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Sensitivity of Radiation Schemes in the WRF-ARW Model to Predict Extreme Temperature Due to Heat Wave over Bangladesh

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Abstract

A heat wave is a weather phenomenon that is distinguished by marked heating of the air, or with the invasion of very hot air, over a large area. In the present study, the Weather Research and Forecasting (WRF) model was tested through 30 different combinations of radiation parameterization schemes to simulate the regional weather over the Bangladesh. The main objective was to investigate the response to the radiation parameters schemes for dynamic down-scaling of weather variables. The temperature from the 30 different WRF setups were compared with the BMD observed data and were found sensitive to the radiation physics. The 30 combination of radiation physics along with the fixed WRF Single-moment 3-class microphysics, Kain-Fritiches cumulus physics, Noah Land Surface Physics and YSU planetary boundary-layer physics produced comparable results for 24 to 27 April 2019, 09 to 12 May 2019 and 19 to 22 May 2019. Having analyzed the simulation results using the different radiation physics schemes on the basis of RMSE at 2-meter height air temperature at 34 stations over Bangladesh, it is concluded that the Rapid Radiative Transfer Model (RRTM) for longwave and Dudhia for shortwave schemes combination are the most appropriate to simulate in the pre-monsoon extreme temperature. Then the selected combinations of WRF parameterizations were used to downscale the Extreme hot weather events, which showed good agreement with the reference data. The suggested WRF parameters from this study could be utilized for regional weather modeling of Bangladesh.

Keywords: *Heat wave, radiation scheme and regional modeling.*

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I. Introduction

Bangladesh has a unique geographical location with the Bay of Bengal in the south and the Himalayan range in the north and is the most vulnerable in the world in respect of disasters of hydrometeorological origin. The country acts as the playground of different types of disasters like thunderstorms/tornado, drought, tropical cyclones and associated storm surges, floods, flash floods, cold waves and heat waves, heavy rainfall, erratic rainfall, etc. Of these, heat wave is the common meteorological event, which occurs in the pre-monsoon season (March-May) over Bangladesh and has worst disastrous impact in the western part of the country as a whole. Sometimes drought is associated with the heat wave. The combined effect of heat wave and drought causes great loss to agriculture in the country. The global and local warming contributes to increase in frequency and intensity of these disasters. The adverse effects of climate change, increased frequency and intensity of different disasters have aggravated the overall economic development scenarios of the country as well as food security and livelihoods to a great extent. Bangladesh falls in tropical zones and receives plenty of sunshine throughout the year. Bangladesh has a distinct summer season, known as pre-monsoon season (March – May) which is preceded by winter season (December-February) and followed by monsoon season (June-September). After the retreat of winter from Bangladesh and surroundings, the temperature of the country begins to rise due to the apparent movement of the sun from Southern Hemisphere to Northern Hemisphere. In April and May, even sometimes in early June, the day temperature attains the extremely higher values. The increase in temperature is being accentuated due to the advection of higher temperature form the northwestern India by the west-northwesterly winds. Presence of desert in the western and north-western parts of India, Himalayas in the north and northeast, and the physiography of northern plains and central plateau over the Indian Sub-continent are key factors which play a role in determining the strength of Indian summer. As the sun's path shifts to the northern hemisphere, the Indian Sub-continent gets hot, which is a precursor to pull the monsoon winds from southern Indian Ocean (NIUA, 2016). Dominance of sub-tropical high pressure and its prolonging condition over India-Bangladesh-Pakistan Sub-continent during the summer season causes the temperature to rise excessively and as a result heat waves occur. The definition of heat wave differs from one country to another. A heat wave is a prolonged period of abnormally hot weather. While definitions may vary across and even within countries, heat waves are generally measured relative to the usual weather in the area and relative to normal temperatures for the season. Bangladesh Meteorological Department (BMD) uses the term 'heat wave' when maximum day temperature attains 36^0C or more. The operational classifications of heat wave in BMD are as follows (Khatun et al., 2016): Mild = $(36\text{-}38)^0$C, Moderate = $(38.1\text{-}40)^0$C, Severe = $(40.1\text{-}42)^0$C and very Severe >= 42^0 C.

