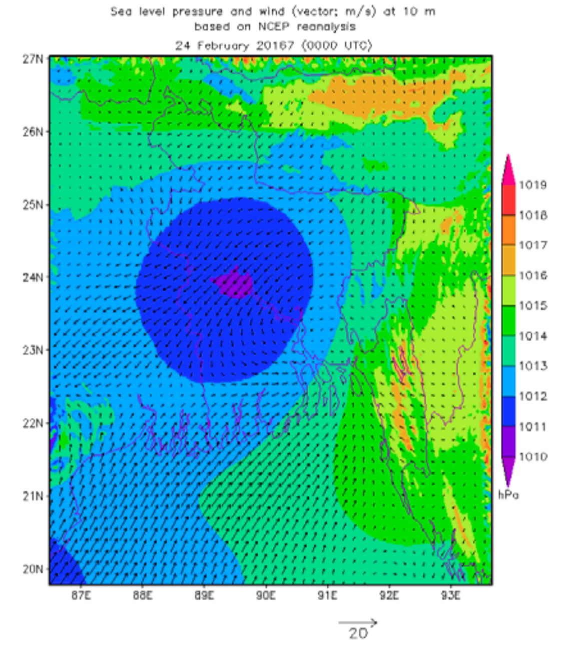

Figure 9(a): Sea level pressure and wind vectors at 10 meter on 24 February 2016 at 0000UTC

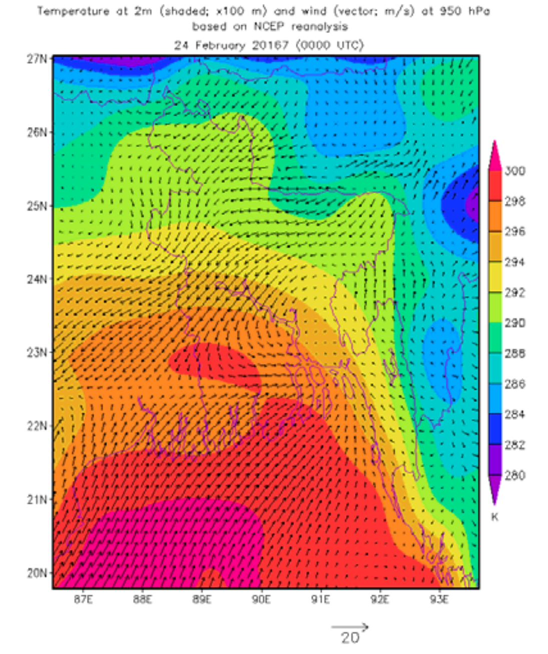

Figure 9(b): Temperature at 2 m and wind vectors at 950 hPa on 24 February 2016 at 0000UTC

4.5. Vertical time cross-section of cloud water and ice water mixing ratio simulated by WRF model

Figure 7a reveals that the cloud water mixing ratio extends from 1000 to 250 hPa during 0300-0700 UTC at Barisal. The maximum cloud water mixing ratio is 200 mg Kg^{-1}. Figure 7b shows the vertical time cross-section of cloud water mixing ratio simulated by WRF model at Dhaka on 24 February 2016. This figure indicates the mixing of cloud and water from the beginning of the day and become maximum of 400-450 $mgkg^{-1}$ between 950 hPa and 800 hPa, when the nor'wester occurred at Dhaka. The cloud water mixing ratio is found to extend upwards more over Dhaka after 0600 UTC. The model has simulated the cloud water mixing during the occurrence of the nor'wester with sufficient lead time. On 24 February 2016, the cloud water mixing ratio is found in the layer 750-580 hPa during 0130-0300 UTC over Satkhira and in the layer 900-680 hPa during 0600-1200 UTC, having maximum cloud water mixing ratio of 300-700 mg kg^{-1} as shown in Figure 7c. The nor'wester occurred at Satkhira before 0300 UTC.

