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Feasibility of Radiation Schemes to Predict Extreme Temperature Conditions over Bangladesh

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ABSTRACT

An extreme temperature is a weather phenomenon that is distinguished by marked cooling or heating of the air, or with the invasion of very cold or hot air, over a large area. The present study is associated with the simulation of regional climate using the Weather Research and Forecasting (WRF) model that was experimented through 30 different combinations of radiation parameterization schemes over Bangladesh. The intention was to investigate the response to the radiation parameters schemes for dynamic down-scaling of climatic variables. The predicted temperature of 30 different WRF setups were analyzed and compared with the Bangladesh Meteorological Department (BMD) recorded data and were found sensitive to the radiation physics on the basis of Root Mean Square Error (RMSE) at 2-meter air temperature on 02-05 January 2019, 02-05 February 2019 and 28-31 December 2019 for Cold Wave (CW), and 24-27 April 2019, 09-12 May 2019 and 19-22 May 2019 for Heat Wave (HW) at 34 stations over Bangladesh. We conclude that the Rapid Radiative Transfer Model (RRTM) for long wave and Dudhia for short wave schemes are the most appropriate combinations to simulate in the extreme temperature. Using the selected combinations of WRF parameterizations to downscale the extreme weather events, which showed good agreement with the reference data. It was suggested WRF parameters from this study could be utilized for regional climate modeling of Bangladesh.

Keywords: Intergovernmental Panel on Climate Change (IPCC), Extreme, Feasibility, Scheme, Predict

1. INTRODUCTION

Extreme temperature is a rare weather phenomenon involving two parts “Heat Wave” and “Cold Wave”. A heat wave is a prolonged period of excessively hot and sometimes also humid weather relative to normal climate patterns of a certain region [http://www.ifrc.org]. A cold wave can be both a prolonged period of excessively cold weather and the sudden invasion of very cold air over a large area. Because heat waves are not visible as other forms of severe weather, like cyclones, tornadoes, thunderstorms, etc. they are one of the less known forms of extreme weather (Thornbrugh et al, 2007). The manifestation of severe heat weather damaged populations and crops due to potential dehydration. Dried soils are more susceptible to erosion as well as diminution of lands available for agriculture. There is no doubt that evaporation of bodies of water is devastating to marine populations, as it reduces the size of the habitats available and the amount of nutrition in the water. A cold wave can cause death and injury to livestock and wildlife. Exposure to cold motivates animals, including humans, to increase their caloric intake, and if a cold wave is accompanied by heavy and persistent snow, grazing animals may be unable to reach necessary food and water,

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and die of hypothermia (Thornbrugh et al, 2007). Due to this fact, study and experiment on the climatology of extreme temperature conditions both theoretically and practically have become a major concern in scientific research since the last century. Heat waves and its stress occur almost every year in Bangladesh, the severity of which is more over western, northwestern and northeastern parts of the country. These events affect severely on agricultural crops, reduce crop production significantly, livelihoods and deteriorate human and animal health as well as hampers food security greatly. The wind circulations associated with heat and cold waves at different levels of the troposphere have not yet been studied broadly in Bangladesh. The prediction of extreme temperature condition is necessary for precautionary measures and also for early warning and early action to reduce disaster risks. The prediction capability of extreme temperature conditions by Numerical Weather Prediction (NWP) model like Weather Research and Forecasting (WRF) model and role of its radiation physics is not studied fully in Bangladesh. So, the research is prerequisite on extreme temperature condition in Bangladesh sustainability of socio-economic development.

Advance information of cold waves is very important to avert their adverse impact on the life and economy of a given region. Prediction of the cold weather events are a challenging issue for the meteorologists and researchers and are useful to minimize the damage and for accepting necessary mitigation measures. Cold waves belong to the weather phenomenon which occurs when marked cooling of the air persists for a period of at least few days (Moberg & Jones, 2005). Generally cold waves occur with an advection of cold air mass over a large area associated with radiative cooling when a blocking anticyclone develops and persists for at least few days. Numerical simulation of cold waves requires combination of the various atmospheric processes in the model such as the interaction of the large-scale atmospheric flow with the local-scale circulation, interaction of the surface and planetary boundary layer (PBL) with the free atmosphere and vice versa, and radiation transfer. In numerical models the sub-grid scale processes are parameterized to define their interaction with grid-resolvable prognostic variables. The application of recently developed high resolution atmospheric models like the Advanced Research Weather Forecasting Model (ARW) is expected to improve the prediction of extreme weather events as the regional models are based on more advanced dynamical and physical processes. However, an important aspect of high-resolution models is their spin-up time. When operated in climate mode, they require simulation lengths exceeding the spin-up time which is of the order of several days (Dickinson et al, 1989) for the atmospheric component, and even much longer for the surface component. The theoretical limit for the useful daily weather forecast is about 10–14 days, but in practical application, the current limit is about 5–7 days. For longer periods of about months or seasons average temperature and precipitation can only be assessed; however, the skill of such forecasts is low. The developments of numerical models provide the basis for an improved understanding of monthly and seasonal weather variation and for an enhanced ability to predict them with reasonable skill. Even a small improvement in the skill of extended range forecasting of extreme weather events may be helpful to take necessary precautions and to minimize weather-related losses or deaths and is important for substantial economic benefit.

Extreme temperature events have been of great concern recently, due to their associated public health risk, plant growth and/or ecosystems (Ciais et al, 2005), the energy supply, and more (IPCC, 2014). The conditions and mechanisms of large-scale extreme temperature events have been extensively studied throughout the world, especially in Europe (Dasari et al, 2014) and North America (Gershunov et al, 2009). Panda et al (2017) made a study on the increasing heat waves and warm spells in India, observed from a multi-aspect framework. This study examines whether and to what extent heat waves and warm spells in India have changed since the mid-20th century, using a multi aspect framework to accommodate wide range of impact sectors. Consistent with the simultaneous increase in dry and hot extremes over several regions of the world, the Indian subcontinent has experienced a general rise in the frequency of heat waves. It is, however, interesting to find the distinctive spatial, temporal, and diurnal evolution of heat wave characteristics.

At the global scale, Seneviratne et al (2014) observed that the hot extremes continued to increase during the global warming hiatus, without any major El Niño event. As India is projected to be a global hot spot of heat stress on agricultural crops, persistence of dry-hot spells, particularly the pronounced night-time warming causing significant rice yield reduction (Peng et al, 2004), could pose a risk to the country's future food security. Globally, the year 2010 stands out clearly in terms of extreme events, with the largest summer-time warming over the Northern Hemisphere during June to August (Trenberth & Fasullo, 2012).

The recent increasing trend in the frequency and intensity of heat waves is often attributed to climate change (Mishra et al, 2015). According to the report of Japan Ministry of Environment, deaths due to heat stroke during the unusually hot summer in 2010 amount to 1745 in Japan. Deaths were also reported in India due to heat waves over the years. The heat wave of 1988 caused an estimated number of 1300 of deaths (De et al, 2004), and likewise the heat waves of 1998 and 2003 caused deaths of about 2042 people (Jenamani, 2012) and 3054 people (Bhadram, 2005), respectively. Climatologically heat waves occur during March to June (Pai et al, 2013), with high frequency over north, northwest, central and the eastern coastal regions of India. Some studies also linked the heat waves to the re-curving tropical cyclones in the Bay of Bengal (Jenamani, 2012). The recurving tropical cyclones before the onset of the heat waves could change the direction of the winds and cut-off moisture to the inland regions leading to heat waves. In spite of the large societal impact, there has been no systematic attempt to understand the principal mechanism of heat waves over India.

A recent study (Russo & Sterl, 2011) analyzed climate model temperature output for the period 1950–2100 and documented the global changes in extreme temperatures by using various climate indices. The study suggested significant increase in temperature extremes like warm days over the Indian region during the period 2001–2100. Therefore, there is an urgent need to develop a strategy for forewarning and mitigation efforts to minimize adverse effects of heat waves over the country. Karmakar (2018) made a study on climate change patterns, future trends and impacts in northwest Bangladesh. Rainfall data is used to compute the non-rainy days (dry days), and the relative humidity is used to compute heat stress over the places under the study. The trends of dry days and heat stress are studied. Daily maximum and minimum temperatures are used to find out the frequencies of days with temperature >36^0 C and temperature 36^0 C in the month of May whereas Dinajpur and Rangpur have the maximum mean frequency of maximum temperature >36^0 C in the month of April. Heat waves will be more long lasting in Rajshahi during April-July. In order to avoid the mass destruction of lives and property due to extreme temperature conditions an accurate region specific and timely prediction is required. But unfortunately, the improvement in prediction of these vital weather phenomena is still handicapped due to the lack of mesoscale observations and insufficient understanding. That is why more and more intense study, realistic simulation and reasonable modeling of extreme temperature conditions are required. This study is an attempt to provide those crucial features so that further future analysis and improved forecasting can be made possible. It is derived that solar radiation is the ultimate source of energy for the earth climate. Many scientists have studied radiative transfer for inhomogeneous atmospheres, RRTM, a validated correlated-*K* model for the long wave. The evaluation of the flux and cooling rate results of RRTM indicate that the model has accuracy consistent with line-by-line models. The speed of the model makes it suitable for use in general circulation models, and it is versatile enough to maintain these levels of accuracy and speed for diverse range of molecular abundance, temperature profiles, and layering schemes.

So, simulating different heat and cold wave events using WRF model by fixing up the radiation schemes, an attempt will be taken how these events forecasted reasonably well.

The objectives of this research are to:

i. finalize the best radiation physics options of WRF model for simulating extreme temperature for the heat and cold wave over Bangladesh,
ii. simulate some other extreme temperature events by using the best radiation physics options of WRF model and
iii. find out the performance of WRF model through validation and verification.

2. METHODOLOGY

2.1 Numerical Model

Major part of this research was done using a next-generation Numerical Weather Prediction (NWP) system, the WRF-ARW model developed mainly by the Mesoscale and Microscale Meteorology Laboratory (MMM) of National Center for Atmospheric Research (NCAR). Version 4.3.0 of the WRF model installed at Atmospheric Physics Laboratory of Department of Physics, Khulna University of Engineering & Technology (KUET) will be used for simulation of the extreme temperature conditions. The radiation schemes will provide atmospheric heating due to radiative flux divergence and surface downward long wave and shortwave radiation for the ground heat budget. The downward long wave radiation includes infrared (or thermal) radiation absorbed and emitted by gases and surfaces. The upward long wave radiative flux from the ground will be determined by the surface emissivity (depends upon land-use type and the ground (skin) temperature). Shortwave radiation covers the visible and surrounding wavelengths that make up the solar spectrum. Here, the only source is the Sun, but processes include absorption, reflection, and scattering in the atmosphere and at surfaces. For shortwave radiation, the upward flux is the reflection due to surface albedo. Within the atmosphere, the radiation responds to model-predicted cloud and water vapor distributions, as well as specified carbon dioxide, ozone, and (optionally) traces gas concentrations. All the radiation schemes in WRF currently are column (one-dimensional) schemes, so each column is treated independently. The fluxes correspond to these schemes in infinite horizontally uniform planes, is a good approximation if the vertical thickness of the model layers is much less than the horizontal grid length. This assumption would become less accurate at high horizontal resolution (Skamarock et al, 2005).

2.2 Data

Data needed to run the WRF-ARW model will be downloaded from https://rda.ucar.edu. Global Final Analysis (FNL) data will be used. The FNL data will be prepared on 1-degree by 1-degree grids operationally every six hours. This product is from the Global Data Assimilation System (GDAS), which continuously collects observational data from the Global Telecommunication System (GTS), and other sources, for many analyses. The FNL data will be prepared about an hour or so after the GFS is initialized. Recent 30 years observed data will be collected from BMD to construct recent climatology and trend analysis of extreme temperature. BMD observed and European Centre for Medium-Range Weather Forecasts (ECMWF) model data with horizontal resolution (0.125^{o} x 0.125^{o}) will also collected to validate and verify the WRF model performance.

2.3 Reach to the Objectives

For construction of recent climatology of extreme temperature (hot and cold weather), MS Excel and Surfer software will be used to draw the scenario of climatology of extreme temperature using recent 30 years observed data collected from BMD in the basis of yearly, seasonally, monthly and regionally for Bangladesh. For trend analysis of extreme temperature, MS Excel and Mann Kendall software will be used to draw the scenario of trend of climatology of extreme temperature using recent 30 years observed data collected from BMD in the basis of yearly, seasonally, monthly and regionally for Bangladesh.

WRF is computationally expensive and its optimal performance requires a tedious investigation over different combinations of parameterization schemes which vary from region to region. To find out the best combination of radiation physics options of WRF model, at first 6 shortwave and 5 longwave radiation physics schemes will be selected among all available radiation schemes. 6 (six) shortwave radiation physics schemes will be Dudhia, Goddard Space Flight Center (GSFC), Community Atmosphere model (CAM), Rapid Radiative Transfer model Goddard (RRTMG), New Goddard and Fu-Liou-Gu. Again, 5 longwave radiation physics schemes will be Rapid Radiative Transfer Model (RRTM), Community Atmosphere model (CAM), Rapid Radiative Transfer model Goddard (RRTMG), New Goddard and Fu-Liou-Gu. All of these 6 shortwaves and 5 longwave radiation physics schemes will make 30 independent combinations for 30 independent runs using WRF model. Model will run one combination of radiation (both shortwave and longwave) scheme along with fixed of other physics options. Fixed physics option chosen for PBL, cumulus, land surface model, Surface layer and micro-physics schemes will be Younsi State University (YSU), Kain-Fritisch, Noah unified, Monin–Obukhov similarity theory and WRF single moment 3 class respectively. Domain configurations and grid resolutions play a major role in the performance of WRF. Domain will be taking 10km horizontal resolution with the center at (18^o N, 89^o E) and grid numbers will be (w-e x s-n) 310 x 290, integration time step will be 30 seconds. WRF will be finally set up with 38 vertical pressure levels and the top level will be at 50 hPa. The initial and lateral boundary conditions of WRF are based on the most recent, NCEP final reanalysis (FNL) data for Medium Range Weather Forecasts at 1^o x 1^o resolution and 6-h time steps. Fixing the above physical parameter, model will be run for 3 heat waves and 3 cold waves.