Generally, extreme temperature condition results in short-term increase in daily mortality (Braga et al., 2001; Huynen et al., 2001; McGeehin and Mirabelli, 2001; Curriero et al., 2002; Mercer, 2003 etc.) because of the heat wave conditions. Heat wave occurrence basically depends upon certain thresholds of maximum temperature over a region. The threshold value of maximum temperature varies from location to location and these variations are mainly due to other atmospheric conditions and geographic locations (Das and Smith, 2012). However, in the context of Bangladesh and India, very few studies have been carried out (Raghavan, 1966; Mohan and Bhati, 2011). Some projection studies using multiple climate models and CMIP5 data revealed that extreme temperature over Bangladesh and India are projected to be more intense, of longer durations and are occur at higher frequency (Murari et al., 2015). These projections also indicated that many parts of Bangladesh and India will experience heat stress conditions in the near future. Due to the high risk of vulnerability of large population to heat waves in this region, greater efforts are needed to improve the forecast skill of Numerical Weather Predication (NWP) models and to use these forecasts in disaster management (De et al., 2005). With growing power of high-resolution computer simulation using NWP models and the availability of high frequency data, it is now very much possible to predict the extreme temperature at very high resolution with sufficient lead time. Mesoscale models, viz. WRF, are being used by some researchers for the simulation of local weather conditions (heat waves) including extreme temperature over different regions especially over Europe and North America (Bohnenstengel et al., 2011; Salamanca et al., 2012; Giannaros et al., 2013; Giovannini et al., 2013 etc.). However, that kind of study is lacking over the Southwest monsoon region. According to Mitra et al. (2017), heat waves with large impacts have increased in the recent past and would continue to increase under future warming. They did not explore the implication for population exposure to severe heat waves. Khatun et al. (2016) documented the definition of heat waves in their Met Report on Climate of Bangladesh, which have been used operationally in the Storm Warning Centre of Bangladesh Meteorological Department (BMD). Northern, western, central and south-central parts of India experience heat waves during summer (NIUA, 2016). These conditions arise due to winds which blow from the hot and dry state of Rajasthan. Anticyclone which develops over this state prevents western disturbances from entering into the Indian Sub-continent, leading to clear skies. It should be noted that Anticyclone over Rajasthan's Thar Desert leads to hot winds blowing out and increases the temperature of the surrounding regions. Nissan et al. (2017) made a study on defining and predicting the heat waves in Bangladesh. According to them, this paper proposes a heat-wave definition for Bangladesh that could be used to trigger preparedness measures in a Heat Early Warning System (HEWS) and explores the climate mechanisms associated with heat waves. Using a generalized additive regression model, a heat-wave definition is proposed that requires elevated minimum and maximum daily temperatures over the 95th percentile for 3 consecutive days, confirming the importance of nighttime conditions for health impacts. Panda et al. (2017) made a study on the increasing heat waves and warm spells in India, observed from a multi-aspect framework. Frich et al. (2002) examined whether conditions 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 (Perkins et al., 2012; IPCC, 2013), the Indian Sub-continent 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. 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°C and temperature 36°C in the month of May>It was found that Dinajpur and Rangpur have the maximum mean frequency of maximum temperature >36°C in the month of April. They also predicted that, heat waves will be more long lasting in Rajshahi during April-July.

Heat waves and heat stress occur almost every year in Bangladesh, the severity of which is more over western and northwestern parts of the country. These events affect severely 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 waves at different levels of the troposphere have not yet been studied broadly in Bangladesh.

The objective of this research is to examine the WRF-ARW model capability for the prediction of extreme temperature by simulating the extreme heat weather event that occurred over Bangladesh during pre-monsoon season using the WRF model through sensitivity test of radiation physics. The model-derived intensity and development of the heat wave will be analyzed by comparing temperature at 2m height, surface pressure, low level wind flow, and other associated parameters. The specific objectives of this research are as follows:

- Test the sensitivity of radiation physics for simulating Extreme (Heat wave) temperature by WRF model.
- Simulation of few parameters of extreme temperature event due to Heat wave by WRF model.
- Verification of WRF model.

II. Experimental setups

2.1 Model description and configuration

This study was conducted using the advanced weather research and forecasting regional climate model, version WRF 4.3.0. WRF is a non-hydrostatic, primitive-equation, mesoscale meteorological model with advanced climate dynamics, physics and numerical schemes. Detailed descriptions of the WRF can be found in the model manual of Skamarock et al. (2021) and also on the WRF user web site (http://www.mmm.ucar.edu/wrf/users). The selection of schemes and fine tuning of parameters for various modules of WRF, domain configurations and grid resolutions play a major role in the performance of WRF. The parameterization schemes in WRF are grouped into these modules: (1) microphysics (MP), (2) longwave radiation (LW), (3) shortwave radiation (SW), (4) land surface model, (5) cumulus (Cu), and (6) planetary boundary layer (PBL). Each of these modules has two or more parameterization schemes, with some schemes more applicable for climate modeling while others for weather forecasting, or both, thus making WRF a popular RCM. In fine tuning WRF, we could only test 30 combinations make with 5 longwave and 6 shortwave radiation parameterization schemes, instead of testing all possible combinations. The performance of WRF for modeling the regional weather of Bangladesh is assessed by its ability to reproduce the spatial and temporal patterns of the observed weather of Bangladesh.

2.2 Domain configuration and Data

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 (18^0 N, 89^0 E) and grid numbers is (w-e x s-n) 310 x 290, integration time step is 30 seconds. WRF is finally set up with 38 vertical pressure levels and the top level is 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 1^0 x 1^0 resolution and 6-h time steps. Fixing the above physical parameter, model is run.

Table 1: Summary of radiation parameterization combination schemes that are tested in this study

