# Simulation of Thunderstorm Event over Bogura and Its Adjoining Area of Bangladesh Using WRF-ARF Model

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## Abstract

In this study, an attempt has been made to simulate a thunderstorm event that occurred over Bogura (24.85°N and 89.22°E) on 1 May 2017 by using the WRF-ARW (Advanced Research WRF) model. The model is configured for this study by setting latitude 23°N and longitude 90°E as a central point of the domain with 259 grid point in East-West and North-South directions and WSM 3-Class Simple Ice Scheme microphysics option, Yonsei University (YSU) Scheme as PBL Parameterization, Revised MM5 Scheme for the surface layer, Unified Noah Land Surface Model as a land surface model, Rapid Radiation Transfer Model Scheme for both short wave radiation and longwave radiation and Kain-Fritsch (new Eta) Scheme as cumulus physics option. Then the model is compiled for 48 hours using the 1°×1° six-hourly Global Forecast System (GFS) data on a single domain of 9 Km horizontal resolution and 38 vertical layers. Half hourly model is output is visualized by Grid Analysis and Display System (GrADS). The model performance was done by analyzing different meteorological parameters, for example, mean sea level pressure (MSLP), wind pattern, two-meter height temperature and relative humidity (RH) as well as their vertical cross-section, convective available potential energy (CAPE), convective Inhibition (CIN), rainfall, and K-Index. For the validation of model-simulated different weather, parameters have also been compared with the 3 hourly observed value of the Bangladesh Meteorological Department, for instance, MSLP, Temperature and RH at 2-m height, and rainfall. All of the outcomes for various parameters have been presented in graphical form. It is found that the model simulated result is good enough to predict thunderstorm events over Bangladesh particularly, Bogura on the above-mentioned date. By way of conclusion, the result of the current research will help to detect thunderstorms precisely to forecast the weather timely to minimize the destruction of the environment and death of human beings.

***Keywords:*** Thunderstorms, ARW-ARW, CAPE, CIN, Rainfall.

## 1. Introduction

Thunderstorms (TSs) are quite common over Bangladesh (20°34´ N to 26°38´ N and 88°01´ E to 92°41´E) during the pre-monsoon season. These type of storms are locally known as 'Kalbaishakhi' in Bangla because of the heavy damage to life and property inflicted by them during the month of 'Baishakh'-the first month of the Bangla calendar (from mid-April to mid-May). Bangladesh has an estimate of 60–100 thunderstorm days per year [1]. According to Habib [2], TS is ranked 3rd in the list of hazards that affect Bangladesh (BD). Thunderstorms are the products of a highly unstable atmosphere. The instability depends on the incursion of moisture from the Bay of Bengal and the increase in solar heating of the Earth's surface. During the pre-monsoon season (March-May) generally, a low pressure area developed over Bihar/Sub-Himalayan West Bengal/Gangetic West Bengal and adjoining Bangladesh. Low-level winds from south-southeasterly direction coming from the Bay of Bengal converge over the low pressure and as a result, convection occurs. The moist air rises condense to form clouds and latent heat is released. This latent heat is responsible for the generation of instability in the atmosphere. Because of convergence, convection, and instability, the cloud passes through different stages forming cumulonimbus cloud (Cb-cloud), which in the mature stage produces strong updrafts and downdrafts. The high convective cumulonimbus cloud (Cb-cloud) is responsible for thunderstorms and related hazards. The top of the Cb-cloud may grow up to 15-18 Km. Strong updrafts and downdrafts persist in the cloud, which produces severe lightning, large hail, and heavy precipitation. Because of updrafts, downdrafts, and mixing of cloud water and ice water, large hails are formed and fall to the ground.

The economic consequences and therefore the loss of human lives because of thunderstorms is a growing concern. In recent years, BD has seen a record number of deaths due to lightning strikes of thunderstorms throughout the Pre-monsoon season. TS adversely impacts agricultural production, natural environment moreover as our economy. Due to this fact, study and experiment both theoretical and practical on the climatology of TS became a serious concern in scientific research since the last century. TS is a very complicated weather phenomenon. For understanding the thermodynamic features and forecasting the TS events, a large number of studies of TSs have been made by different authors. Karmakar *et al.* [3] analyzed the spatial and temporal distribution of the monthly and seasonal frequency of TS days together with the variability of TS days over BD during pre-monsoon season using the data from 1972 to 1993 where the mean TS days over BD significantly increase as the season progresses from March to May and are maximum in May. Karmakar *et al.*

[4] also studied different modified stability indices concerning the occurrence of Nor'wester over BD. The stability indices have been modified by considering the data at the 925 hPa pressure level. Das *et al.* [5] conduct a coordinated field experiment on severe thunderstorm observations and regional modeling over the South Asian region. Das *et al.* [6] also studied the characteristics of Nor'westers (severe TSs) observed over northeast India and adjoining BD during the pre-monsoon season based on synoptic, Radar, and TRMM observations and simulated using the WRF model. Ahsan *et al.* [7] performed a simulation study of a TS event over BD using the WRF-ARW model and concluded that the WRF-ARW model may be adopted in the study of research and prediction of the TSs during pre-monsoon season over Bangladesh, but it needs to do more case study. Mijanur *et al.* [8] have attempted to simulate the thermodynamic features of thunderstorm events over Dhaka on 4 April 2015 using an Advanced research dynamics solver of the WRF model. Rahman *et al.* [9] studied the statistics of thunderstorms and lightning in Bangladesh for a period from 1990 to 2017.