From the output of WRF Model, 3 hourly 2m temperature have been extracted during the study periods. 34 meteorological stations of BMD will be considered to cover the different places of Bangladesh. The WRF model output gives the control (ctl) file and which is converted into text (txt) format data by using the Grid Analysis and Display System (GrADS). These data transformed into Microsoft Excel and finally compared with the BMD observed temperature at 34 meteorological stations. BMD observed temperature and model simulated temperatures are used for calculating RMSE. The RMSE is mathematically expressed as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2},$$

where n is the total number of simulated outputs, x is the model simulated values, y is the observed values. After calculating the RMSE for 2m air temperature at 34 stations over the Bangladesh for the 6 (six) cases, the appropriate radiation combination will be fixed out using average lowest RMSE value. Among the existing observed data collected from BMD, 5 (five) extreme heat wave and 5 (five) extreme cold waves will be selected for the case study. These selected cases will be simulated using the best combination of physics option in WRF model. Using the visualization software's meteorological parameters will be presented in graphical and tabular form. GrADS and Excel will be used for this purpose, observed parameters will be also presented by Surfer and Excel. Few selected parameters like pressure, 10m wind, 2m temperature, relative humidity at 2m and different levels, vorticity at different lower levels, vertical wind share of horizontal wind and different levels, latent heat flux at lower level (surface level), outgoing long-wave radiation, downward long-wave radiation, cloud fraction, shortwave downward radiation, temperature advection, construction of dry line, composite picture of temperature and wind speed, convective available potential energy, veering and backing for warm advection and cold advection etc. will be discussed.

For validation of the performance of WRF model, model output will be compared with observed data obtained from BMD and model data from ECMWF (0.125° x 0.125°).

3. RESULTS AND DISCUSSION

3.1 Sensitivity Test of Radiation Physics

Analysis of the meteorological fields corresponding to selected radiation combination with both of long wave and short-wave parameterization schemes and its associated impact temperature over Bangladesh has been performed using the Fifth-Generation NCAR Mesoscale WRF Model (Grell et al, 1994; Skamarock et al, 2005). The following investigations were done for the selected cases to complete the final goal of this research work:

- ✓ Sensitivity test of the different radiation parameterization combination with both of long wave and short-wave schemes of WRF model with coupling of the other fixing physical schemes for the prediction of the temperature due to cold wave (02-05 January 2019, 02-05 February 2019, 28-31 December 2019) and heat wave (24-27 April 2019, 09-12 May 2019 and 19-22 may 2019) and to settle the suitable radiation combination scheme.
- ✓ After finalization of radiation parameterization combination schemes of WRF model, selected meteorological parameters related to temperature are simulated accordingly.
- ✓ Afterwards an attempt has been made to validate the simulated temperature with the observed temperature of Bangladesh Meteorological Department.

3.1.1 Sensitivity test of the different radiation parameterization schemes both of long wave and short wave of WRF model for the prediction of the temperature due to cold wave (02-05 January 2019, 02-05 February 2019, 28-31 December 2019) and heat wave (24-27 April 2019, 09-12 May 2019 and 19-22 may 2019).

The radiation schemes provide atmospheric heating due to radiative flux divergence and surface downward long wave and shortwave radiation for the ground heat budget. This downward long wave radiation includes infrared (or thermal) radiation absorbed and emitted by gases and surfaces. Upward long wave radiative flux from the ground is determined by the surface emissivity (depends upon land-use type and the ground (skin) temperature). Shortwave radiation covers the visible and surrounding wavelengths that make up the solar spectrum. Hence, the only source is the Sun, but processes include absorption, reflection, and scattering in the atmosphere and at surfaces. For shortwave radiation, the upward flux is the reflection due to surface albedo. Within the atmosphere, the radiation responds to model-predicted cloud and water vapor distributions, as well as specified carbon dioxide, ozone, and (optionally) trace gas concentrations. All the radiation schemes in WRF currently are column (one-dimensional) schemes, so each column is treated independently. The fluxes correspond to these schemes in infinite horizontally uniform planes, is a good approximation if the vertical thickness of the model layers is much less than the horizontal grid length. This assumption would become less accurate at high horizontal resolution (Skamarock, et al, 2008). Among the available radiation schemes in WRF model, the following are the list of long wave and short-wave radiation schemes which used in this study.

- Rapid Radiative Transfer Model (RRTM) (LW1)
- Dudhia (SW1)
- Goddard Space Flight Centre (GSFC) (SW2)
- Community of Atmospheric Model (CAM) (LW3 and SW3)

- Rapid Radiative Transfer Model Goddard (RRTMG) (LW4 and SW4)
- New Goddard (LW5 and SW5)
- Fu-Liou-Gu (LW7 and SW7)

To checkup the sensitivity of the different Radiation (Rad) Parameterization Schemes to predict temperature of 3 cold wave and 3 heat wave of 2019, at first the WRF model was run for 120 hours using thirty combinational radiation physics which is made with above mentioned five long wave and six short wave Rad parameterization schemes and the simulated temperature at 2m height is tabulated and at last the simulated parameter is compared with observed values of Bangladesh Meteorological Department (BMD) and finalize the Rad for the simulation of temperature of others extreme events over the Bangladesh.

Table of RMSE on the basis of 2m air temperature

Time	lw1_sw1	lw1_sw2	lw1_sw3	lw1_sw4	lw1_sw5	lw1_sw7
Jan 2-5/19	2.160187	2.561455	2.489089	2.430999	2.455829	13.773188
Feb 2-5/19	2.126005	2.395583	2.324905	2.28295	2.34739	16.563725
Dec 28-31/19	2.335643	3.053864	2.973296	2.885945	3.107309	12.556504
Apr 24-27/19	2.157815	2.366742	2.323617	2.302439	2.30922	16.336184
May 9-12/19	2.004482	2.077395	1.987058	2.001775	2.131801	12.65726
May 19-22/19	2.060455	2.161884	2.071597	2.044351	2.244326	10.941935
RMSE	2.140764	2.436153	2.361593	2.324743	2.432645	13.804799

Time	lw3_sw1	lw3_sw2	lw3_sw3	lw3_sw4	lw3_sw5	lw3_sw7
Jan 2-5/19	2.324644	2.240535	2.216355	2.198702	2.212819	15.697282
Feb 2-5/19	2.313886	2.214456	2.187184	2.174439	2.192131	18.231027
Dec 28-31/19	2.409827	2.545686	2.487052	2.468975	2.557428	14.577083
Apr 24-27/19	2.61533	2.391594	2.354435	2.349375	2.366168	19.670882
May 9-12/19	2.356228	2.22233	2.162297	2.175644	2.225002	14.782481
May 19-22/19	2.533836	2.160664	2.202673	2.158643	2.1732	12.776729
RMSE	2.425625	2.295877	2.268332	2.254296	2.287791	15.955914

Time	lw4_sw1	lw4_sw2	lw4_sw3	lw4_sw4	lw4_sw5	lw4_sw7
Jan 2-5/19	2.168555	2.560013	2.490944	2.429045	2.469511	13.829642
Feb 2-5/19	2.126101	2.421981	2.345419	2.302769	2.246984	16.484734
Dec 28-31/19	2.313908	3.046594	2.967234	2.930875	2.752727	12.550685
Apr 24-27/19	2.161187	2.401375	2.350884	2.326369	2.351382	16.350716
May 9-12/19	2.045807	2.148025	2.044366	2.095508	2.097529	12.814666
May 19-22/19	2.068796	2.168701	2.10656	2.128896	2.090336	11.207767
RMSE	2.147392	2.457781	2.384234	2.368910	2.334744	13.873035

Time	lw5_sw1	lw5_sw2	lw5_sw3	lw5_sw4	lw5_sw5	lw5_sw7
Jan 2-5/19	2.16424	2.331819	2.275821	2.209166	2.260389	14.984038
Feb 2-5/19	2.197436	2.24848	2.202597	2.174106	2.17591	17.670787
Dec 28-31/19	2.15156	2.690573	2.644407	2.772737	2.540496	13.808499
Apr 24-27/19	2.0379	2.328353	2.274112	2.257735	2.295315	17.746197
May 9-12/19	2.198478	2.263769	2.176258	2.046549	2.050962	15.840896
May 19-22/19	2.14898	2.273918	2.21337	2.209892	2.173539	13.921865
RMSE	2.149765	2.356152	2.297760	2.278364	2.249435	15.662047

Time	lw7_sw1	lw7_sw2	lw7_sw3	lw7_sw4	lw7_sw5	lw7_sw7
Jan 2-5/19	2.099292	2.363887	2.305264	2.256062	2.285311	2.333906
Feb 2-5/19	2.143403	2.351847	2.296754	2.260605	2.387064	2.331219
Dec 28-31/19	2.411592	3.119917	3.045992	2.964139	3.179866	2.701205
Apr 24-27/19	2.549432	2.560867	2.524589	2.419849	2.295693	2.336684
May 9-12/19	1.952981	2.086974	1.995877	2.001323	2.123792	2.198828
May 19-22/19	2.075276	2.218112	2.164646	2.218293	2.365644	2.204516
RMSE	2.205329	2.450267	2.388853	2.353378	2.439561	2.351059

3.1.2 Spatial Distribution of RMSE using the best combination

The spatial distribution of the average RMSE based on the temperature (° C) at 2m height for (a) CW (02 to 05 January 2019) and (b) HW (24 to 27 April 2019) are shown in Figure 3.1.2.1. The highest average RMSEs (above 2° C) for the CW are found south eastern coastal areas of Bangladesh and some other places like Rajshahi, Chuadanga and Tangail (Figure 3.1.2.1(a)). The average RMSEs which are reasonably acceptable (2° C or less) are found in the rest of the parts of the country. The maximum average RMSE is found in Hatiya (4.76° C) and minimum is Dhaka (0.92° C).

The highest average RMSEs (above 2.2° C) for the HW are found southern coastal areas, middle western and north eastern parts of Bangladesh (Figure 3.1.2.1(b)). The average RMSEs which are reasonably acceptable (2.2° C or less) are found in rest of the parts of the country. The maximum average RMSE is found in Sandwip (3.81° C) and the minimum in Feni (1.16° C) and Bhola (1.17° C) is remarkable.

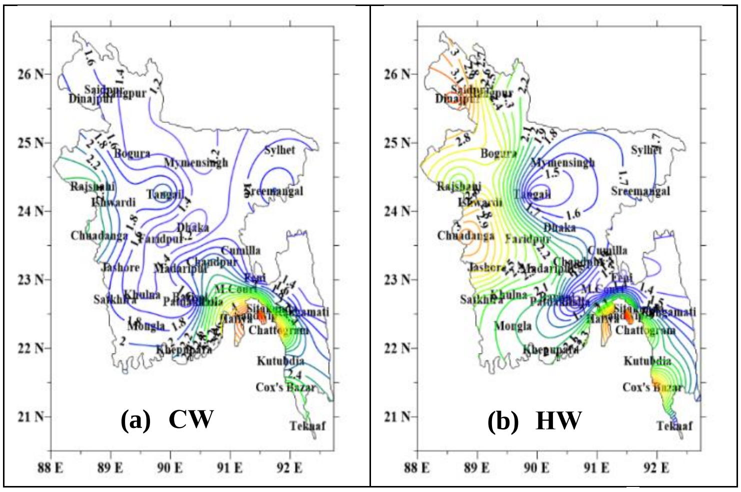


Figure 3.1.2.1: Spatial distribution of RMSE of temperature (° C) at 2m height for (a) CW and (b) HW

It is also found that the stations Bogura, Dinajpur, Faridpur, Ishurdi, Jashore, Rangpur, Satkhira and Syedpur obtained reasonable average RMSE for CW but did not obtain those for HW as good as CW. Again, the stations Bhola, Chandpur, Khepupara, M. Court, Sitakunda, Tangail and Teknaf obtained reasonably average RMSE for HW but did not obtain those for CW as good as HW.

Overall, the stations Barisal, Comilla, Dhaka, Feni, Khulna, Mongla, Mymensingh, Patuakhali, Rangamati, Srimongal and Sylhet have obtained reasonably average RMSE, whereas the stations Chuadanga, Cox's Bazar, Chattogram, Hatiya and Sandwip did not obtain reasonable average RMSE for both of CW and HW. The highest and the lowest bias stations of RMSE for both CW and HW over Bangladesh are Sandwip (5.91° C and 3.81° C) and Feni (1.3° C and 1.16° C). Finally, it is noted that RMSEs are not constant but it is a variable with respect to place (station) as well as time (event).

The sensitivity test of radiation physics of WRF model has been tested, verified and found that the RRTM long wave and Dudhia short wave scheme has captured the meteorological parameter reasonably well by which the extreme temperature events in the Bangladesh can be predicted deterministically.

From the Table of RMSE on the basis of 2m air temperature, it is found that radiation physics scheme RRTM for long wave and Dudhia for short wave of WRF model respectively are finalized for this study.