EXPT. No.	EXPT. Name	Longwave	Shortwave	EXPT. No.	EXPT. Name	Longwave	Shortwave
01	Lw1_sw1	RRTM	Dudhia	16	Lw4_sw4	RRTMG	RRTMG
02	Lw1_sw2	RRTM	GSFC	17	Lw4_sw5	RRTMG	Goddard
03	Lw1_sw3	RRTM	CAM	18	Lw4_sw7	RRTMG	Fu-Liou-Gu
04	Lw1_sw4	RRTM	RRTMG	19	Lw5_sw1	Goddard	Dudhia
05	Lw1_sw5	RRTM	Goddard	20	Lw5_sw2	Goddard	GSFC
06	Lw1_sw7	RRTM	Fu-Liou-Gu	21	Lw5_sw3	Goddard	CAM
07	Lw3_sw1	CAM	Dudhia	22	Lw5_sw4	Goddard	RRTMG
08	Lw3_sw2	CAM	GSFC	23	Lw5_sw5	Goddard	Goddard
09	Lw3_sw3	CAM	CAM	24	Lw5_sw7	Goddard	Fu-Liou-Gu
10	Lw3_sw4	CAM	RRTMG	25	Lw7_sw1	Fu-Liou-Gu	Dudhia
11	Lw3_sw5	CAM	Goddard	26	Lw7_sw2	Fu-Liou-Gu	GSFC
12	Lw3_sw7	CAM	Fu-Liou-Gu	27	Lw7_sw3	Fu-Liou-Gu	CAM
13	Lw4_sw1	RRTMG	Dudhia	28	Lw7_sw4	Fu-Liou-Gu	RRTMG
14	Lw4_sw2	RRTMG	GSFC	29	Lw7_sw5	Fu-Liou-Gu	Goddard
15	Lw4_sw3	RRTMG	CAM	30	Lw7_sw7	Fu-Liou-Gu	Fu-Liou-Gu

2.3. Methodology

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 is selected among all available radiation schemes. 6 (six) shortwave radiation physics schemes are 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 are 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 have made 30 independent combinations for 30 independent runs using WRF model. Model is run one combination of radiation (both shortwave and longwave) scheme along with fixed of other physics options. Fixed physics option is chosen for PBL, cumulus, land surface model, Surface layer and micro-physics schemes are Younsi State University (YSU), Kain-Fritisch, Noah Unified, Monin–Obukhov similarity theory and WRF single moment 3 class respectively.

From the output of WRF Model, 3 hourly 2m temperature have been extracted during the study periods. 34 meteorological stations of BMD are 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 are 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 (El-Shafie et al., 2011):

RMSE= $\sqrt{[1/n\ \Sigma^{n}_{i=1}\ (x_i - y_i)^2]}$; 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 case, the appropriate radiation combination is fixed out using average lowest RMSE value.

For validation of the performance of WRF model, model output is compared with observed data obtained from BMD and model data from ECMWF (0.125^0 x 0.125^0).

III. Sensitivity test of radiation physics

Analysis of the meteorological fields corresponding to selected radiation combination with both of longwave and shortwave parameterization schemes and its associated impact temperature over Bangladesh has been performed using the Fifth-Generation NCAR Mesoscale WRF Model (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 longwave and short-wave schemes of WRF model with coupling of the other fixing physical schemes for the prediction of the temperature due to 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, other selected meteorological parameters are simulated accordingly.

✓ Afterwards an attempt has been made to validate the simulated temperature with the observed temperature of Bangladesh Meteorological Department.

3.1 Sensitivity test of the different radiation parameterization schemes both of longwave and shortwave of WRF model for the prediction of the temperature due to 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 longwave and shortwave radiation for the ground heat budget. This downward longwave radiation includes infrared (or thermal) radiation absorbed and emitted by gases and surfaces. Upward longwave 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).

Table 2: Comparison of radiation schemes in WRF

Schemes Name	Gases	Clouds	Aerosols	Band	Flux Solution
Dudhia-shortwave only (ra_sw_physics=1)	H2O (no O3, CO2)	Look-up tables: Cloud albedo and absorption	Aerosol scattering		Downward integration Sloping and shadowing
RRTM-Longwave only (ra_lw_physics=1	H2O, O2, CO2 Trace Gases	Water and Ice clouds: prescribed mass abs coef & LWP/IWP		Multiple	Two-stream

	K-distribution				
GSFC-shortwave only (ra_sw_physics=2)	H2O, O3, CO2	Water & ice, rain parameterized ~ LWC/IWC & re /De	GOCART (WRF-Chem)	Multiple	Two-stream
CAM (3)	H2O, O3, CO2 Trace gases	Water & ice, parameterized ~ LWC/IWC & re /De re /De ~ temperature	Allow: monthly climatology 7 groups	Multiple	Solar: Two-stream IR: Absorptivity emissivity
RRTMG (4) New Goddard of RRTM	H2O, O3, CO2 Trace gases K-distribution	Water & ice parameterized ~ LWC/IWC & re /De McICA random overlap		Multiple	Two-stream
Goddard (5) New Goddard scheme	H2O, O3, CO2 Trace gases K-distribution	Water & ice, snow, rain and graupel: parameterized LWC/IWC & re /De De ~ temperature		Multiple	Two-stream
FLG (7)	H2O, O3, CO2, O2 Trace gases K-distribution	Water & ice, rain and graupel: parameterized ~ LWC/IWC & re/De De ~ IWC or IWC & AOD Maximum/random overlap Horizontal inhomogeneity	Allow: 18 aerosol type	Multiple	Solar: Four-stream IR: two/four combination
GFDL (99)	H2O, O3, CO2	Water and Ice: prescribed abs coef; COD ~ Qc Maximum/random overlap		Multiple	Two-stream

3.2 Final selection of radiation physics of WRF model for the prediction of the temperature due to heat wave (24-27 April 2019, 09-12 May 2019 and 19-22 may 2019).