Although a huge number of studies are made on TSs, it is still not possible to predict TS events over BD accurately. So, we need more study on TSs. In this paper, we are interested in a thunderstorm event over Bogura on 1 May 2017 simulated by using the WRF-ARW model and analyzed the thermodynamic features related to the development of thunderstorms over Bangladesh. The WRF-ARW model performance of capturing thunderstorms is also validated by comparing the model-simulated data with observational data. The remainder of this paper is arranged as follows: The event description and data are provided in Sections 2 and 3, respectively. The governing equations for the WRF model are explained in Section 4, and the model description and configuration are presented in Section 5. A brief results and discussion is presented in Section 6. Finally, a conclusion is drawn in Section 7.

## 2. Event Description

For the present study, a thunderstorm event has been considered for the NWP study, which was occurred on 1 May 2017 over Bogura and the adjoining area at 1345 UTC. On that day, the wind speed (10m height) was 1.03 m/s, 26.40 mm rainfall was recorded by BMD over Bogura and the recorded mean sea level pressure was 1008.90 hPa at 1200 UTC.

## 3. Data

The WRF-ARW model is run by using the Global Forecast System (GFS) data. The NCEP FNL (Final)/GFS Operational Global Analysis data are on 1°×1° grids prepare operationally every six-hour time interval. This product is from the Global Data Assimilation System (GDAS), which continuously collects observational data from the Global Telecommunications System (GTS), and other sources, for many analyses. Typically, FNL (Final) ingests about 10% more observations than GFS. But, GFS is run earlier in support of time-critical forecast needs. In this study, GFS data for 48 hours run on 30 April at 0000 UTC produced by NCEP are used as the initial condition and lateral boundary condition. Moreover, the observed data, recorded by the BMD is used to validate the model simulated result for the same period.

## 4. Governing Equation of WRF-ARW Model

The WRF-ARW model equations are formulated using a terrain-following hydrostatic-pressure vertical coordinate denoted by $\eta$ and defined as,

$$\eta = \frac{P_h - P_{ht}}{\mu}, \quad (1)$$

$$\mu = P_{hs} - P_{ht}, \quad (2)$$

where, $P_h$ is the hydrostatic component of the pressure, and $P_{hs}$ and $P_{ht}$ refer to values along the surface and top boundaries, respectively [10].

The coordinate definition (Equation 1), proposed by Laprise, (1992) [11], is the traditional $\sigma$ coordinate used in many hydrostatic atmospheric models. $\eta$ varies from a value of 1 at the surface to 0 at the upper boundary of the model domain (Figure 1). This vertical coordinate is also called a mass vertical coordinate.

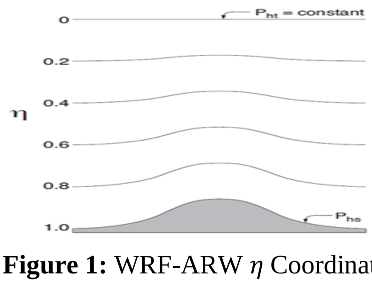


**Figure 1:** WRF-ARW $\eta$ Coordinate

Since $\mu(x, y)$ represents the mass per unit area within the column in the model domain at $(x, y)$, the appropriate flux form variables are

$$\boldsymbol{V} = \mu \boldsymbol{v} = (U, V, W), \quad (3)$$

$$\Omega = \mu\dot{\eta}, \quad (4)$$
$$\Theta = \mu\theta, \quad (5)$$

where, $\boldsymbol{v} = (u, v, w)$ are the covariant velocities in the two horizontal and vertical directions, $\dot{\eta} = \omega$ is the contravariant 'vertical velocity' and $\theta$ is the potential temperature. Also appearing in the governing equations of the ARW are the non-conserved variables $\phi = gz$ (the geo-potential), pressure (P), and $\alpha = 1/\rho$ (the inverse density). To resolve atmospheric dynamics, WRF uses a non-hydrostatic Euler equation. By using the method, flux-form Euler equations can be described as follow:

$$\partial_t U + (\boldsymbol{\nabla}\cdot\boldsymbol{V}_u) - \partial_x(P\phi_n) + (P\phi_x) = F_U, \quad (6)$$
$$\partial_t V + (\boldsymbol{\nabla}\cdot\boldsymbol{V}_v) - \partial_y(P\phi_n) + \left(P\phi_y\right) = F_V, \quad (7)$$
$$\partial_t W + (\boldsymbol{\nabla}\cdot\boldsymbol{V}_w) - g\left(\partial_\eta P - \mu\right) = F_W, \quad (8)$$
$$\partial_t\Theta + (\boldsymbol{\nabla}\cdot\boldsymbol{V}_\theta) = F_\Theta, \quad (9)$$
$$\partial_t\mu + (\boldsymbol{\nabla}\cdot\boldsymbol{V}) = 0, \quad (10)$$
$$\partial_t\emptyset + \mu^{-1}\left[\left(\mathbf{V}\cdot\boldsymbol{\nabla}_\phi\right) - gW\right] = 0. \quad (11)$$