Figure 8a for Barisal shows vertical time cross-section of ice water mixing ratio on 24 February 2016. The ice-water mixing at Barisal is found to extend from 700 to 200 hPa during 0300-0700 UTC when the nor'wester occurred there. The maximum ice water mixing ratio is 100 mg kg^{-1}. Figure 8b gives vertical time cross-section of ice water mixing ratio simulated by WRF model at Dhaka on 24 February 2016 and indicates significant ice water mixing ratio between 0430-0900 UTC extending from 700 hPa to 150 hPa. The maximum value of ice water mixing ratio is 110-170 mg kg^{-1} over Dhaka. Because of this vertically significant and maximum ice water mixing ratio, enormous hails and ice pellets occurred over Dhaka at about 0448 UTC. Ice water mixing ratio is simulated by WRF Model at different levels and time over

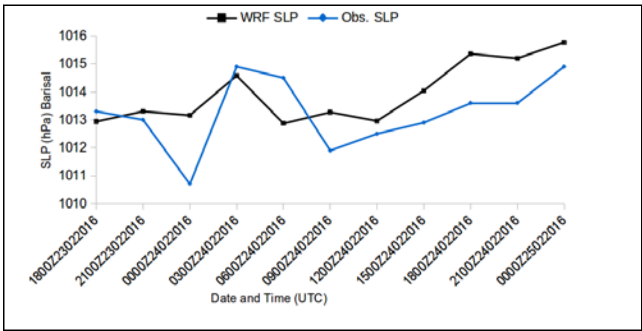

Figure 10 (a): Model simulated and observed SLP over Barisal

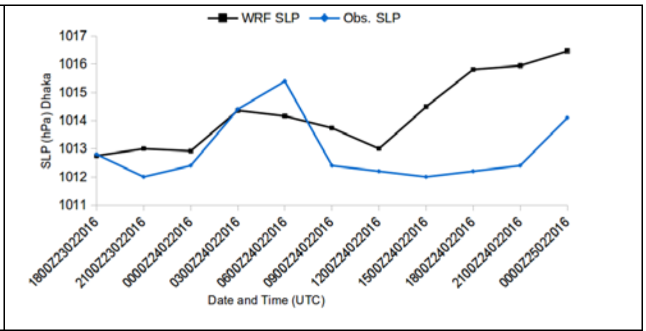

Figure 10 (b): Model simulated and observed SLP over Dhaka

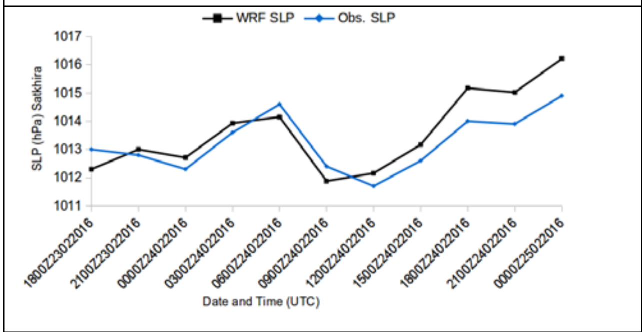

Figure 10 (c): Model simulated and observed SLP over Satkhira

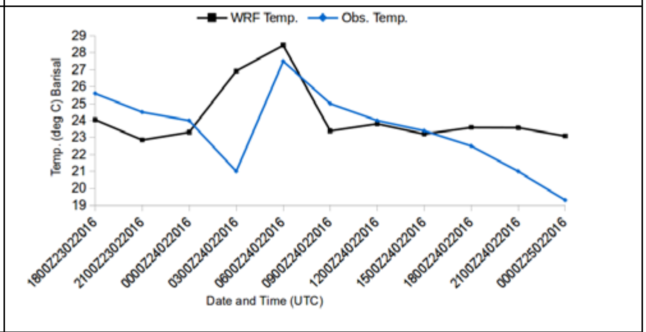

Figure 10 (d): Model simulated and observed temperature over Barisal

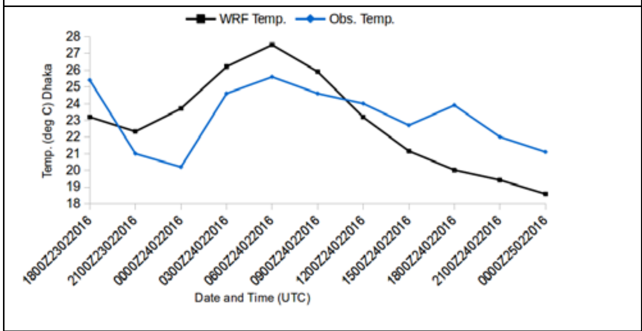

Figure 10 (e): Model simulated and observed temperature over Dhaka

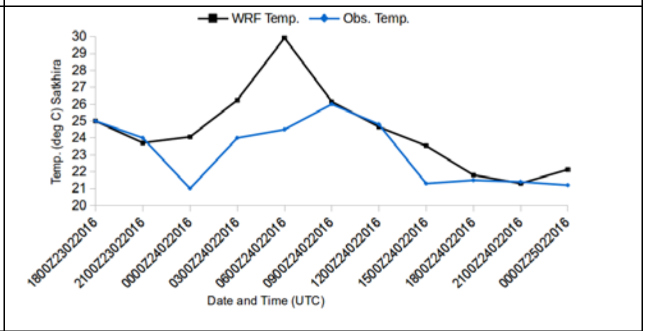

Figure 10 (f): Model simulated and observed temperature over Satkhira

Satkhira on 24 February 2016 (Figure 8c). The figure shows the ice water mixing ratio in the layer 700-560 hPa during 0300-0600 UTC and in the layer 600-150 hPa, having highest ice water mixing ratio of 40-90 mg kg^{-1} at 0800 UTC, 1100 UTC and 1200 UTC. The nor'wester occurred at Satkhira in the morning when there does not exist ice water mixing ration. So, the model has simulated the ice water mixing during the time of occurrence of the nor'wester on 24 February 2016 and the value is compatible with the previous study done by Das *et al.*, (2015d).

4.7 Synoptic flow pattern from reanalysis data