Date	lw1_sw1	lw1_sw2	lw1_sw3	lw1_sw4	lw1_sw5	lw1_sw7
Apr24-27/19	2.1578153	2.3667428	2.3236171	2.3024394	2.3092206	16.336184
May9-12/19	2.0044826	2.0773957	1.9870584	2.0017757	2.1318016	12.657266
May19-22/19	2.0604557	2.1618848	2.0715971	2.0443515	2.2443268	10.941936
RMSE	2.0742512	2.2020078	2.1274242	2.1161888	2.2284497	13.311795

Date	lw3_sw1	lw3_sw2	lw3_sw3	lw3_sw4	lw3_sw5	lw3_sw7
Apr24-27/19	2.6153305	2.3915946	2.3544354	2.349376	2.3661682	19.670882
May9-12/19	2.3562282	2.2223308	2.1622978	2.1756444	2.2250021	14.782482
May19-22/19	2.5338363	2.1606643	2.2026738	2.158643	2.173201	12.776729
RMSE	2.5017983	2.2581966	2.2398024	2.2278878	2.2547904	15.743364

Date	lw4_sw1	lw4_sw2	lw4_sw3	lw4_sw4	lw4_sw5	lw4_sw7
Apr24-27/19	2.1611878	2.4013758	2.3508843	2.3263693	2.3513826	16.350716
May9-12/19	2.0458074	2.1480255	2.0443667	2.0955084	2.0975299	12.814666
May19-22/19	2.068796	2.1687016	2.1065605	2.1288968	2.090337	11.207768
RMSE	2.0919304	2.2393677	2.1672705	2.1835915	2.1797498	13.457717

Date	lw5_sw1	lw5_sw2	lw5_sw3	lw5_sw4	lw5_sw5	lw5_sw7
Apr24-27/19	2.0379	2.3283534	2.2741125	2.2577353	2.2953151	17.746198
May9-12/19	2.1984785	2.2637693	2.176259	2.0465495	2.050963	15.840896
May19-22/19	2.1489809	2.2739186	2.2133706	2.209892	2.1735398	13.921866
RMSE	2.1284531	2.2886804	2.2212474	2.1713923	2.1732726	15.83632

Date	lw7_sw1	lw7_sw2	lw7_sw3	lw7_sw4	lw7_sw5	lw7_sw7
Apr24-27/19	2.5494324	2.5608678	2.5245897	2.4198493	2.295694	2.3366849
May9-12/19	1.9529814	2.0869744	1.9958779	2.0013231	2.1237929	2.198829
May19-22/19	2.0752762	2.2181122	2.1646462	2.2182934	2.365645	2.2045166
RMSE	2.1925633	2.2886515	2.2283713	2.2131553	2.2617106	2.2466768

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

RMSE data on the basis of 2m air temperature and the radiation physics scheme, the RRTM for longwave and Dudhia for shortwave of WRF model respectively are finalized for this study.

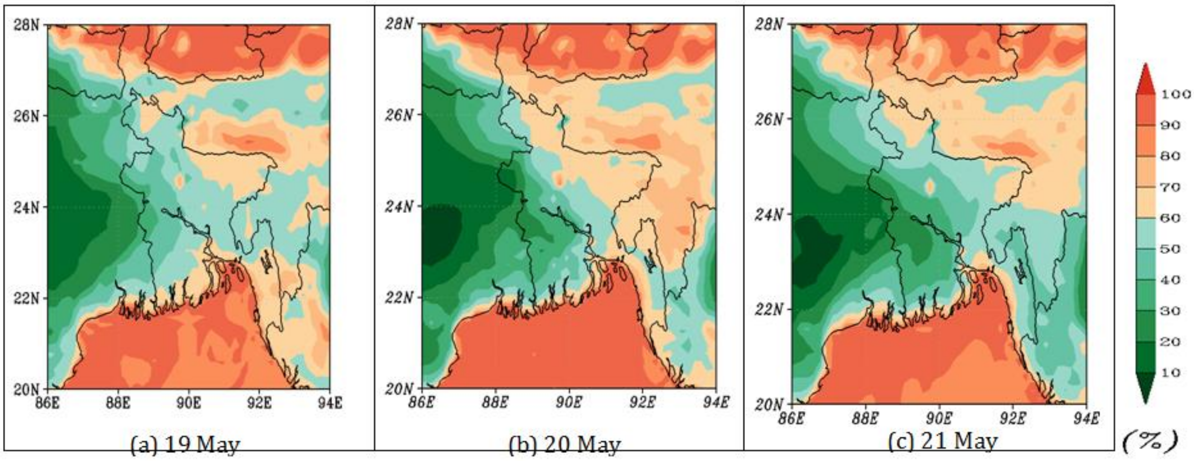
IV. Result and Discussion

The simulation of the HW event over Bangladesh, on 19 May to 21 May 2017 for HW is analyzed and presented in this chapter graphically. Comparisons of model simulated values with observational data for several parameters are also provided. To simulate these cases, the WRF-ARW model was run with radiation combination physics scheme, namely RRTM-Dudhia, using NCEP-FNL 6-hourly data from 0000 UTC of 18 May to 0000 UTC of 24 May 2017 as initial and lateral boundary conditions for run, and also analyzed and discussed these cases.