The diagnostic relation for the inverse density,

$$\partial_\eta\Phi = -\alpha\mu. \quad (12)$$

And, the equation of state

$$P = P_o(R_d\theta/P_o\alpha)^\gamma. \quad (13)$$

In the equations (6-13) the subscripts $x, y,$ and $\eta$ denote differentiation

$$\boldsymbol{\nabla}\cdot V_a = \partial_x(U_a) + \partial_y(V_a) + \partial_\eta(\Omega_a), \quad (14)$$

and,

$$\boldsymbol{V}\cdot\boldsymbol{\nabla}_a = \mathrm{U}\partial_x a + V\partial_y a + \Omega\partial_\eta a, \quad (15)$$

where '$a$' represents a generic variable. $\gamma = C_p/C_v$= 1.4 is the ratio of the heat capacities for dry air, $R_d$ is the gas constant for dry air, and $P_o$ is a reference pressure (typically $10^5$ Pascals). The right-hand-side terms, $F_U$, $F_V$, $F_W$, and $F_\Theta$ represent forcing terms arising from model physics, turbulent mixing, spherical projections, and the earth's rotation. Using Euler equations, the model calculates the atmospheric process in a selected projection system [10]. Equations (6)-(8) and (9)-(10) are referred to as the conservation of momentum and equation of continuity, respectively and equation (11) represents the material derivative of the definition of the geopotential. The ARW dynamic solver solves the above equations of the WRF-ARW model is given in the reference [12].

## 5. Model Description and Configuration

The weather research and forecasting (WRF) model is a numerical weather prediction (NWP) model which is widely used in weather forecasting and meteorological research nowadays. There is two dynamics solvers in the WRF: (a) Advanced Research WRF (ARW) solver; (b) Non-hydrostatic Mesoscale Model (NMM) solver. The

**Table 1:** Overview of WRF model configurations

| Domain & Dynamics | |
|---|---|
| WRF core - | ARW |
| Data - | NCEP–GFS |
| Input Data Interval- | 6 hours |
| Run Time | 48 hours |
| Output Data Interval- | 30 mins |
| Number of Domain - | 1 |
| Central Point of the Domain - | 23° N, 90° E |
| Resolution - | 9 Km × 9 Km |
| Grid Size - | 259 × 259 × 38 |
| Covered Area - | 15°– 28° N and 82°– 98° E |
| Map Projection - | Mercator |
| Integration Time Step - | 30 s |
| Vertical Coordinates - | Pressure Coordinate |
| Time Integration Scheme - | 3rd Order Runge-Kutta |
| Spatial Differencing Scheme - | 6th Order Centered Difference |
| Physics | |
| Microphysics - | WSM 3-Class Simple Ice Scheme |
| PBL Parameterization - | Yonsei University (YSU) Scheme |
| Surface Layer Physics - | Revised MM5 Scheme |
| Land-Surface Model - | Unified Noah LSM |
| Short and Long Wave Radiation - | RRTM Scheme |
| Cumulus Parameterization - | Kain–Fritsch (new Eta) Scheme |

ARW dynamic solver together with other components of the WRF modeling system compatible with that solver is referred to as the WRF-ARW Model. Thus, it is a subset of the WRF modeling system that, additionally to the ARW solver, encompasses physics scheme, dynamics options, initialization routines, and a data assimilation package (WRF-Var). For detailed information about the WRF model and how to run an ARW system, ARW User's Guide has the details on its operation [7]. The latest version of this model is the WRF-ARW version 4.2.2 which was released on 15 January 2021 and we use WRF-ARW version 4.1 in this study. An overview of the configurations for the WRF model used in this study is given below.

## 6. Result and Discussion

Different kinds of meteorological parameters, for instance, mean sea level pressure, temperature, relative humidity, wind pattern, and the total amount of rainfall, etc. play a vital role in the formation and development of TSs. These parameters along with the instability index e.g., CAPE, CIN, and K-index during a TS event on 1 May 2017 over Bogura, performed by the WRF-ARW model are deeply analyzed. A comparison with the observed data is also made for the validation of the model performance to capture a TS event over this region.

### 6.1 Analysis of Mean Sea Level Pressure

One of the most important ingredients for the formation of thunderstorms is the development of the low-pressure area [13]. Low pressure means depression is present and warm air with high RH approaching these regions. So, the analysis of MSLP is very important for the simulation of any thunderstorm events. From the model-simulated MSLP analysis, it is found that a trough of a westerly low is extended up to Bangladesh and its adjoining area (shown in Figure 3) where the value of MSLP is about 1002 hPa to 1008 hPa from 0900 UTC to 1500 UTC on 1 May 2017. This trough of westerly low conjugates with easterly waves, then thunderstorm usually forms. The lowest pressure of magnitude of 1002 hPa is found in West Bengal and the adjoining area. So, the model simulates the westerly trough very well which is the supportive condition for the formation of thunderstorms based on 0000 UTC 30 April 2017 initial conditions.