3.2 Case Study

After findings the best radiation combination physics and setting up that in the model to run up for five days with per hourly time interval. The output of the WRF Model gives/provides the control (ctl) file. The first 24 hours are discarded for a model spin up and the next successive 3 (three) days are taken for the study purpose. 6 extreme temperature cases are discussed in this chapter. Cases 1, 2 and 3 are for cold waves. Again, cases 4, 5 and 6 are for heat waves cases. To understand the extreme temperature (cold and heat wave), some meteorological parameters like MSLP, relative humidity at 2 meters, temperature at 2 meters, wind pattern, rain and latent heat flux are discussed from the model output along with data obtained from BMD observed and ECMWF predicted in the following subsection.

3.2.1 Case 01: Cold Wave of 13 to 15 January 2017

A cold wave event has been taken for NWP study, which occurred on 08 January 2017 to 25 January 2017 over some stations of Bangladesh but considered 13 to 15 January 2017 in this case study. Because, during this period, cold waves covered most of the stations. It was a severe cold wave. This severe CW does sweep over the following stations and the minimum temperature of those stations are Chuadanga, Dinajpur, Ishurdi, Rajshahi, Rangpur, Srimangal and Syedpur on 14 January at 0000 UTC 6.7^{O} C, 6.8^{O} C, 6.0^{O} C, 5.9^{O} C, 7.4^{O} C, 6.1^{O} C and 7.5^{O} C respectively. The WRF model is run for 5 days using fnl data at 0000 UTC of 12 January 2017 as an initial condition.

3.2.1.1 MSLP Analysis

Mean sea level pressure plays a very important role in the formation of cold waves. The development of a high-pressure area is one of the most important ingredients in the formation of cold waves. Figure 3.2.1.1.1 shows the WRF model-simulated MSLP at 0000 UTC of 12 to 16 January 2017. Figure 3.2.1.1.1(a) and Figure 3.2.1.1.1(e) have been used to observe if is there any changes before and after the study period respectively. On 12 January, Figure 3.2.1.1.1(a) indicated that a ridge of westerly high (1014-1015) hPa is simulated over Bihar, (1015-1016) hPa is simulated over west Bengal and adjoint parts of the northwestern and middle western parts of Bangladesh. This ridge of high is increasing day by day and further moved to east from west gradually till 15 January, and on 16 January, Figure 3.2.1.1.1(e) shows that the model simulated MSLP has decreased more rapidly than the previous day.

On 13 January at 0000 UTC, it is found that a ridge of westerly high (1015 − 1016) hPa is simulated over Bihar, the north part of West Bengal and the middle-western parts of Bangladesh while (1013 − 1015) hPa is simulated over the whole area of the country Bangladesh. The ridge of high moved farther to the east on 14 January and on 15 a convergence zone of high MSLP (1019−1020) hPa is simulated over West Bengal and the adjoining western part of Bangladesh.

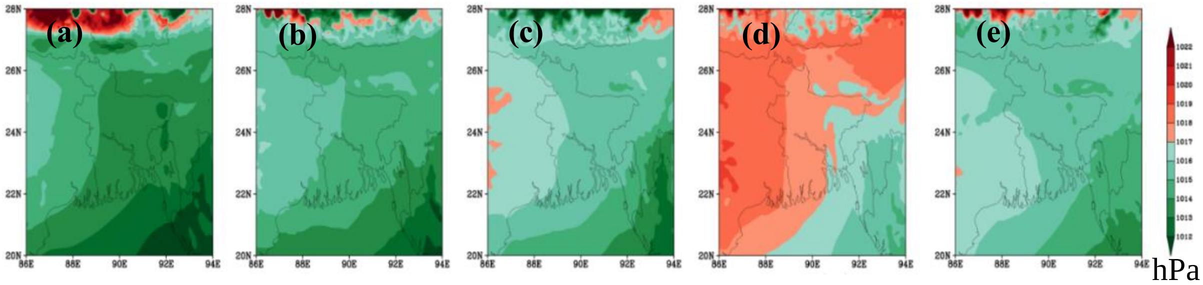


Figure 3.2.1.1.1: Model-simulated MSLP (hPa) at 0000 UTC of (a) 12, (b) 13, (c) 14, (d) 15 and (e) 16 January 2017

For the inspection of the model performance, simulated maximum MSLP during 3 days from 0000 UTC on 13 January to 0000 UTC on 16 January 2017 were compared with the values observed by BMD in Figure 3.2.1.1.2. It is found that the model simulated MSLP over all stations sometimes overestimates and sometimes underestimates compared to that of BMD observed MSLP. It is noted that The WRF model is capable to simulate MSLP reasonably well for cold waves.

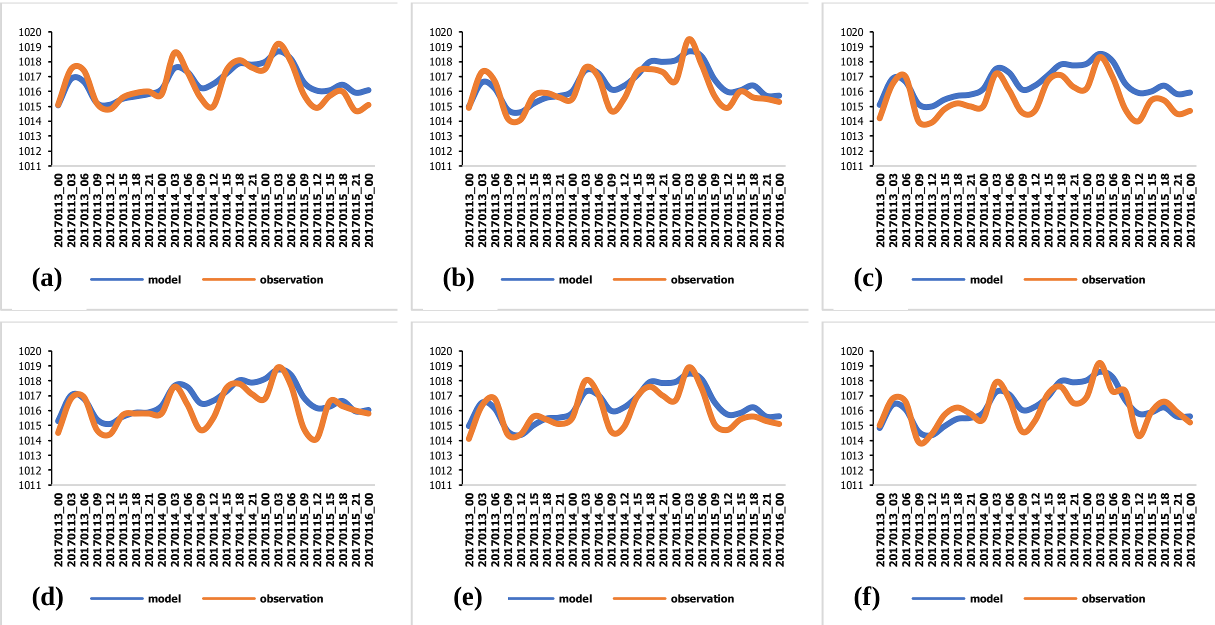


Figure 3.2.1.1.2: Comparison of Model simulated MSLP (hPa) with observation data at (a) Chuadanga, (b) Dinajpur, (c) Ishurdi, (d) Rajshahi, (e) Rangpur and (f) Syedpur

3.2.1.2 Wind Analysis

Figure 3.2.1.2.1shows the model simulated wind pattern of 12 to 16 January 2017 at the 850, 500 and 200 hPa levels to understand the rotation and movement of wind in the direction or strength at the same geographical coordinates, but at different altitudes.

Figure 3.2.1.2.1(a, f, k) and Figure 3.2.1.2.1(e, j, o) have been used to observe any change before and after the study period. On 12 January, Figure 3.2.1.2.1(a, f, k) shows that the model simulated wind pattern at different levels. On that day a backing is found in entire the country. Figure 3.2.1.2.1(e, j, o) shows the wind pattern at different levels on the next day of the study period which has indicated a similar result of the study period days. The study period (from 13 to 15 January) has been discussed below.

At 850 hPa level Figure 3.2.1.2.1(b-d), on 13 January 2017, a westerly zonal wind of speed (8 − 12) ms^{-1} is simulated over some parts of Rajshahi and Rangpur Division. A divergence zone is seen over Rajshahi. On 14 January, the zonal wind speed is (08−12/more) ms^{-1} simulated over the Rajshahi, Khulna, Barisal and some parts of Dhaka. Northwesterly wind with the speed of (08-11) ms^{-1} is found over the Khulna Division and wind with the speed of (04-07) ms^{-1} is found over Rajshahi and Barisal Division and connecting region of Dhaka at 0000 UTC on 15 January 2017.

At 500 hPa level Figure 3.2.1.2.1(g-i), strong westerly wind of speed (33 − 36) ms^{-1} is simulated over West Bengal and Bangladesh zonally on 13 January 2017 at 0000 UTC. For the next 2 days, the wind speed (27 − 33) ms^{-1} is simulated in the same direction and same area except for Sylhet; Sylhet wind speed is (15−20) ms^{-1}.

At 200 hPa level Figure 3.2.1.2.1(l-n), strong southwesterly wind of high speed (65 − 70) ms^{-1} is simulated over Rangpur, Dinajpur and Syedpur at 0000 UTC on 13 January 2017. And this speed is gradually decreasing from North West to South East. Next 2 days, wind speed is increasing from the south side to the north side of the country gradually.

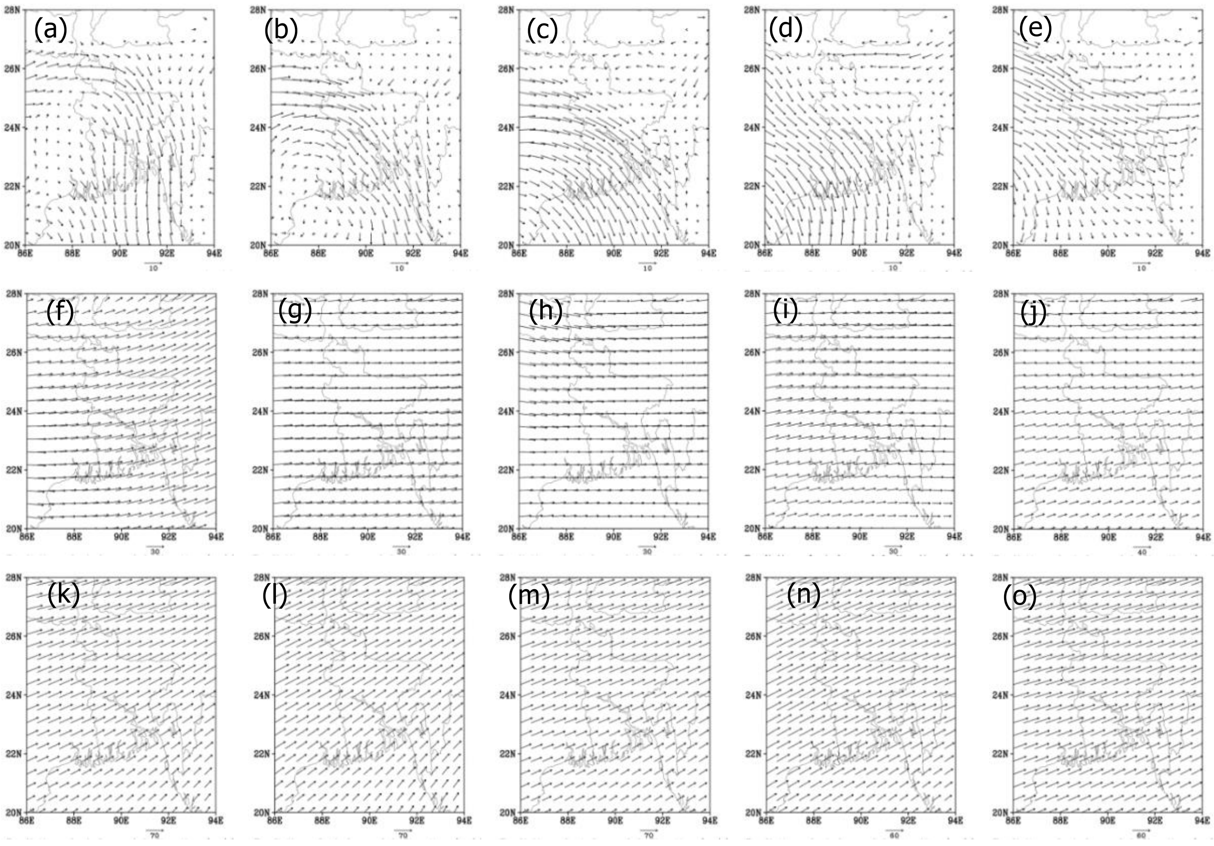


Figure 3.2.1.2.1: Model simulated wind (m/s) analysis of 12 to 16 January 2017 (From left to right); (a-e)1st row indicated 850 hPa, (f-j)2nd is 500 hPa and (k-o)3rd is 200 hPa level respectively

From the wind direction at different levels, a backing is found over the middle-west and southwest part of Bangladesh from 13 to 16 January 2017. Overall, a backing does occur in all five days. So, most probably there is a possibility to occur a severe cold condition in that area on mentioned days.

3.2.1.3 Temperature at 2m Height Analysis

Temperature is the nucleus of extreme weather phenomena. Temperature is responsible for the formation of thunderstorms, rainfall, droughts, tornados, nor'wester, storm surges, tropical cyclones, monsoon depressions and other natural hazards.