According to Bangladesh Meteorological Department (BMD), a HW occurred over the western part of Bangladesh and far eastern India on 19 May to 21 May 2017. The maximum temperature (◦ C), from 19 to 21 May, was recorded by BMD to be 36.6, 36.8 and 37.3 respectively and also the country maximum relative humidity (%) was recorded by BMD to be 97, 96 and 100 respectively. This event is simulated by WRF model with evaluating different meteorological parameters are described briefly in the following subsections.

4.1 Analysis of Relative Humidity (RH) at 2m Height

Relative Humidity (RH) is an important ingredient of HW formation. The RH of 19 May to 21 May, 2017 at 0900 UTC of model simulation for 3 days based on the initial conditions 0000 UTC of 18 May are presented in Figure 4.1.1 (a-c) respectively. The high amount of RH is an important environmental variable associated with cloud and rain formation.From the analysis of relative humidity, on 19 May, (10 − 40) % RH is found over West Bengal and Bihar, and (40 − 60)% RH is found over western and central part of Bangladesh, while the RH of northwest part of Bangladesh i.e. Rangpur, Mymensingh



(a) 19 May (b) 20 May (c) 21 May

Figure 4.1.1: Model-simulated RH (%) at 2m height valid for 0900 UTC from 19 to 24 May 2017 for 3 days respectively.

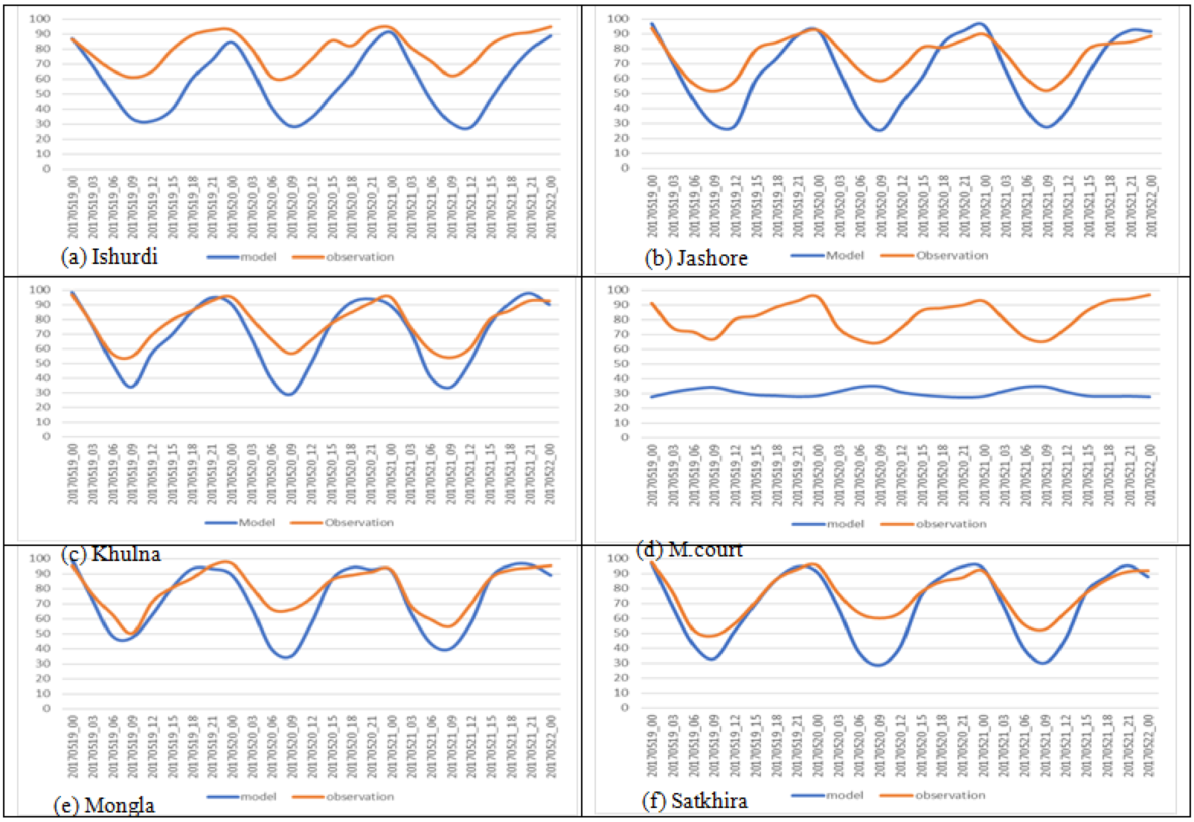


Figure 4.1.2: Comparison of model simulated Relative Humidity (%) with the observation (BMD) data.