The synoptic flow pattern with sea level pressure, wind vector and temperature distribution has been prepared from NCEP FNL data of 0000UTC of 24 February 2016 (Figures 9 a,b). The distribution of sea level pressure and wind vectors at 10 m height in Bangladesh and adjoining areas are shown in Fig. 9a. The figure shows a low pressure system over western and central Bangladesh including Satkhira, Barisal, Dhaka and surroundings. A micro low exists over the area northwest of Dhaka with minimum pressure of about 1010 hPa. This micro low is conducive for the formation of severe thunderstorm/ nor'westers. The wind vectors at 10 m shows strong south-southwesterly wind flows over the Bay of Bengal, entering Bangladesh forming a circulation over the area a little southeast of Dhaka. This circulation indicates a favorable situation for thunderstorm.

Table 3. RMSE of Meteorological Parameters for Different Stations

Station	SLP (hPa)	RH (%)	Rainfall (mm)	Temperature (^oC)
Barisal	1.31	7.39	5.08	2.46
Dhaka	1.97	19.17	1.51	2.29
Satkhira	0.75	15.44	18.45	2.13

A circulation is found vertically at 950 hPa levels as shown in Figure 9b at 0000 UTC on 24 February 2016. Southwesterly wind is also strong at 950 hPa level over the coastal region of the country. The strong southwesterly winds and the circulation with its vertical extension confirm the strong influx of moisture over Bangladesh and adjoining area. The wind speed < 20 ms^{-1} over coastal region. Figure 9(b) also shows the spatial distribution of temperature at 2 m with relatively more warm air in Bay of Bengal and adjacent coastal region. The air over north and northeast of Bangladesh is comparatively cooler. The air temperature at 950 hPa level is >300K over the Bay of Bengal south of 21°N between87-90° E and temperature is about 298-300K over the head Bay and less that 298K over coastal region except Satkhira region where it is 298-300K. The higher temperature over the Bay of Bengal supports moisture and energy fluxes over the country.

4.8 Model performance evaluation

Figures 10(a-c) to 10 (d-f) indicate the comparison of model simulated and observed three hourly sea level pressure and temperature at 2m over Barisal, Dhaka and Satkhira respectively from 1800 UTC 23 February to 0000 UTC 25 February 2016. There are some similarities and dissimilarities in the variation of SLP and temperature along with underestimation and overestimation of the values. The statistical analysis of root mean square errors (RMSE) of SLP, temperature, RH and rainfall is shown in the Table 3. The table shows that the model performance for SLP and temperature is better at Satkhira, performance for rainfall is better at Dhaka and the performance for RH is better at Barisal.