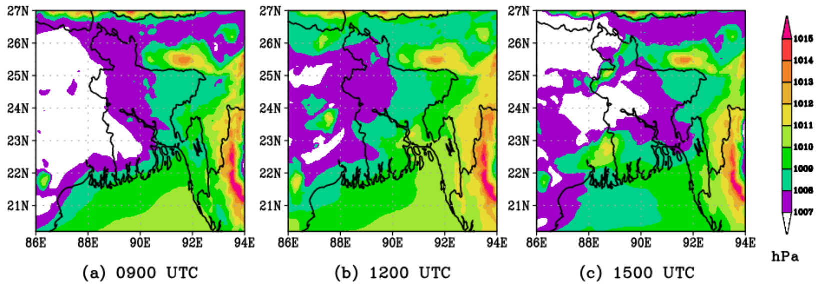


**Figure 3:** ARW model simulated MSLP using GFS data on 1 May 2017.

For the validation of model-simulated MSLP, a comparison is made with three hourly observed MSLP recorded by BMD over Bogura on 1 May 2017. This comparison is shown in Figure 4. From the simulation result, a sharp fall of MSLP from 1010.03 hPa to 1005.71 hPa, is found over Bogura, from 0600 UTC to 1200 UTC. From Figure 4, it is also found that observed data shows a fall of MSLP from 1011.20 hPa to 1008.90 hPa over Bogura during the same period. So, it can be said that the model captures the sharp fall of MSLP very well which confirms the validity of our model. Here, the Root Mean Square Error (RMSE) is 3.22 hPa on that day. The values of RMSE are acceptable due to errors found beyond the event time.

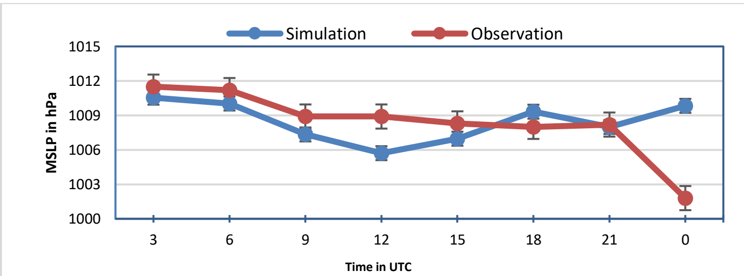


**Figure 4:** Comparison of MSLP between model-simulation and observation over Bogura.

### 6.2 Analysis of Wind Pattern at 850 hPa Level

The model-simulated wind was analyzed at levels 850 hPa. Figure 5 shows the model-simulated patterns at 0900 UTC, 1200 UTC, and 1500 UTC. From the analysis of model-simulated wind speed and direction at 850 level, it is found that a well-organized convergence zone is found in the foot hill of Himalaya and adjoining north Bihar.

The model has simulated the westerly trough of wind very well where the magnitude of wind speed is lower in the center of the convergence zone where the higher value of wind speed is found at the surrounding adjacent of the convergence zone. On the other hand, a high-pressure area or a divergence zone is found on the south-west part of the Bangladesh and Bay of Bengal. So, from the divergence zone wind travels to the convergence zone, from the Bay of Bengal towards Bangladesh. These wind carry a high amount of moisture over Bangladesh which is the initial condition for the thunderstorm formation and gathering lower level heat energy flux. So, it can be said that the model has simulated the wind speed at 850 level very well based on 0000 UTC 30 April 2017 initial conditions as shown in Figure 5. The wind speed over Bogura at this level is around 29 $Kmh^{-1}$ and at the upper level of the atmosphere (low-pressure level) wind speed increases (Figures are omitted here).

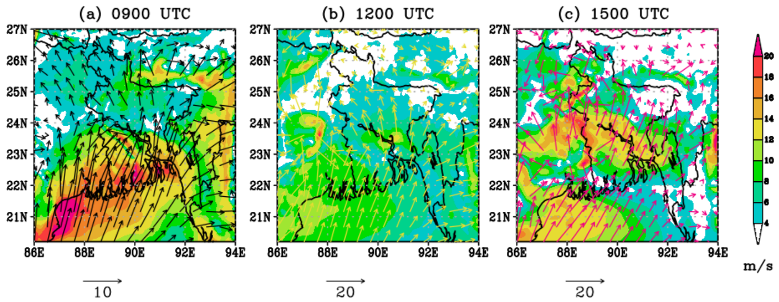


**Figure 5:** ARW model simulated wind pattern on 1 May 2017 based on 0000 UTC 30 April 2017 initial condition.

## 6.3 Analysis of Temperature at 2m Height and Vertical Cross-section of Temperature

From the analysis of model-simulated temperature at 2-meter height, it is found that the western part of Bangladesh and adjoining Indian regions have a higher magnitude of temperature which is more than 34°C at 1200 UTC on 1 May 2017 [Figure 6(a)]. After that temperature declines to less than 30°C at 1500 UTC which is very much supportive for occurring of convective precipitation and the model simulates the temperature very well based on the 0000 UTC 30 April 2017 initial conditions.

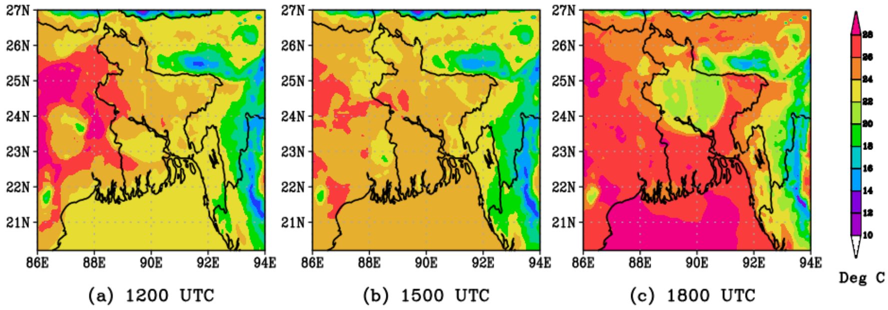


**Figure 6:** ARW model simulated temperature at 2-m height using GFS data on 1 May 2017.

For the validation of model-simulated 2-meter height temperature, three hourly temperatures of 1 May 2017 simulated by the WRF-ARW model using GFS data combination is compared with three hourly temperatures recorded by BMD. This comparison over Bogura is shown in Figure 7. From the observed temperature, a sudden fall from 32°C to 23°C is found over Bogura on 1 May 2017 during 0900 UTC to 1500 UTC. From Figure 6, it is also found that the simulated result shows a drop of temperature from 33.42°C to 28.87°C over Bogura during