Figure 3.2.1.3.1shows the WRF model-simulated temperature at 2m height at 0000 UTC of 12 to 16 January 2017. Figure 3.2.1.3.1(a) and Figure 3.2.1.3.1(e) have been used to observe any change before and after the study period. On 12 January, Figure 3.2.1.3.1(a) shows that the model simulated temperature was more than 12^{O} C in the whole country except Srimangal and Rangamati; the temperature of these two places was 06^{O} -12^{O} C. Figure 3.2.1.3.1(b-d) shows the study period temperature which have analyzed the next figure caption (Figure 3.2.1.3.2). Figure 3.2.1.3.1(e) shows the temperature of the next day of the study period which has indicated a similar result to the study period days.

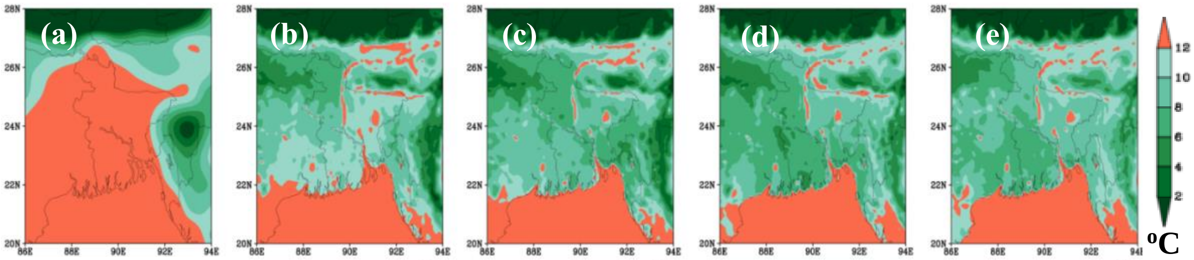


Figure 3.2.1.3.1: Model-simulated temperature (^{O} C) at 2m height at 0000 UTC of (a)12, (b)13, (c)14, (d)15 and (e)16 January 2017

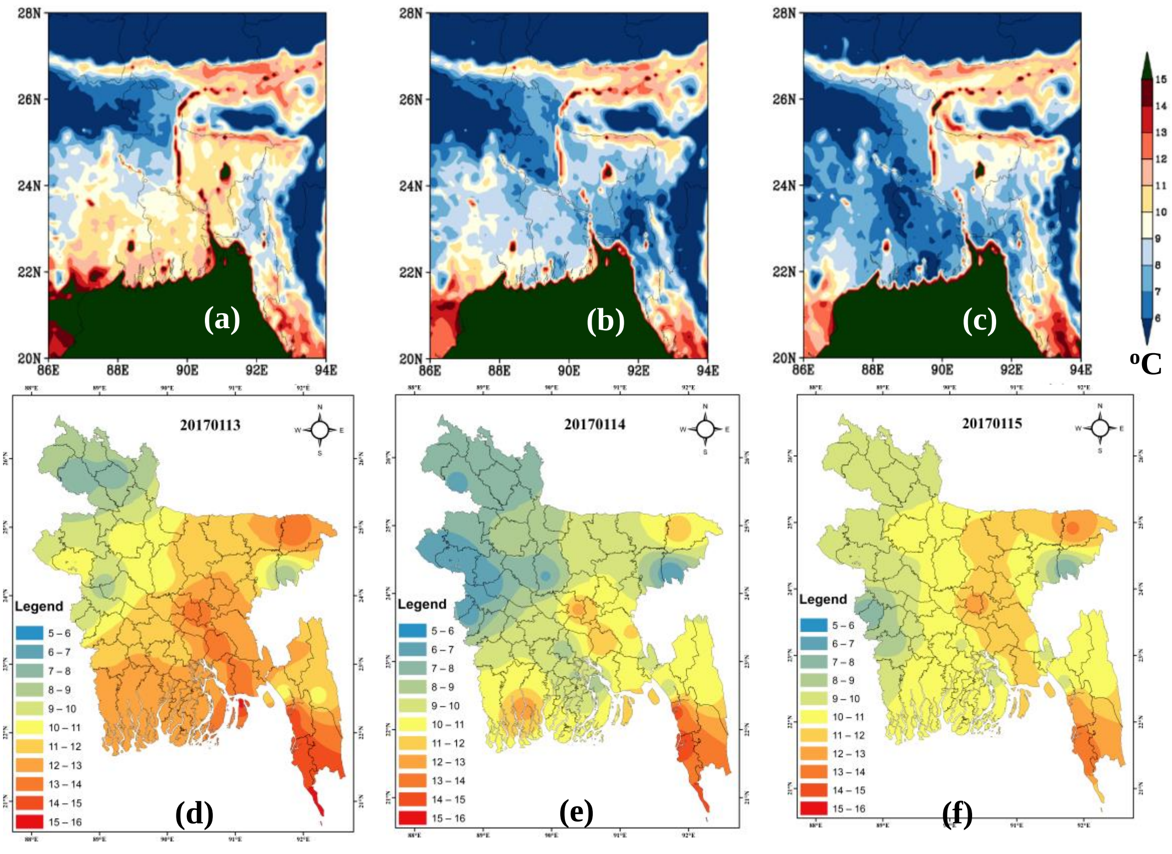


Figure 3.2.1.3.2: Temperature (^{O} C) at 2m height valid for 0000 UTC on 13 to 15 January 2017 using (a-c) model data and (d-f) observed data

Figure 3.2.1.3.2 shows the temperature (^{O} C) at 2m height valid for 0000 UTC on 13 to 15 January 2017 using (a-c) WRF model simulated data and (d-f) observed (BMD) data spatially. From the temperature analysis, it is observed that on 13 January 2017, the temperature (below 06 - 09)^{o} C is simulated by the model over the Bihar and Northwestern part of Bangladesh i.e. over the Rajshahi, Rangpur, Dinajpur and Bogura whereas the observed data indicated, the temperarure of those stations is (06 − 09)^{o} C; (09 − 10)^{o} C is Faridpur, Jashore , Chuadanga, Ishurdi and Chattogram Division whereas the observation data are indicated (10 − 12)^{o} C at 0000 UTC. On 14 January at 0000 UTC, (06 − 07)^{o} C temperature is found over Rajshahi, Ishurdi, Chuadanga, Dinajpur and some parts of Chattogram division whereas the observation data are indicated the temperature of those stations is (05 − 07)^{o} C , the rest of the country's temperature (07 – 09)^{o} C is simulated by the WRF model. At 0000 UTC on 15 January 2017, the minimum temperature of about 07^{o} C or less is simulated by the model over west Bengal and western and southwestern parts of Bangladesh whereas the observed temperature of those areas (in Bangladesh) is (07-10)^{o} C. The model simulated temperature of other places in the country is (08 − 10)^{o} C. From this analysis, the results have been represented that the WRF model simulated results have been reasonably well matched with the observation data.

For the inspection of the model performance, simulated minimum temperatures during 3 days from 0000 UTC on 13 January to 0000 UTC 16 January 2017 were compared with the values observed by BMD in Figure 3.2.1.3.3. It is found that the model simulated temperature slightly overestimates and underestimates the temperature compared to that of BMD observed temperature for all stations. It has concluded that the WRF-ARW model is capable to capture the temperature at 2m height reasonably well.

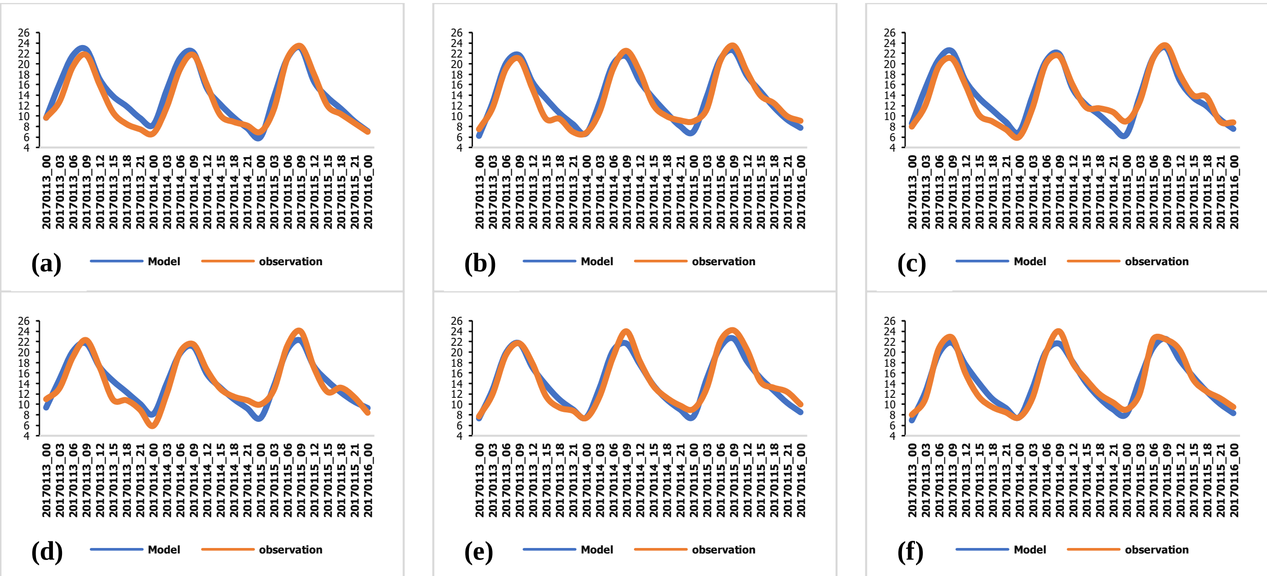


Figure 3.2.1.3.3: Comparison of Model simulated Temperature (^{O} C) with observation data at (a) Chuadanga, (b) Dinajpur, (c) Ishurdi, (d) Rajshahi, (e) Rangpur and (f) Syedpur

Figure 3.2.1.3.4 shows the comparison of the WRF model simulated 2m air temperature with that observed by BMD and simulated by the ECMWF model. From the figure, it is found that the WRF model predicted data has been well matched than the ECMWF predicted data with the observation data for every station. After analyzing these figures, here it is found that the performance of the WRF model is better than the ECMWF model.

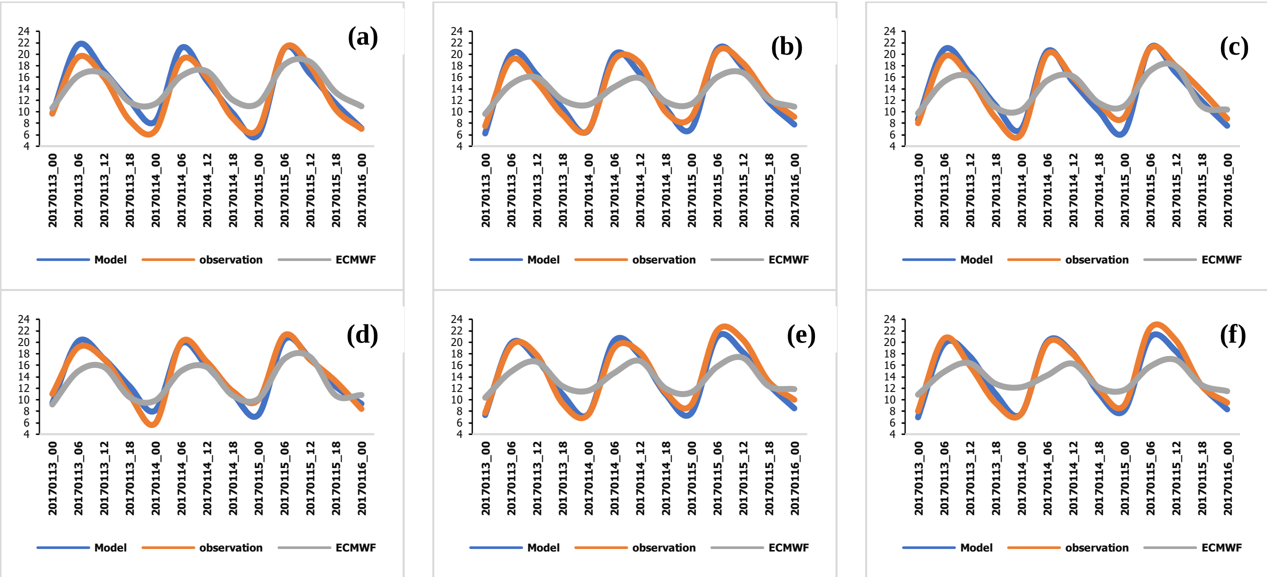


Figure 3.2.1.3.4: Comparison of Model simulated Temperature (^{O} C) with observation and ECMWF data at (a) Chuadanga, (b) Dinajpur, (c) Ishurdi, (d) Rajshahi, (e) Rangpur and (f) Syedpur

To confirm the performance of the WRF model, it has calculated the RMSE values for all six stations which are tabulated in Table 1, and it has revealed that the WRF model gives the lowest RMSE based on 2m height temperature compared to the ECMWF model to predict cold wave without any exception.

Table 1: RMSE of WRF and ECMWF Models

Station Name	RMSE	
	WRF Model	ECMWF Model
Chuadanga	1.50	2.98
Dinajpur	1.14	2.95
Ishurdi	1.34	2.67
Rajshahi	1.27	2.68
Rangpur	1.10	3.22
Syedpur	1.06	3.65

3.2.1.4 Analysis of Relative Humidity at 2m Height

Surface level relative humidity is an essential factor for intense convection. Cold nights require an insufficiently humid and deep layer in the lower and middle atmosphere. Figure 3.2.1.4.1 shows the WRF model-simulated 2m relative humidity at 0000 UTC of (a)12, (b)13, (c)14, (d)15 and (e)16 January 2017. Figure 3.2.1.4.1(a) and Figure 3.2.1.4.1(e) have been used to observe any change before and after the study period. On 12 January, Figure 3.2.1.4.1(a) shows that the model simulated relative humidity is (60-100) % in the whole country which has rapidly changed in the next day. Figure 3.2.1.4.1(b-d) shows the study period relative humidity which have analyzed in the next para. On 16 January, Figure 3.2.1.3.1(e) shows the relative humidity of the next day of the study period which has indicated a similar result of the study period days.