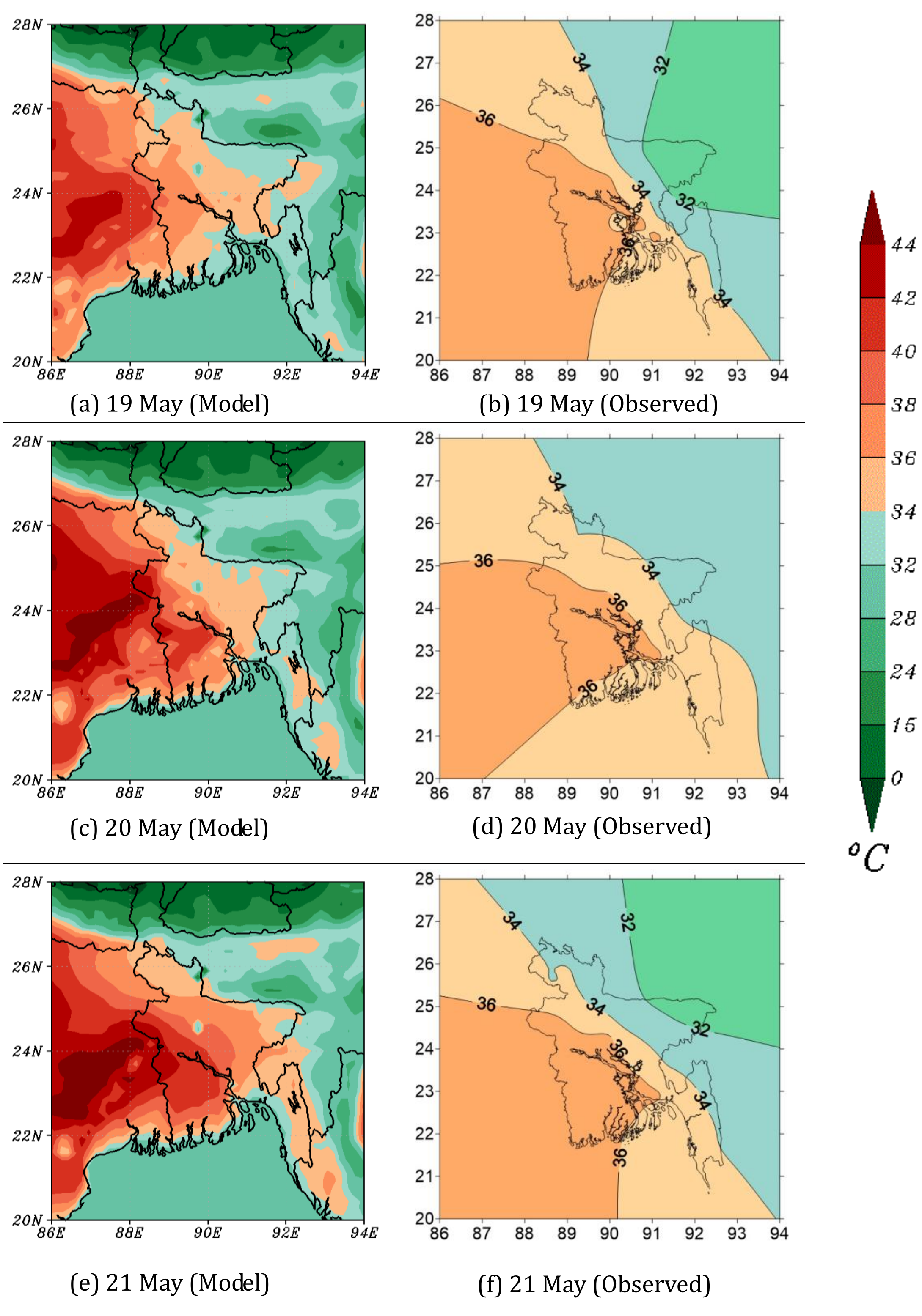
and Sylhet divisions, is about (60 − 70)%, whereas it is about (40 − 60)% in the central area, on 20 May. From these Figures, model RH at 0900 UTC from 19 to 21 May is (80 − 100)% in the Bay of Bengal. To investigate the model performance, simulated relative humidity of 2m height during 3 days from 0000 UTC on 19 May to 0000 UTC on 22 May 2017 were compared with the values observed by BMD in Figure 4.1.2. Here it has showed that the WRF-ARW model is under prediction to capture the RH.

4.2 Analysis of Temperature at 2m Height

Temperature is a vital element of heat wave. Frich et al. (2002) defined that a heat wave occurs when the daily maximum temperature of more than five consecutive days exceeds the average maximum temperature by 5^o C (9^o F). Model-simulated temperature at 2m height from 19 May to 21 May 2017 at 0900 UTC based on 0000 UTC of 19 May, with observed simulated temperature by BMD are shown in Figure 4.2.1(a-f).

From the temperature analysis it is observed that on 19 May 2017, the temperature is about $(34 - 38)^o$ C is simulated by model over the western and middle part of Bangladesh i.e. over the Rajshahi, Dhaka and Khulna divisions and also a small part over some adjoining area of Chittagong division at 0900 UTC. Also, on 19 May at 0900 UTC, $(28 - 32)^o$ C temperature is found over Sylhet and Bay of Bengal and nearest region of Chittagong division. On 20 May at the same time i.e. 0900 UTC, the temperature is about $(38 - 40)^o$ C in Dhaka division and also the nearest region in Khulna. In 21 May, the temperature is about $(40 - 42)^o$ C is simulated by model and $(36 - 38)^o$ C is simulated by observed data over West Bengal and adjoining western part of Bangladesh in Rajshahi and Khulna division and small part of Dhaka division.

For the inspection of the model performance, simulated maximum 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 4.2.2, and ECMWF simulated and observed by BMD in Figure 4.2.3. After analyzing these two figures, it has concluded that the WRF-ARW model is capable to capture the Temperature at 2m height reasonably well. Here it is also noted that the performance of model is better than ECMWF for first two days.