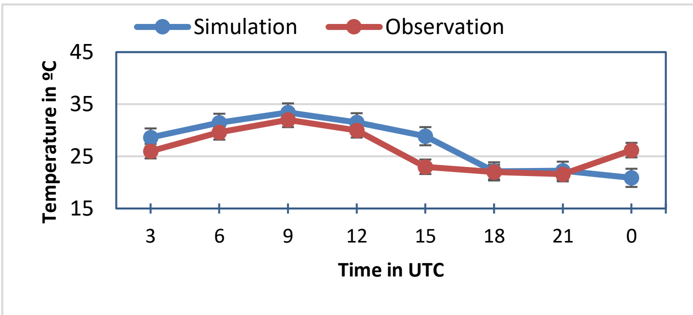


**Figure 7:** Comparison of 2-meter height temperature between model-simulation and observation over Bogura.

the same time. So it can be said that the model shows a decrease in temperature (i.e., a high value of RH), similarly, the model captures the sharp fall of temperature very well over Bogura. Here, RMSE is 3.12°C on that day. The values of RMSE are acceptable due to errors found beyond the event time.

Cross-section of temperature, for example, can give the idea where temperature inversions are located and also where the gradient of temperature is the strongest [14]. Model-simulated vertical cross-section of temperature between 1000 hPa (level-1) and 0 hPa (level-21) along 24.85ºN (latitude of Bogura) using GFS data at 1200, 1500, and 1800 UTC on 1 May 2017 based on 0000 UTC 30 April 2017 initial conditions is shown in Figure 8. The model-simulated vertical cross-section of temperature varies from -10ºC to 30ºC over Bogura and adjoining areas for different pressure levels. It is seen that temperature inversion has occurred between 300 hPa and 250 hPa (levels 15 and 16) levels. It is also found that the lower the pressure level (levels from 1 to 10) higher the temperature (around 25 ºC) i.e., vice-versa. Temperature fall is clear in the Bogura (longitude 89.37°E). By way of conclusion, a thunderstorm occurs in this region.

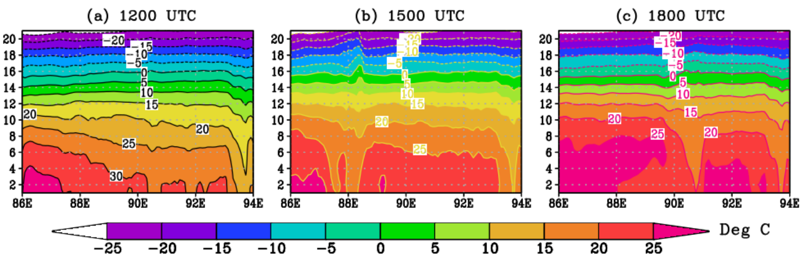


**Figure 8:** ARW model simulated vertical cross-section of temperature along 24.85ºN (Bogura) using GFS data.

## 6.4 Analysis of RH at 2-meter Height and Vertical Cross-section of RH

RH is a very important factor for the detection of clouds and rainfall. From the analysis of model-simulated relative humidity at 2-meter height, it is found that from 0900 UTC to 1200 UTC over West-Bengal and adjoining areas of Bogura is less than 60% to around 70%. Usually, thunderstorm forms at the higher value of RH (i.e., >60 %) [15]. The increase of relative humidity is the pre-condition of the formation of thunderstorms. So, we can say, the model has simulated the relative humidity very well based on the 0000 UTC 30 April 2017 initial conditions (shown in Figure 9).

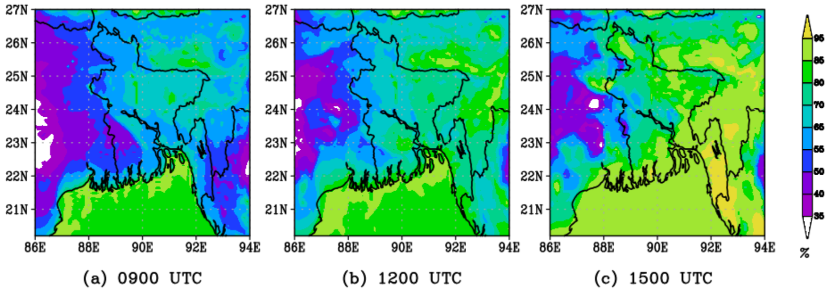


**Figure 9:** ARW model simulated relative humidity at 2-m height using GFS data on 1 May 2017.

For the validation of model-simulated 2-meter height RH, three hourly RH of 1 May 2017 simulated by WRF-ARW model using GFS dataset combination is compared with three hourly RH recorded by BMD. From the observed data, a sharp rise of RH from 49% to 87% during 0900 UTC to 1500 UTC is found over Bogura. From the model simulation result, the increase of RH over Bogura is 58.09% to 79.09% which is shown in Figure 10.