From the analysis of relative humidity, on 13 January, (40 − 60) % RH is found over Meghalaya, West Bengal and western –middle part of Bangladesh, and (60 − 80) % RH is found over the rest of the maximum part of Bangladesh, while the RH of Sylhet, Madaripur, Barisal, Comilla, Feni and M. Court is about (80 − 90) %. On the next day, West Bengal and the western–middle part of Bangladesh are the same as the previous day whereas it is about (60 − 80) % in the rest part of Bangladesh except Sylhet; Sylhet is (80 − 90) %. On 15 January, the maximum relative humidity (70-90) % is simulated by the model is Jashore, Chuadanga, division of Sylhet and Mymensing and also some parts of Dhaka and Chattogram division; rest of the parts of the country is (60-70) %. (50-60) % relative humidity is simulated by the model over the Kolkata, BOB and the stations of coastal area.

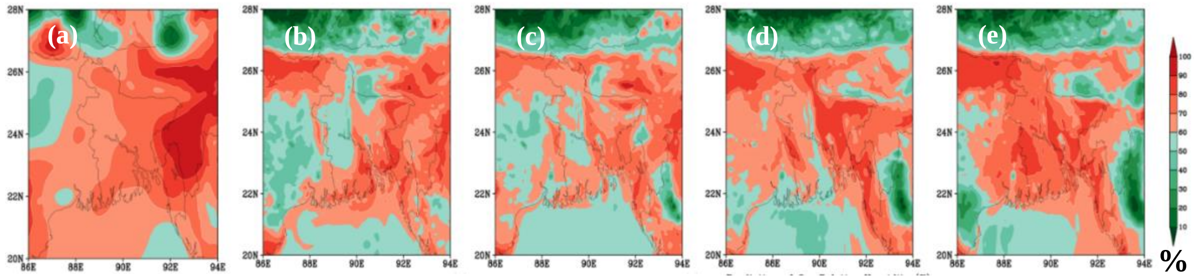


Figure 3.2.1.4.1: Model-simulated 2m Relative Humidity (%) at 0000 UTC of (a) 12, (b) 13, (c) 14, (d) 15 and (e) 16 January 2017

To investigate the model performance, simulated relative humidity of 2m height during 3 days from 0000 UTC on 13 January to 0000 UTC on 16 January 2017 were compared with the values observed by BMD in Figure 3.2.1.4.2. Here it has shown that the value of RH simulated by the WRF-ARW model is lower than that of observed without exception.

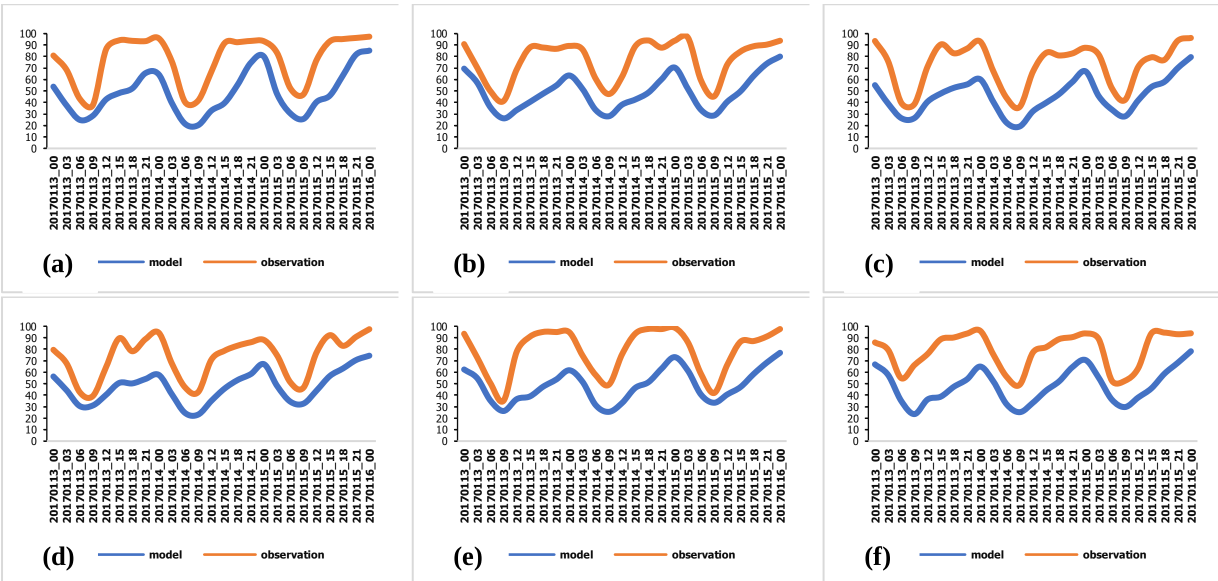


Figure 3.2.1.4.2: Comparison of Model simulated RH2(%) with observation data at (a) Chuadanga, (b) Dinajpur, (c) Ishurdi, (d) Rajshahi, (e) Rangpur and (f) Syedpur

3.2.1.5 Convective Rainfall Analysis

Convective rainfall is a vital element of cold wave formation. When rainfall does occur in some particular area that region resulting to help in the development of a CW zone. Normally in winter, no rainfall does occur in Bangladesh according to the BMD recorded data. Figure 3.2.1.5.1 shows the WRF model-simulated convective rainfall on (a) 12, (b) 13, (c) 14, (d) 15 and (e) 16 January 2017. Figure 3.2.1.5.1(a) and Figure 3.2.1.5.1(e) has been used to observe if any change before and after the study period. Figure 3.2.1.5.1(a-e) shows that no significant rainfall amount is simulated over Bangladesh from 12 to 16 January 2017. So, it is an important argument for normal CW continuation.

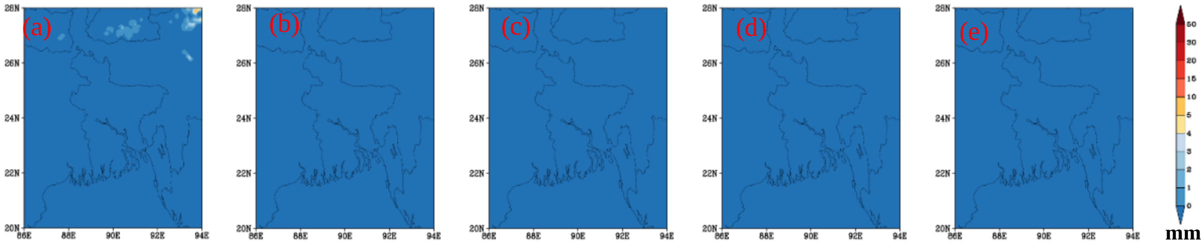


Figure 3.2.1.5.1: Model-simulated Total convective Rainfall (mm) on (a) 12, (b) 13, (c) 14, (d) 15 and (e) 16 January 2017

3.2.1.6 Latent Heat Flux Analysis

Latent Heat (LH) is another ingredient of CW formation. When LH of some particular area becomes lower or decreasing day by day that region results in the development of a CW. Figure 3.2.1.6.1 shows the WRF model-simulated Latent Heat Flux at the surface at 0000 UTC of (a) 12, (b) 13, (c) 14, (d) 15 and (e) 16 January 2017. Figure 3.2.1.6.1(a) and Figure 3.2.1.6.1(e) have been used to observe any change before and after the study period. On 12 January, Figure 3.2.1.6.1(a) shows the initial data and it cannot simulate any LHF and on 16 January, Figure 3.2.1.6.1(e) shows the LHF of the next day of the study period which has indicated as similar as a result of the study period days.

No significant Latent Heat amount is simulated over Bangladesh from 13 to 15 January 2017 3.2.1.6.1(b-c), because at 0000 UTC at that time, there is no solar insolation over Bangladesh. Though the water heat capacity is larger than the land surface heat capacity; so, the Latent Heat present over the Bay of Bengal, and a very low amount of the Brahmapootra river and other water land area of Bangladesh in the required time, so it is an important argument for normal CW formation.

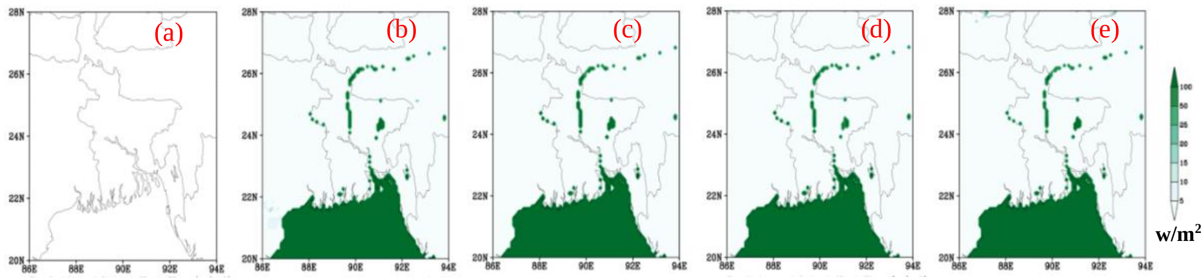


Figure 3.2.1.6.1: Model-simulated Latent Heat Flux (w/m^2) at the surface at 0000 UTC of (a) 12, (b) 13, (c) 14, (d) 15 and (e) 16 January 2017

3.2.2 CASE 02: Heat wave of 19 To 21 May 2017

A heat wave event has been taken for the NWP study, which occurred on 18 May 2017 to 29 May 2017 over some stations of Bangladesh but was considered from 19 to 21 May 2017 in this case study. Because, during this period, heat waves covered most of the stations. It was a mild heat wave. On 21 May 2017, the maximum temperature of the stations Ishurdi, Rajshahi, Jashore, Khulna, Mongla, Satkhira, Barisal, M. Court and Srimangal are 36.5^O C, 37.3^O C, 37.8^O C, 37.7^O C, 37.5^O C, 37.6^O C, 36.5^O C, 36^O C and 37.3^O C respectively. The WRF model is run for 5 days using fnl data at 0000 UTC on 18 May 2017 as an initial condition. For model spin up, first 24 hours has been discarded.

3.2.2.1 MSLP Analysis

Mean sea level pressure plays a very important role in the formation of extreme temperatures (HW). The development of a low-pressure area is one of the most important ingredients in the formation of HW.

Figure 3.2.2.1.1 shows the WRF model-simulated MSLP at 0900 UTC from 18 to 22 May 2017. Figure 3.2.2.1.1(a) and Figure 3.2.2.1.1.1(e) have been used to observe any change before and after the study period respectively. On 18 May, Figure 3.2.2.1.1.1(a) indicated that a trough of westerly low (1000-1002) hPa is simulated over Bihar and middle-western parts of Bangladesh, the rest of the parts of the country MSLP is (1002-1004) hPa simulated by the WRF model except a part of Chattogram division and coastal area. This trough of low is increasing day by day and further moved from west to east gradually till 21 May, and on 22 May, Figure 3.2.2.1.1.1(e) shows that the model simulated trough of low further shifted to west from east.

On 19 May at 0900 UTC, a trough of westerly low (998 − 1000) hPa is simulated over Bihar, north part of West Bengal and adjacent parts of Rajshahi (Bangladesh) while (1002 − 1004) hPa is simulated over whole area in Bangladesh. And also, a convergence zone of very high (1004 − 1010) hPa is simulated over the adjoining area of Meghalaya (Figure 3.2.2.1.1.1(b)). This trough of low is increasing the next day and further moved to east from west and covered the stations Panchagar, Rangpur, Dinajpur, Bogura, Rajshahi, Chuadanga, Ishurdi, Tangail, Faridpur Jashore and Khulna (Figure 3.2.2.1.1.1(c)). The trough of low moved farther to the southwest on 21 (Figure 3.2.2.1.1.1(d)).

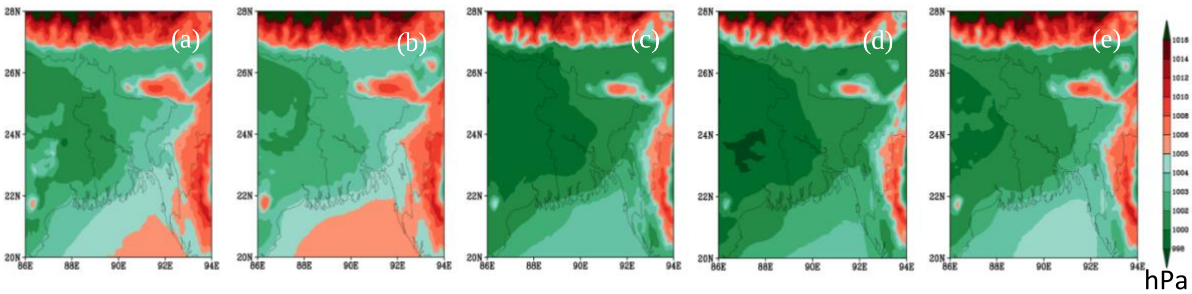
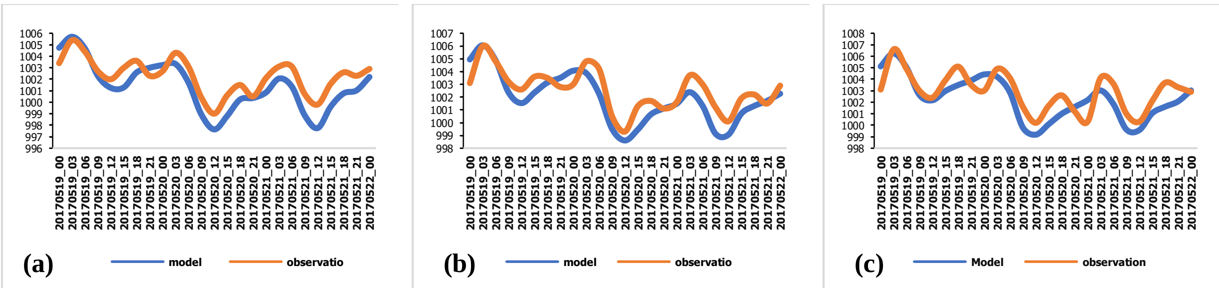


Figure 3.2.2.1.1: Model simulated MSLP (hPa) analysis valid for 0900 UTC of (a) 18 May, (b) 19 May, (c) 20 May and (d) 21 May and (e) 22 May 2017

For the validation of model simulated MSLP, a comparison is made with three hourlies observed MSLP recorded by BMD, the comparison is shown in Figure 3.2.2.1.2. It is found that the model simulated MSLP over all stations always underestimates compared to that of BMD observed MSLP with slight variation. So, the WRF-ARW model is capable to capture the MSLP reasonably well.