(a) 19 May (Model)

(b) 19 May (Observed)

(c) 20 May (Model)

(d) 20 May (Observed)

(e) 21 May (Model)

(f) 21 May (Observed)

Figure 4.2.1: Temperature (° C) at 2m height valid for 0900 UTC, using model data (left side) and observed data (right side).

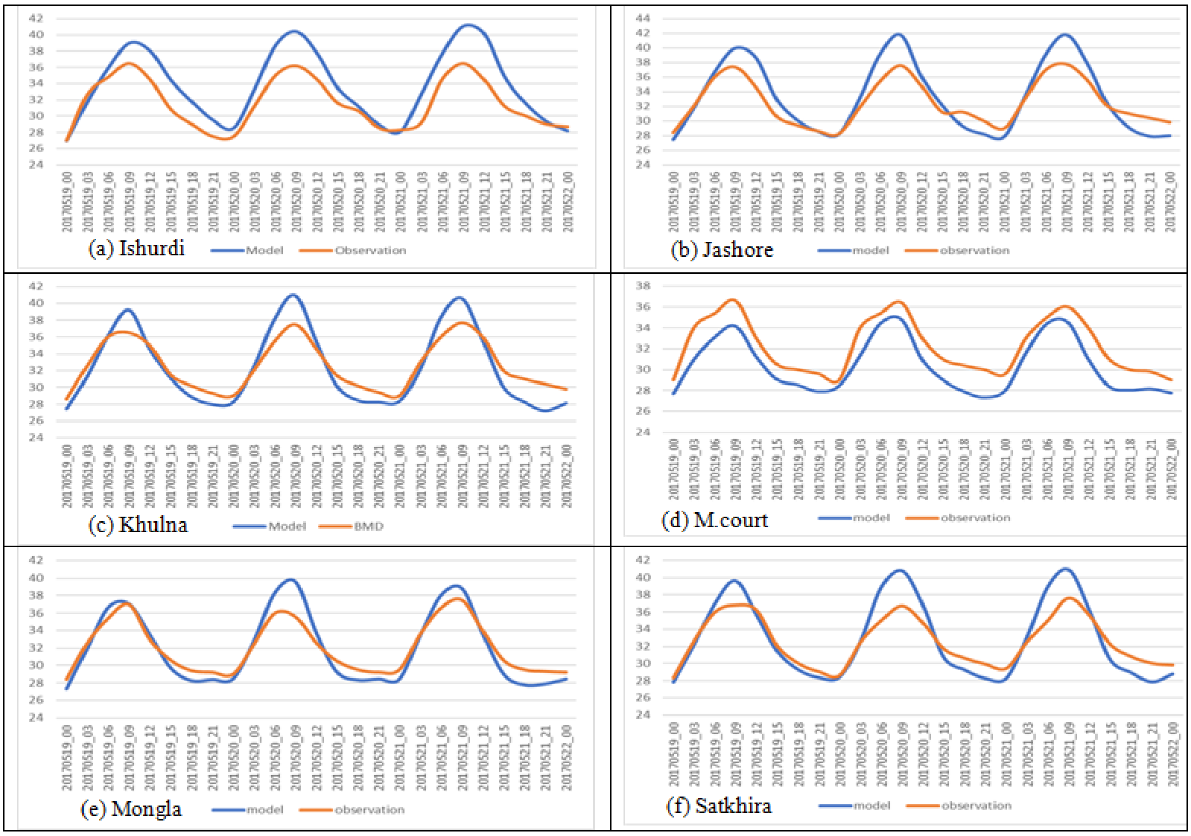


Figure 4.2.2: Comparison of model simulated 2m air Temperature (^{o} C) with the observation (BMD) data.