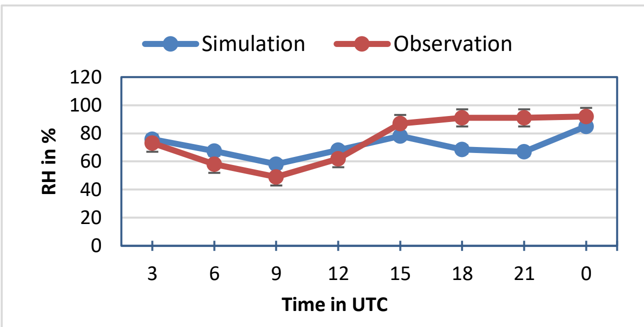


**Figure 10:** Comparison of 2-meter height relative humidity between model-simulation and observation.

From the above analysis, it is found that the model captures the rise of RH very well. In conclusion, we can say that thunderstorms occurred after 1200 UTC because of RH value is more than 60% at that time.

A cross-section of relative humidity shows the distribution of humidity in the vertical. In the example here it is the case of intensive convection with high humidity levels reaching up to the top of the troposphere [14]. Model-simulated vertical cross-section of RH from 1000 hPa to 0 hPa (1-21) levels along 24.85ºN (latitude of Bogura) using GFS data at 1200 UTC, 1500 UTC, and 1500 UTC on 1 May 2017 based on 0000 UTC 30 April 2017 initial conditions is shown in Figure 11. The model simulated a vertical column of RH 60-100% over Bogura and adjoining areas. This column is well organized and looks like towering cumulous type clouds. Also, a small zone in this column between 650 hPa and 550 hPa (8-10) levels has RH 100%. It indicates possible rainfall and hail formation which is very much favorable to the occurrence of thunderstorms over these areas. It is seen that a tower has been formed in Bogura from at 1200 UTC and afterward it became mature with the value RH around 100% up to level 11 which confirmed occurrences of thunderstorms in this region.

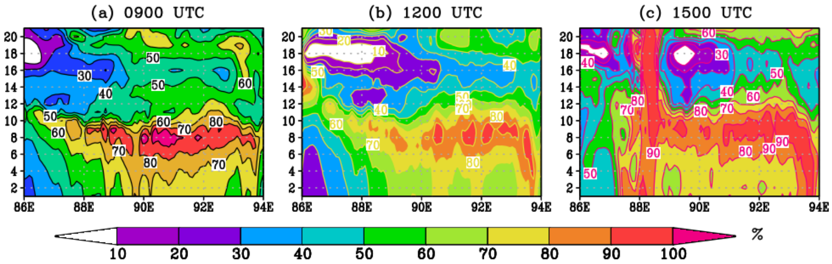


**Figure 11:** ARW model simulated vertical cross-section of RH along 24.85ºN (Bogura) using GFS data.

## 6.5 Convective Available Energy (CAPE)

CAPE provides a measure of the maximum possible kinetic energy available for convection and indicates tropospheric instability at a given time [16]. CAPE is calculated as the positive temperature difference between the theoretical parcel and environmental lapse rates, vertically integrated to the natural logarithm of pressure, P, between the level of free convection (LFC) and equilibrium level (EL):

$$CAPE = \int_{LFC}^{EL} R_g(T_{ve} - T_{vp})dlnP,$$

where, $T_{ve}$ and $T_{vp}$ are the environmental and parcel virtual temperature, $R_g$ is the gas constant of dry air. CAPE is measured in $JKg^{-1}$. The following table gives a greater understanding of the indication of the numerical values

**Table 2:** Indication of CAPE value related to the convection of air parcels

| CAPE Value in $JKg^{-1}$ | Convective Potential |
|---|---|
| 0 | Stable |
| 0-1000 | Marginally Unstable |
| 1000-2500 | Moderately Unstable |
| 2500-3500 | Very Unstable |
| 3500+ | Extremely Unstable |

According to the national weather service, CAPE values in thunderstorm environments often may exceed 1000 joules per kilogram ($JKg^{-1}$), and in extreme cases may exceed 5000 $JKg^{-1}$.

From the analysis of model-simulated convective available potential energy, it is found that the value of CAPE at the most unstable layer started at 1200 UTC on 1 May 2017, is greater than 2500 J/Kg. A CAPE value greater than 1500 J/Kg is required for the formation of a supercell thunderstorm [17]. From the model-simulated result,

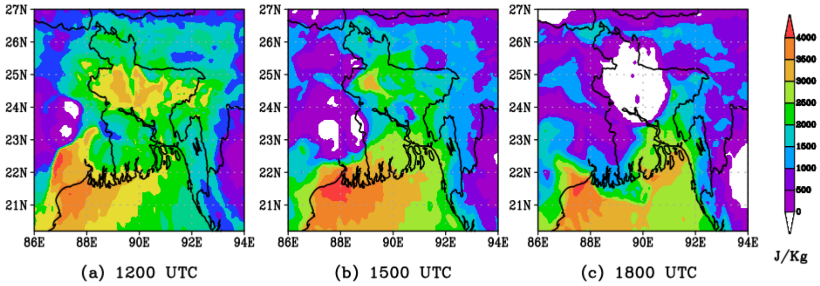


**Figure 12:** ARW model simulated CAPE using GFS data on 1 May 2017.

it is seen that over Bogura CAPE value reaches around 2000 J/Kg at 1500 UTC. Subsequently, the value started to decrease for the rest of the time. So, the value of CAPE is greater than 1500 J/Kg throughout the country which is the pre-condition of formation of thunderstorms, and the model simulates CAPE very well based on the 0000 UTC 30 April 2017 initial conditions. This is depicted in Figure 12.