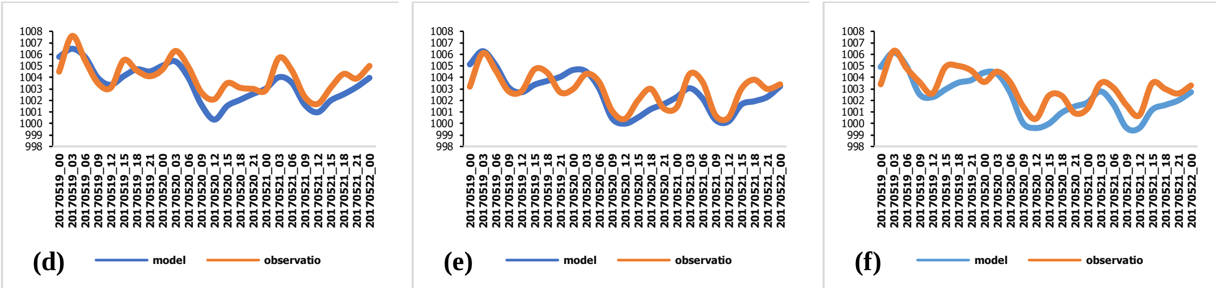


Figure 3.2.2.1.2: Comparison of Model simulated MSLP (hPa) with observation data at (a) Ishurdi, (b) Jashore, (c) Khulna, (d) M.Court, (e) Mongla and (f) Satkhira

3.2.2.2 Wind Pattern Analysis

During heatwave events, a strong wind blows over the event area which sometimes becomes vigorous and devastating. From the analysis of wind direction, it is possible to find out what categories of HW does occur. A veering wind is indicated that the HW may be severe or very severe.

Figure 3.2.2.2.1(a,f,k) and Figure 3.2.2.2.1(e,j,o) have been used to observe any change before and after the study period respectively. On 18 May, Figure 3.2.2.2.1(a, f, k) shows that the model simulated wind pattern at different levels. On that day: at 850 hPa level, the southwesterly wind blows over the country except for the northern parts of Bangladesh; a northwesterly wind entire the northern part of the country from west Bengal and Bihar (India) (Figure 3.2.2.2.1(a)). At 500 hPa level, the wind blows over the country from the west zonally (Figure 3.2.2.2.1(f)). At 200 hPa level, the southwesterly wind blows over the whole country (Figure 3.2.2.2.1(k)). So, no veering is found entire the country. Figure 3.2.2.2.1(e, j, o) shows the wind pattern at different levels on the next day of the study period which has indicated a similar result to the previous day. The study period (from 19 to 21 May) has been discussed below.

At 850 hPa level, Northwesterly wind of speed (05 − 08) ms^{-1} is simulated over Bihar (west Bengal) and south-westerly wind of speed (01-04) ms^{-1} over the Kolkata (southwest Bengal) and Khulna division made a convergence zone at the Rajshahi, Chuadanga and Ishurdi area at 0900 UTC on 19 May 2017 (Figure 3.2.2.2.1(b)). The lowest speed of wind (02-05) ms^{-1} over the country is found at Khulna and Chattogram division and neighboring area. On 20 May 2017 at 0900 UTC (Figure 3.2.2.2.1(c)), Northwesterly wind of speed (06 − 09) ms^{-1} is simulated at Rajshahi division that comes from Bihar and south-westerly wind of speed (06 − 08) ms^{-1} is simulated at Khulna division and adjoining part of Barisal division. A convergence zone is seen over Rajshahi, Chuadanga, Ishurdi and neighboring areas. On 21 May, the south-westerly wind is found over the country Bangladesh; the minimum speed of wind (00 − 04) ms^{-1} is found over in Bihar, West Bengal, Rajshahi, Ishurdi, Chuadanga and some parts of Chattogram division (Figure 3.2.2.2.1(d)).

At 500 hPa level, strong westerly wind of speed (14 − 20) ms^{-1} is simulated over West Bengal and whole part of Bangladesh zonally except southern part of Chattogram division; the highest wind speed is (18 − 20) ms^{-1} is found at Chuadanga, Rajshahi and Ishurdi and lowest is (08 − 12) ms^{-1} is Teknaf, Cox's Bazar and chattogram at 0900 UTC on 19 May 2017 (Figure 3.2.2.2.1(g)). On 20 May, forcible southwesterly wind of speed (16−22) ms^{-1} is found over West Bengal, Rajshahi division and some part of Khulna, Barisal, Sylhet, Mymensingh and Dhaka division. The highest wind speed (16−22) ms^{-1} is found in the same area the previous day (Figure 3.2.2.2.1(h)). The next day, it is seen that the wind direction is the same but the speed is decreasing (Figure 3.2.2.2.1(i)).

At 200 hPa pressure level, strong southwesterly wind of speed (21 − 30) ms^{-1} is simulated over Rangpur and the nearest part of Rajshahi while in Chattogram the speed is

(06−12) ms^{-1} (Figure 3.2.2.2.1(l)), and during the next 2 days, the Southwesterly wind speed is decreasing (Figure 3.2.2.2.1(m-n)). Also, it is found that southwesterly wind is increasing gradually from southeast to northwest. From the wind analyses, no veering is found. So, it may be a mild or moderate HW.

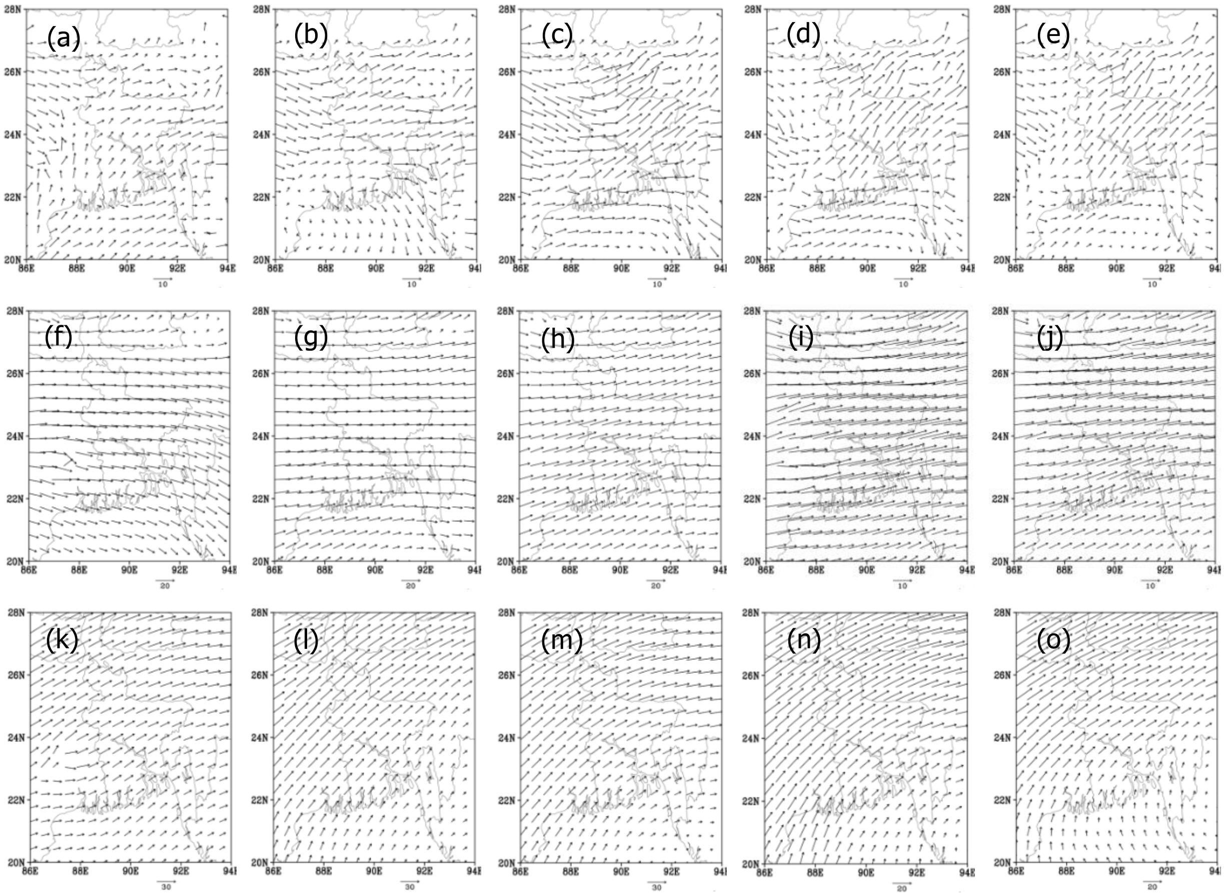


Figure 3.2.2.2.1: Model simulated wind (m/s) analysis of 18 to 22 May 2017 (From left to right); (a-e)1st row is indicated 850 hPa, (f-j) 2nd is 500 hPa and (k-o) 3rd is 200 hPa level respectively

3.2.2.3 2m Air Temperature Analysis

Temperature is the vital element of Heat waves (HW) because it happens when a region experiences very high temperatures for several days and nights. Temperature is responsible for the formation of thunderstorms, rainfall, droughts, tornados, nor‘wester, storm surges, tropical cyclones, monsoon depressions and other natural hazards.

Figure 3.2.2.3.1shows the WRF model-simulated temperature at 2m height at 0900 UTC from 18 to 22 May 2017. Figure 3.2.2.3.1(a) and Figure 3.2.2.3.1(e) has been used to observe if any change before and after the study period. On 18 May, Figure 3.2.2.3.1(a) shows that the model simulated temperature (38 - 40)^{o} C was at the stations Chuadanga, Jashore and Satkhira whereas (36-38)^{o} C was at Bogura, Tangail, Faridpur, Ishurdi, Khulna and Rajshahi stations. The temperature at these stations were increasing gradually on the study period. Figure 3.2.2.3.1(b-d) shows the study period temperature which have analyzed the next figure caption (Figure 3.2.2.3.2). Figure 3.2.2.3.1(e) shows the temperature of the next day of study period which has followed as similar as result of the study period days.

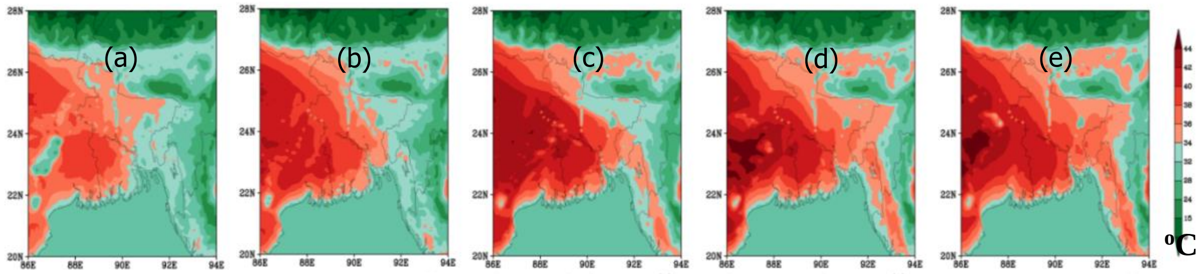


Figure 3.2.2.3.1: Model simulated Temperature (^{O} C) at 2m height valid for 0900 UTC of (a) 18 May, (b) 19 May, (c) 20 May and (d) 21 May and (e) 22 May 2017

At 0900 UTC on 19 May 2017, the temperature about (36 − 38)^{o} C is simulated by model over the western and middle part of Bangladesh i.e., Bogura, Rajshahi, Ishurdi, Chuadanga, Jashore, Khulna, Satkhira and Faridpur (Figure 3.2.2.3.2(a)) whereas the observation data are indicated (36 − 38)^{o} C the same of the model simulated temperature (Figure 3.2.2.3.2(d)). Also, at 0900 UTC on 19 May, the lowest temperature (28 − 32)^{o} C is found over Sylhet and Bay of Bengal and nearest region of Chattogram division. At 0900 UTC on 20 May, the model simulated temperature is about (38 − 42)^{o} C at Rajshahi, Ishurdi, Chuadanga, Jashore, Khulna, Satkhira, Faridpur and M. Court (Figure 3.2.2.3.2(c)) whereas the observation temperature of those stations is (36 − 38)^{o} C (Figure 3.2.2.3.2(e)). In 21 May, the temperature about (40 − 42)^{o} C is simulated by model (Figure 3.2.2.3.2(c)) and (36 − 38)^{o} C is recorded by BMD observed data over West Bengal and adjoining western parts (i.e., the same areas of the previous day) of Bangladesh (Figure 3.2.2.3.2(f)). From this analysis, it has been also observed that the temperature is increasing day by day gradually and further moved to east.