5. Conclusions

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

i. The model is able to simulate the physical and dynamical parameters well with sufficient lead time.

ii. WRF model is able to simulate rainfall associated with nor'westers quite well but not at the specific location where the rainfall occurs. The convection is found to move in the east-southeast or east-northeast, differing from one storm to another.

iii. Low pressure is simulated in the West Bengal and western part of Bangladesh and is found to intensify during the formation and occurrence of nor'westers. Mean sea level pressure is seen to decrease by 2.27 hPa from about 0600 UTC to 0900 UTC on 24 February 2016 at Satkhira.

iv. The model has simulated strong south-southwesterly flow and circulation at 10 m as well as at 950 hPa level on the dates of occurrence of nor'westers over Bangladesh. The model is able to capture maximum wind speed at 10m level but the values are not location specific. There was a trough of strong westerly jet stream of about 40-50 ms^{-1} at 300 hPa over Bangladesh on 24 February, which persisted up to 0000 UTC on 25 February 2016.

v. The model has simulated maximum reflectivity of clouds with 50 dBZ and about 6 hours or more before as compared to the time occurrence of nor'westers but the maximum reflectivity is not location specific. As per the criteria of reflectivity, the intensity of nor'wester was heavy and the rainfall rate was 48.6 mm/hr.

vi. A zone of minimum relative humidity simulated by WRF model is found to exist at 2 m level over West Bengal and adjoining western Bangladesh and high relative humidity exists over northeastern and eastern parts of Bangladesh on the dates of occurrence of nor'westers. The relative humidity is as low as 6-20% over the western part of the country in some cases, indicating very dry atmosphere before the occurrence of nor'westers in Bangladesh. There is an interaction of dry and most air near the place of occurrence.

vii. The vertical time cross-section of relative humidity reveals that the lower atmosphere up to about 600 hPa remains very humid on the dates of occurrence of nor'westers. An atmospheric window is found through which moisture rises upwards up to about 200 hPa level or more near the time of occurrence of nor'westers in Bangladesh. At 200 hundred hPa relative humidity spreads like an anvil with time, indicating severe icing conditions. A drying condition is found near the surface and at 850 hPa before the occurrence of nor'westers.

viii. There exists a small area of higher model simulated temperature at 2m over West Bengal and adjoining western Bangladesh in the morning on the dates of occurrence of Nor'westers. This small area of higher temperature is found to extend in an easterly direction with the increase in temperature and with the progress of the day. On 24 February 2016, which is the end of the of winter season, the simulated temperature is found to be 32°C over Bangladesh.

ix. The surface vorticity simulated by WRF model is found to be positive and increases during the time of occurrence of nor'westers over Bangladesh. A zone of higher vorticity is found to extend from southwestern Bangladesh to northeast up to Comilla from 0600 UTC to 1500 UTC with a value of about 300-400 $\times 10^{-5}$ s^{-1} at 1200 UTC on 24 February 2016.

x. Pockets of positive vertical velocity are found to exist in the morning and this vertical velocity becomes prominent with progress of the day and the time of occurrence of the storms. The updrafts and downdrafts are present in the atmosphere on the dates of occurrence of nor'westers. The values of vertical velocity are found to be about 2 ms^{-1}at Barisal and 1.2 ms^{-1} at Dhaka and Satkhira before the occurrence of nor'westers on 24 February 2016.

xi. The values of the cloud water mixing ratio are about 300-700 mg kg^{-1} on 24 February 2016 at Satkhira before the occurrence of nor'westers. The WRF model simulated ice water mixing ratio occurs in the mid- and upper troposphere mainly but it is found to occur more than one time too on the dates of occurrence of nor'westers. The value of ice water mixing ratio is found to be 40-90 mg kg^{-1} on 24 February 2016 at Satkhira before the occurrence of nor'westers. The ice water mixing ratio is possible to be predicted by WRF model with sufficient lead time of about 24 hours. Significant ice water mixing ratio between 0430-0900 UTC is found to extend from 700 hPa to 150 hPa over Dhaka on 24 February 2016. The maximum value of ice water mixing ratio is 110-170 mg kg^{-1} over Dhaka. Because of this vertically significant and maximum ice water mixing ratio, enormous hails and ice pellets occurred over Dhaka at about 0448 UTC.

xii. Existence of low pressure system, micro low, temperature and wind vectors at the surface and 950 hPa obtained from NCEP data analyses justify occurrence of nor'westers in Bangladesh.

xiii. RMSE reveals that the model performance for SLP and temperature is better at Satkhira, performance for rainfall is better at Dhaka and the performance for RH is better at Barisal.

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