## 6.6 Convective Inhibition (CIN)

Convective inhibition is a measure of the energy required by the atmosphere, at a given time and location, to inhibit the ability of an air parcel to rise (because of convection). It is essentially a measure of how much the current atmospheric conditions can resist the rising of an air parcel and thereby allow for vertical cloud development and thunderstorms. CIN values can range from zero to greater than 200:

- **<50** means that the energy required to develop vertically is low, and thunderstorm development chances are high [18].
- **50 to 200** mean that a certain amount of additional heat energy would be required to break the inhibition and allow for storm development.
- **>200** means that the atmosphere's ability to resist storm development is strong, so the risk for thunderstorms is low.

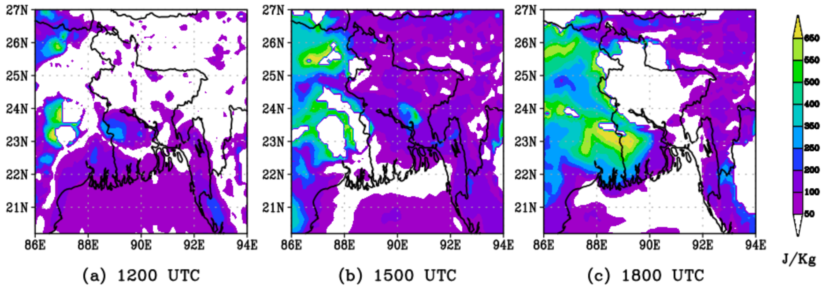


**Figure 13:** ARW model simulated CIN using GFS data on 1 May 2017.

The z-bottom and z-top limits of integration in the equation represent the bottom and top altitudes (in meters) of a single CIN layer, $T_{v,parcel}$ is the virtual temperature of the specific parcel and $T_{v,env}$ is the virtual temperature of the environment. In many cases, the z-bottom value is the ground and the z-top value is the LFC. CIN is an energy per unit mass and the units of measurement are joules per kilogram (J/kg). CIN is expressed as a negative energy value. CIN values greater than 200 J/kg are sufficient to prevent convection in the atmosphere. CIN can be calculated by the following equation:

$$CIN = \int_{z_{bottom}}^{z_{top}} g[(T_{v,parcel} - T_{v,env})/T_{v,env}]dz.$$

The spatial distribution of CIN on 1 May 2017 is presented in Figure 13. It is found that the northern and northwest part of Bangladesh and nearby territory of India is characterized by a low CIN of 0-30 J/Kg at 1200 UTC. It means that the energy required to develop vertically is low, and thunderstorm development chances are high [18]. At 1500 UTC CIN is more than 50 J/Kg over Bogura which means that TSs occurred between 1200 UTC and 1500 UTC. Low CIN value which is favorable to occur convection. A combination of high CAPE (Figure 12) and low CINE would render the environment thermodynamically favorable for convection to occur thunderstorms.

## 6.7 Analysis of Rainfall

When downdraft starts to dominate over updraft, thunderstorm gradually dies through heavy rain. So, rainfall plays an important role in a thunderstorm. Model-simulated 24-hour accumulated rainfall with 3 hours' interval (here, between 1200 UTC and 1800 UTC) on 1 May 2017 based on 30 April 2017 initial condition has been shown in Figure 14. It is found that the model has generated approximately 22 mm amount of rainfall in Bogura and adjoining areas. The highly localized rainfall has occurred over Bogura and adjoining areas due to the formation of deep convective clouds. For the validation of model-simulated rainfall, comparisons are made between the model-simulated 24 hours of rainfall with 3 hours interval using GFS dataset combination and the BMD's observed rainfall data. The comparisons are shown in Figure 15 and it is found that model simulated rainfall is lower than the observed rainfall in Bogura. So, in this case, model-simulated rainfall underestimates compared to the observed rainfall. But the model is capable to capture the rainfall of the thunderstorms though it has biases.

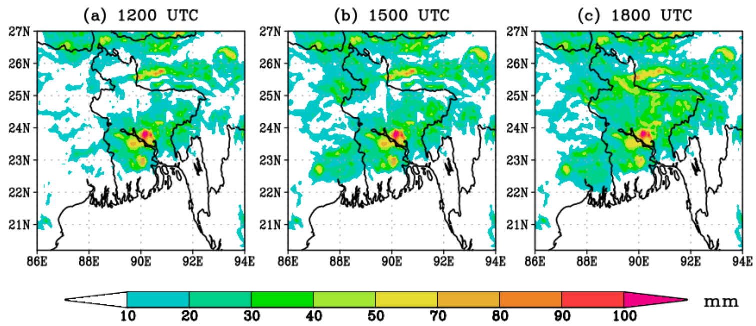


**Figure 14:** ARW model accumulated simulated rainfall using GFS data on 1 May 2017 based on 0000 UTC 30 April 2017 initial conditions.