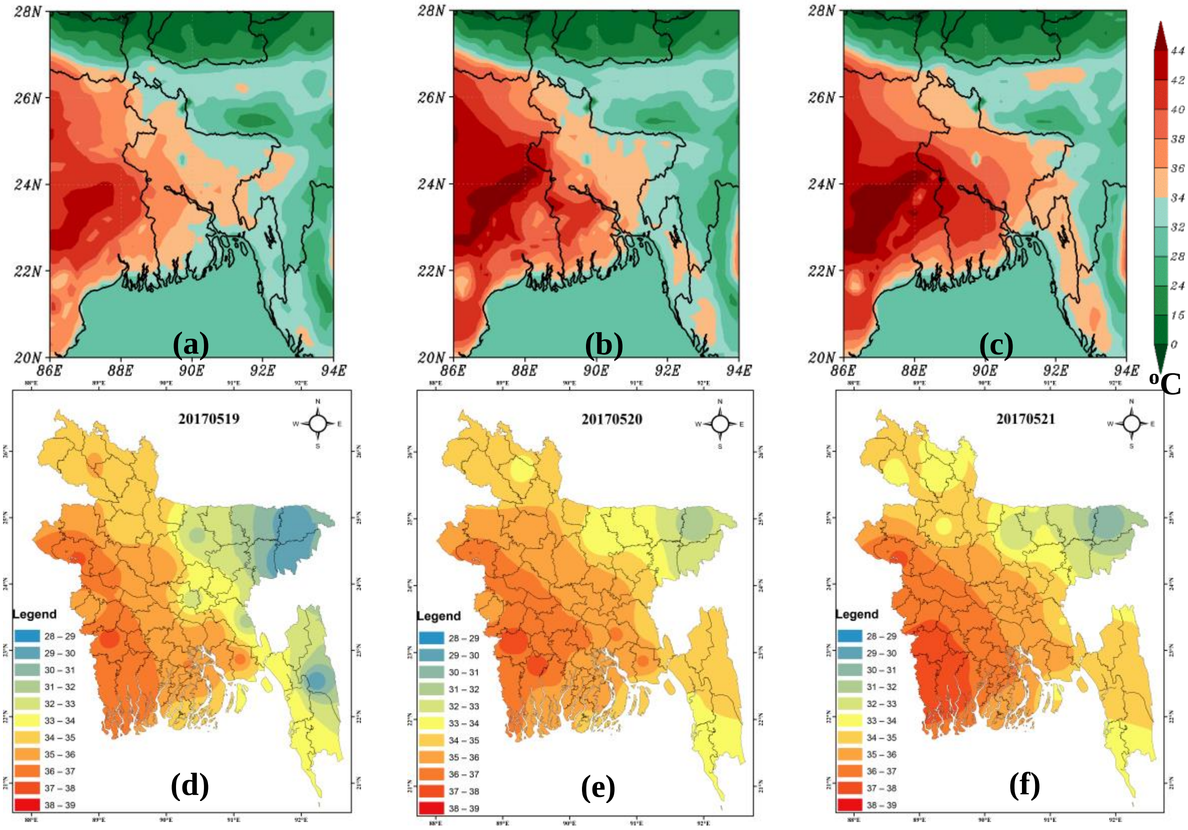


Figure 3.2.2.3.2: Temperature (^{O} C) at 2m height valid for 0900 UTC on 19 to 21 May 2017 using (a-c) model data and (d-f) observed data respectively

For the inspection of the model performance, simulated temperatures during 3 days from 0000 UTC on 19 May to 0000 UTC 22 May 2017 were compared with the values observed by BMD in Figure 3.2.2.3.3. It is found that the model simulated temperature slightly overestimates compared to that of BMD observed temperature for all stations except M. Court. It has concluded that the WRF-ARW model is capable to capture the temperature at 2m height reasonably well.

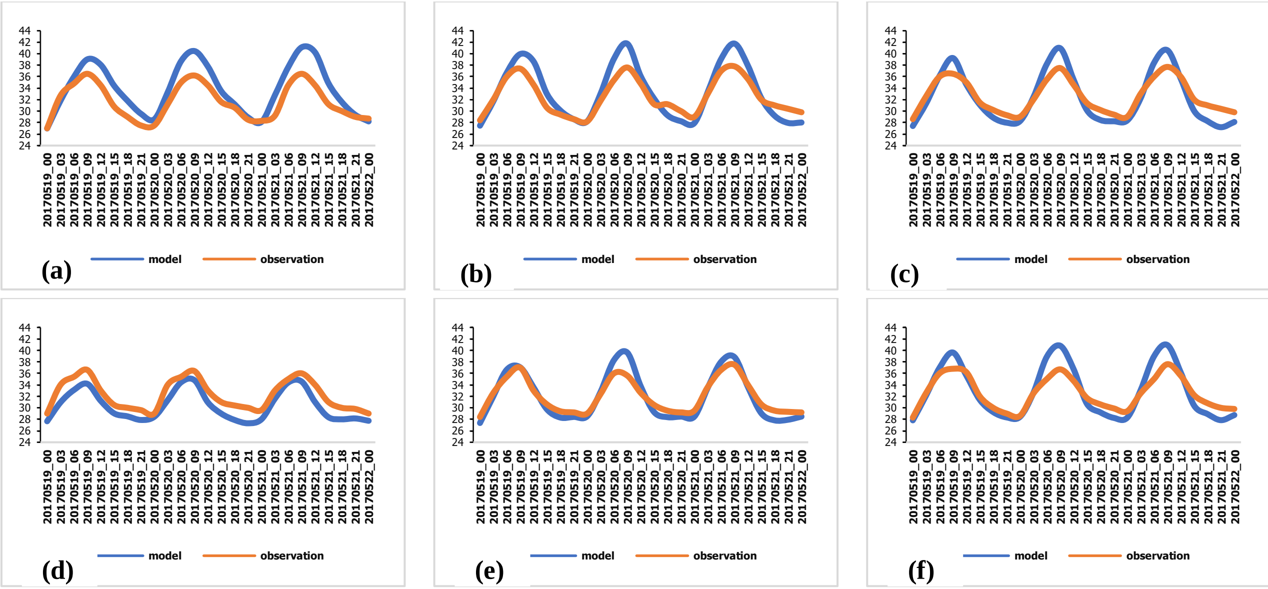


Figure 3.2.2.3.3: Comparison of Model simulated Temperature (^{O} C) with observation data at (a) Ishurdi, (b) Jashore, (c) Khulna, (d) M. Court, (e) Mongla and (f) Satkhira

Figure 3.2.2.3.4 shows the comparison of the WRF model simulated 2m air temperature with that observed by BMD and simulated by the ECMWF model. From the figure, it is found that the WRF model predicted data has been well matched than the ECMWF predicted data with the observation data for every stations. After analyzing these figures, here it is found that the performance of the WRF model is better than the ECMWF model in the context of the study domain.

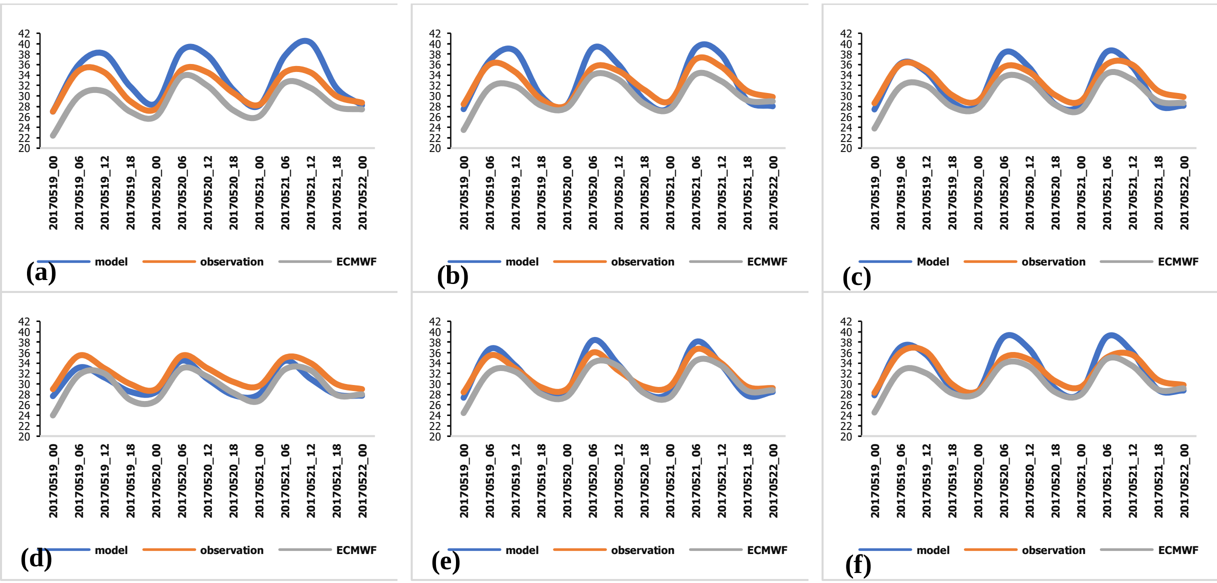


Figure 3.2.2.3.4: Comparison of Model simulated Temperature (^{O} C) with observation and ECMWF data at (a) Ishurdi, (b) Jashore, (c) Khulna, (d) M. Court, (e) Mongla and (f) Satkhira

To confirm the performance of the WRF and ECMWF models, RMSE is calculated for both models using data from 0000 UTC on 19 to 0000 UTC on 22 May 2017 for all six stations which are tabulated in Table 3, and it has revealed that the WRF model gives the lowest RMSE based on 2m height temperature compared to the ECMWF model to predict heat wave.

Table 3: RMSE of WRF and ECMWF models

Station Name	WRF Model	ECMWF Data
Ishurdi	2.68	2.87
Jashore	2.05	2.59
Khulna	1.55	2.59
M. Court	1.29	1.87
Mongla	1.20	1.88
Satkhira	1.86	2.25

3.2.2.4 Relative Humidity at 2m height Analysis

Surface level relative humidity is an essential factor for intense convection. Hot days require a sufficiently humid and deep layer in the lower and middle atmosphere. Figure 3.2.2.4.1shows the WRF model-simulated 2m relative humidity at 0000 UTC, 18 to 22 May 2017. Figure 3.2.2.4.1(a) and Figure 3.2.2.4.1(e) have been used to observe any change before and after the study period. On 18 May, Figure 3.2.2.4.1(a) shows that the model simulated relative humidity is (30-50) % in Bihar and middle- west parts of Bangladesh (i.e., Rajshahi, Ishurdi, Chuadanga, Jashore, Khulna and Satkhira) which has rapidly changed in the next day. Figure 3.2.2.4.1(b-d) shows the study period relative humidity which have analyzed in the next para.

From the analysis of relative humidity, on 19 May, (10 − 30) % RH is found over West Bengal, Bihar and middle-western parts of Bangladesh, while the RH of (20 − 50) % is found over Rajshahi, Ishurdi, Chuadanga, Jashore, Satkhira and Khulna, whereas it is about (50 − 70) % in the rest of the parts of Bangladesh. On 20 May, (10 − 20) % RH is found over West Bengal and Bihar (India) and Rajshahi in Bangladesh, while the RH of (20 − 40) % is found over Rajshahi, Ishurdi, Chuadanga, Jashore, Satkhira, Khulna, Dhaka, Faridpur and Madaripur whereas it is about (40 − 70) % in the rest of the parts of Bangladesh. On 21 May at 0900 UTC, of (20 − 30) % RH is found over Rajshahi, Ishurdi, Chuadanga, Jashore and Satkhira whereas it is about (30 − 60) % in the rest of the parts of Bangladesh. From these Figures, model simulated RH at 0900 UTC from 19 to 21 May 2017 is (80 − 100) % in the Bay of Bengal. On 22 May, Figure 3.2.2.4.1(e) shows the relative humidity of the next day of the study period which has indicated a small change (increasing) as compare to the previous day.

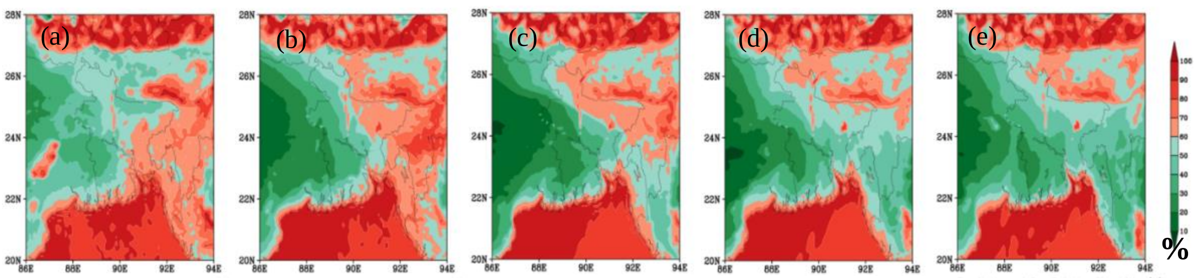


Figure 3.2.2.4.1: Model-simulated RH (%) at 2m height valid for 0900 UTC from (a) 18 May, (b)19 May, (c) 20 May, (d) 21 May and (e) 22 May 2017 based on 0000 UTC 18 May 2017

To investigate the model performance, simulated relative humidity of 2m height during 3 days from 0000 UTC on 19 May to 0000 UTC on 22 May 2017 were compared with the values observed by BMD in Figure 4.3.4.4.2. The RH_2 of M. court bias large, it may be because of the coastal area. Overall, it has showed that the WRF-ARW model is under predict to capture the RH.

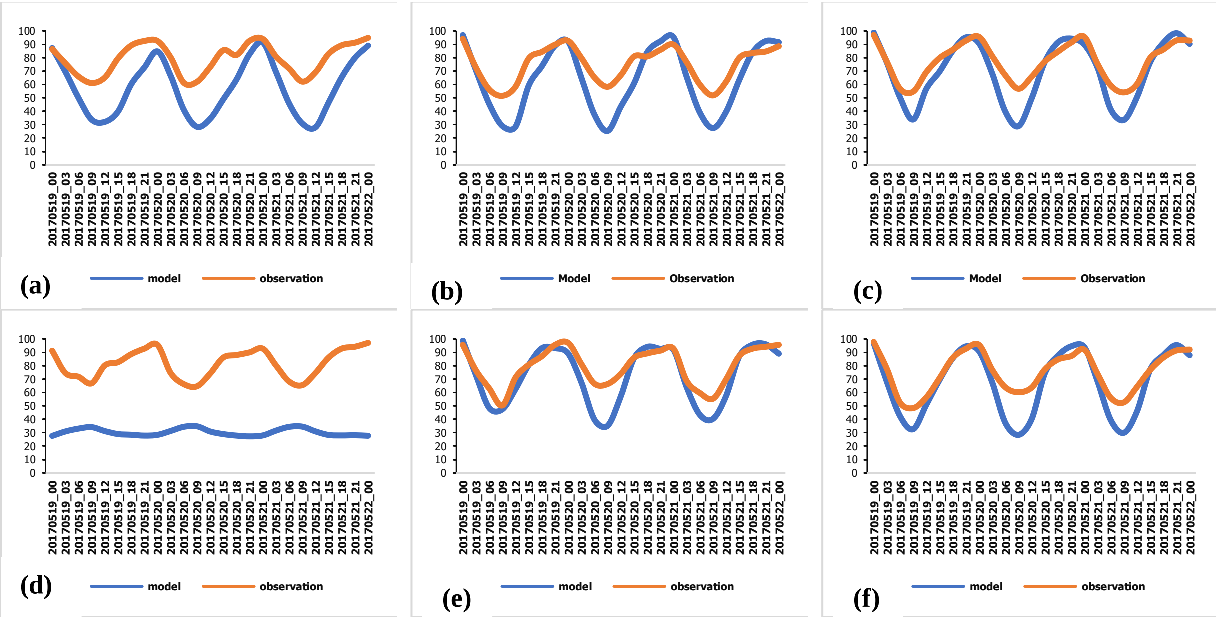


Figure 3.2.2.4.2: Comparison of Model simulated Relative Humidity (%) with observation data at (a) Ishurdi, (b) Jashore, (c) Khulna, (d) M. Court, (e) Mongla and (f) Satkhira

3.2.2.5 Convective Rainfall Analysis

Convective rainfall is an effective element of temperature formation. When rainfall does occur in some particular area that region resulting to help in the development of a cold zone comparatively to the nearest areas. Generally, in pre-monsoon, rainfall does occur in Bangladesh according to the BMD recorded data. Figure 3.2.2.5.1 shows the WRF model-simulated convective rainfall on (a) 18, (b) 19, (c) 20, (d) 21 and (e) 22 May 2017. Figure 3.2.2.5.1(a) and Figure 3.2.2.5.1(e) has been used to observe if any change before and after the study period. Significant rainfall amount is simulated over Bangladesh on 18 May. On 19 May, the maximum rainfall (15 - 30)mm model simulated rainfall is found at the most of the areas in Sylhet and Mymensingh division, (04 - 10)mm is found in Chattogram division and the coastal area of Khulna and Barisal. It is remarkable that no rainfall is found over the western parts of Bangladesh (Figure 3.2.2.5.1(b)). On 20 May, the intense of rainfall is decreasing and moves to northeast from southwest and it is continued the next two days. Only Sylhet and Mymensingh division and some parts of Rangpur and Dhaka division is found significant rainfall. The major parts of western and southern parts of Bangladesh are found rainless except Jashore, Madaripur and Chandpur region (Figure 3.2.2.5.1(c)). The next day, the intense of rainfall is decreased and further moves to northeast. The most of the parts of the country is found rainless; only Northern parts of Bangladesh, Jashore and Madaripur areas are found a small amount of rainfall (Figure 3.2.2.5.1(d)). On 22 May, Figure 3.2.2.5.1(e) shows that the model simulated (05 - 15)mm rain is found over the northern areas of Bangladesh. Rest of the whole areas of the country is found rainless. From these 5 days rainfall analysis, it is found that while the heavy rainfall is simulated over the northeastern and eastern parts of Bangladesh then no rainfall is simulated over the western parts of

Bangladesh during the study period. That is why, it may be swept HW over the middle-western and south western parts of Bangladesh.

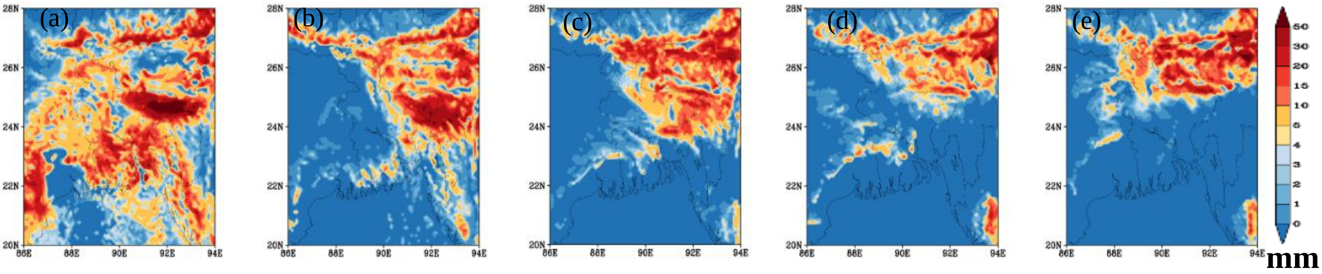


Figure 3.2.2.5.1: Model-simulated convective Rainfall (mm) at (a) 18, (b) 19, (c) 20, (d) 21 and (e) 22 May 2017

To investigate the model performance, simulated convective rainfall during 3 days from 0000 UTC on 19 May to 0000 UTC on 22 May 2017 were compared with the values observed by BMD 3-hourly interval rainfall in Figure 3.2.2.5.2. Here it has showed that the WRF-ARW model has predicted slight over to capture the rainfall. So, it is noted that The WRF model is capable to simulate rainfall reasonably well.

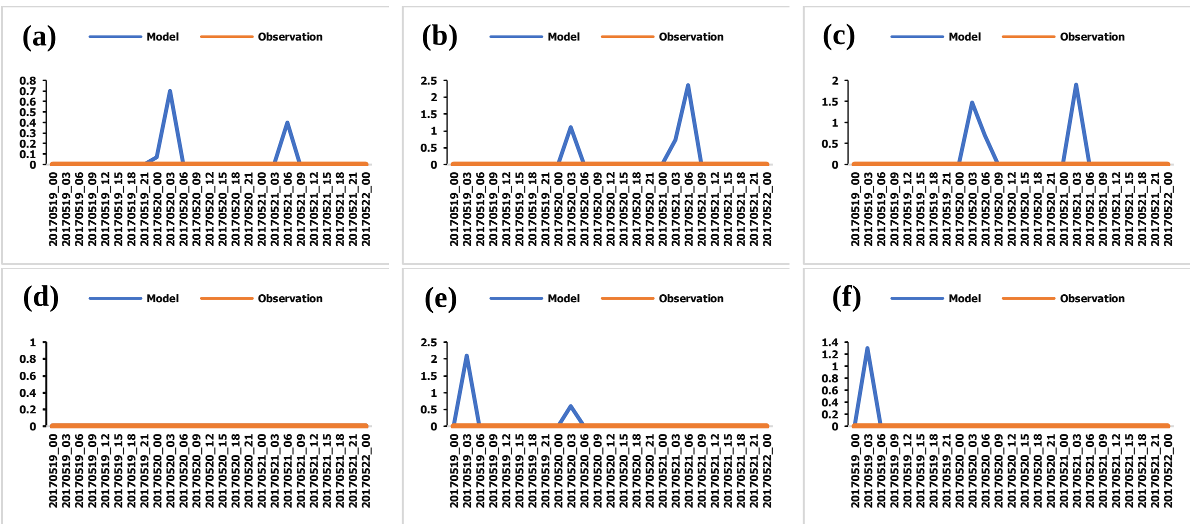


Figure 3.2.2.5.2: Comparison of Model simulated convective Rainfall with observation data at (a) Ishurdi, (b) Jashore, (c) Khulna, (d) M. Court, (e) Mongla and (f) Satkhira

3.2.2.6 Latent Heat Flux Analysis

Latent Heat (LH) is another ingredient of HW formation. When LH of some particular area becomes higher or increasing day by day that region resulting in the development of a HW zone. Figure 3.2.2.6.1 shows the WRF model-simulated Latent Heat Flux at the surface at 0900 UTC from 18 to 22 May 2017. Figure 3.2.2.6.1(a) and Figure 3.2.2.6.1(e) has been used to observe if any change before and after the study period. On 18 May 0900 UTC, Figure 3.2.2.6.1(a) shows the minimum LHF about (00-100) wm^{-2} is simulated by the model in west Bengal (India) and at Jashore, Satkhira and Mongla. While (100-200) wm^{-2} is simulated at Barisal, Chuadanga, Faridpur, Ishurdi, Khulna and M.court; whereas (300-400) wm^{-2} is simulated in the division of Rangpur, Dhaka and Chattogram. On 22 May, Figure 3.2.2.6.1(e) shows the LHF of the next day of study period which has indicated as similar as result of the study period days.

On 19 May, (100 − 200) wm^{-2} LHF is simulated over west bengal (India), the western belt areas of Bangladesh i.e., Rajshahi, Ishurdi, Chuadanga, Jashore, Khulna, Satkhira, Mongla and Khepupara. The minimum LHF about (00 − 100) wm^{-2} is simulated over the BOB and coastal areas of the Bay whereas the maximum LHF (300 − 400) wm^{-2} is simulated over the Mymenmer, Mizoram, Tripura, Asam, Meghalaya (India), and in the division of Rangpur, Dhaka, some parts of Mymensingh, Sylhet and Chattogram. About (200 − 300) wm^{-2} LHF is simulated over the rest of the parts of the country. The next two days, no major changes LHF over the country landmass. Both maximum and minimum LHF is moved from southwest to northeast slightly according to the lead time.

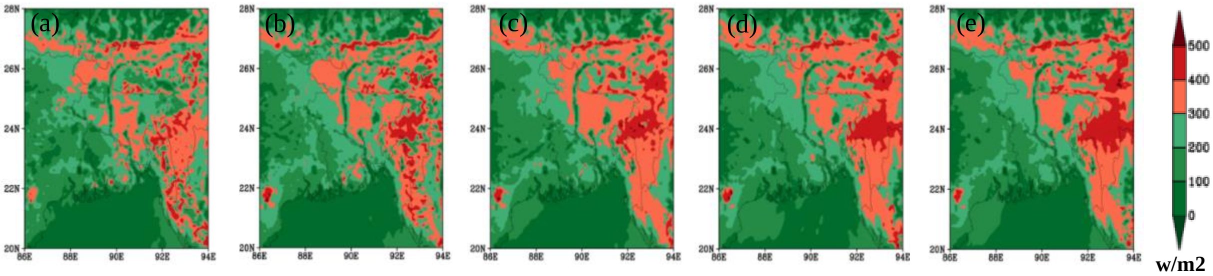


Figure 3.2.2.6.1: Model-simulated daily latent heat (w/m^2) of valid for 0900 UTC from (a) 18 May, (b) 19 May, (c) 20 May, (d) 21 May and (e) 22 May 2017 based on 0000 UTC 18 May 2017

4. CONCLUSIONS

Extreme Temperature (ET) becomes significant over Bangladesh as they caused terrible damage on the live-in recent decades. Forecasting such events, especially in the Pre-monsoon and winter region is quite challenging. Therefore, this study has made an attempt to simulate ET using WRF model to predict the future events more effectively. Different radiation physics schemes which are responsible for ET generation of WRF model have been used in this study. Model outputs are compared with BMD observed data. On the basis of the present study the following conclusion can be drawn:

The sensitivity test of different radiation parameterization schemes of WRF model showed that the RRTM for long wave and Dudhia for short wave option produced more realistic results in quantitative comparisons. Therefore, these schemes have been considered as the best for synoptic analysis and prediction of winter cold wave and Pre-monsoon heat wave over the Bangladesh. Finally, it may be concluded that the Next-Generation NCAR mesoscale and microscale model WRF version 4.3.0 with the right combination of the single domain, the suitable parameterization schemes are able to simulate and predict the ET and its associated high impact 2m air temperature over the Bangladesh reasonably well, though there are some spatial and temporal biases in the simulated temperature. The study recommended that WRF model may be operationally used for predicting the ET, its associated high impact temperature and its thermodynamic features over Bangladesh up to 72-hours advance and WRF-ARW model is better than the ECMWF global model to predict ET. It is also recommended that similar study be extended for a greater number of cases for further refinement of the model application.

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