## K-Index

The **K-Index** measures thunderstorm potential in meteorology. According to the National Weather Service, the index harnesses measurements such as "vertical temperature lapse rate, moisture content of the lower atmosphere, and the vertical extent of the moist layer" [21]. The index is derived arithmetically by [22]:

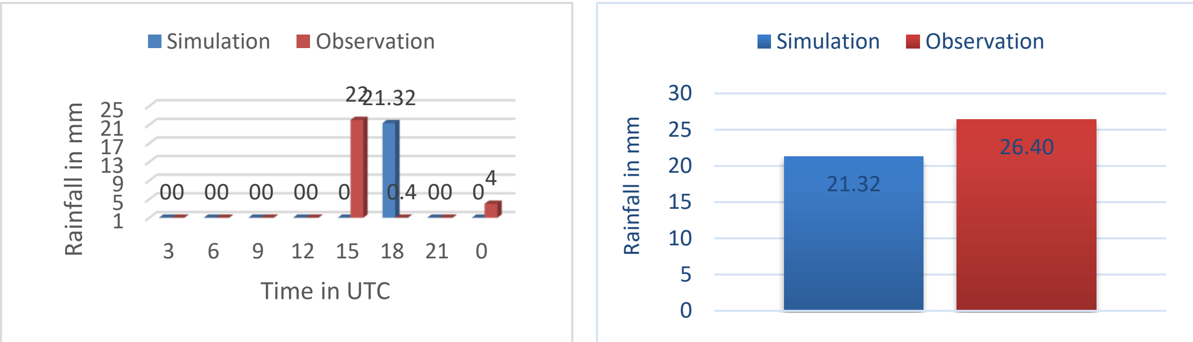


Fig. 15: Comparison of 3-hourly rainfall between model-simulation and observation (left) and comparison of 24 hours model-simulated rainfall and observed rainfall (right) over Bogura.

$$\mathbf{K = (T_{850} - T_{500}) + T_{d_{850}} - (T_{700} - T_{d_{700}}),}$$

where, $T_{850}$ = temperature at 850 hPa, $T_{500}$ = temperature at 500 hPa, $T_{d_{850}}$ = dew-point at 850 hPa, and $T_{d_{700}}$ = dew-point at 700 hPa. It was developed with the idea that Probability (in %) i.e., thunderstorm potential is equal to 4×(KI - 15), which gives the following interpretation [23] and The K-Index is related to the probability of occurrence of a thunderstorm as follows:

**Table 3:** Indication of K-Index value related to the thunderstorm probability and Potential

| **K-Index Value in °C** | **Probability of TSs** | **K-Index Value in °C** | **TSs Potential** |
|---|---|---|---|
| <20 | None | 0-15 | 0% |
| 20-25 | Isolated Thunderstorms | 18-19 | 20% Likely |
| 26-30 | Widely Scattered Thunderstorms | 26-29 | 30% Isolated TSs |
| 31-35 | Scattered Thunderstorms | 30-35 | 80% Numerous TSs |
| >35 | Numerous Thunderstorms | >36 | 100% Chance of TSs |

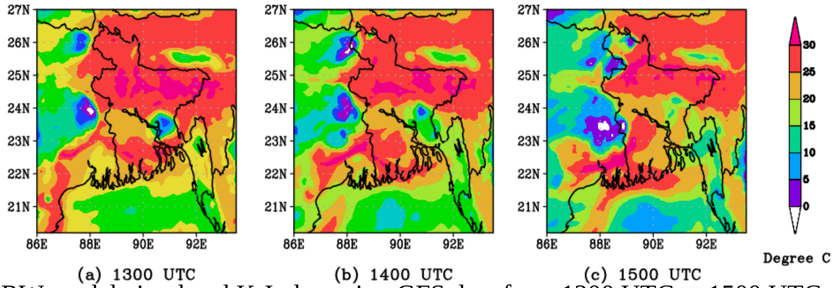


**Figure 17:** ARW model-simulated K-Index using GFS data from 1300 UTC to 1500 UTC on 1 May 2017 based on 0000 UTC 30 April 2017 initial conditions.

The KI is one of the main stability indices that we use to determine the probability of thunderstorm activity in an area. KI value greater than 35°C is supportive of the severe thunderstorms [20]. The spatial distribution of KI valid from 1300 UTC to 1500 UTC on 1 May 2017 are presented in Figure 17. It is found that the value of KI over Bogura is more than 30°C at 1300 UTC which indicates that the scattered thunderstorms with 80% numerous thunderstorms (TS Potential). After that KI declines to <30°C at 1400 UTC.

## 7. Conclusion

After analyzing the various parameters during the TS events over Bogura on 1 May 2017, performed by WRF-ARW for 48 hours, the following conclusion can be made on model performance for capturing TS events over Bangladesh

- The model captures the sharp decline of MSLP precisely well.
- The model is capable of capturing the wind pattern at 850 hPa level.
- Temperature fall has been observed during the TS.
- The model captures the rise of RH reasonably well in comparison with the observation.
- WRF-ARW model is capable to capture the rainfall in thunderstorm events and their surrounding areas.
- WRF-ARW model has done well in capturing the high CAPE value (>1500 J/Kg), low CINE value (<50 J/Kg) which are favorable for convection and considerable reflectivity (dBZ) as well as K-Index value.

Finally, despite some temporal and spatial errors for capturing various parameters, it can be said that the WRF-ARW model captures the TS event reasonably well. So, WRF-ARW model output can be used to forecast the future TS event reasonably well, and model output can be used to forecast the future TS events over Bangladesh.

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