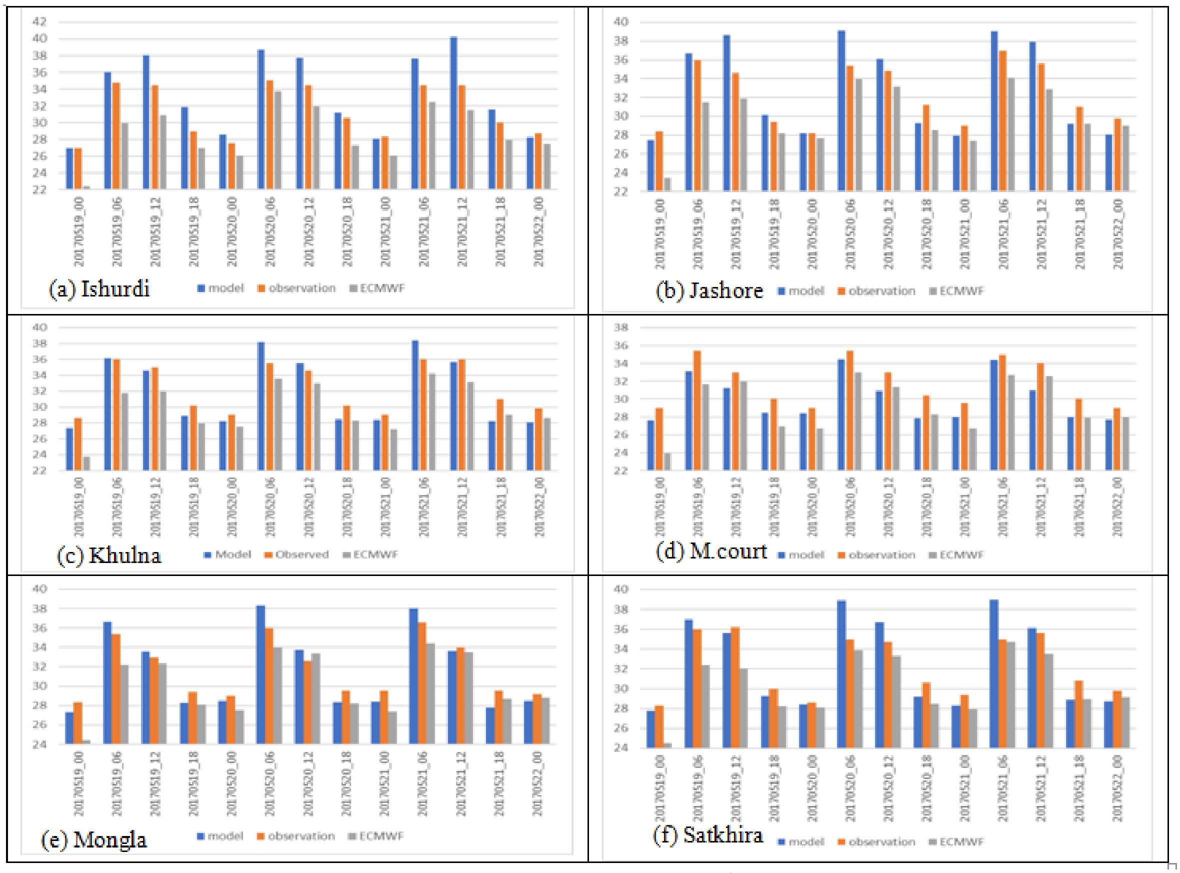


Figure 4.2.3: Comparison of model simulated 2m air Temperature (^{o} C) with the observation (BMD) data and ECMWF data.

4.3 Analysis of Mean Sea Level Pressure (MSLP)

Model simulated MSLP of 3 days from 19 May to 21 May 2017 at 0900 UTC based on the initial conditions of 0000 UTC of 19 May 2017 are shown in Figure 4.3.1(a-c). On 19 May at 0900 UTC it is found that, a trough of westerly low (998 − 1002)hP a is simulated over Bihar, north part of West Bengal and adjoining part of Bangladesh while (1002 − 1004)hP a is simulated over the whole area of the country Bangladesh and also a convergence zone of very high (1004 − 1010)hP a is simulated over the adjoining area of Meghalaya. The trough of low moved farther to east on 20 May and on 21 a convergence zone of low MSLP (998−1000)hP a is simulated over West Bengal and adjoining part of Rajshahi.

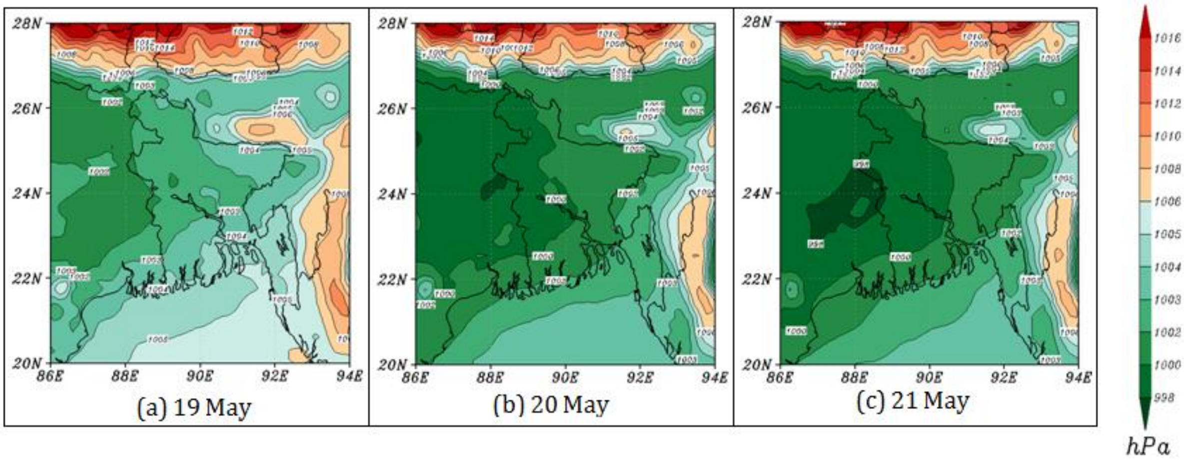

(a) 19 May
(b) 20 May
(c) 21 May

Figure 4.3.1: Model simulated MSLP analysis at 850 hPa level valid for 0900 UTC of 19 to 21 May, 2017 for 3 days respectively.

4.4 Analysis of 850, 500 & 200 hPa Level Wind Flow

The distribution of 850 hPa, 500 hPa and 200 hPa wind flow (ms^{-1}) valid for 0900 UTC from 19 May to 21 May 2017 of model simulation for 3 days based on the initial conditions 0000 UTC of 19 May are shown in Figure 4.4.1(a-c), Figure 4.4.2(a-c) and Figure 4.4.3(a-c) respectively. At 850 hPa level, south/southwesterly wind of speed (5 − 8) ms^{-1} is simulated over Bay of Bengal and western part of Chittagong division.

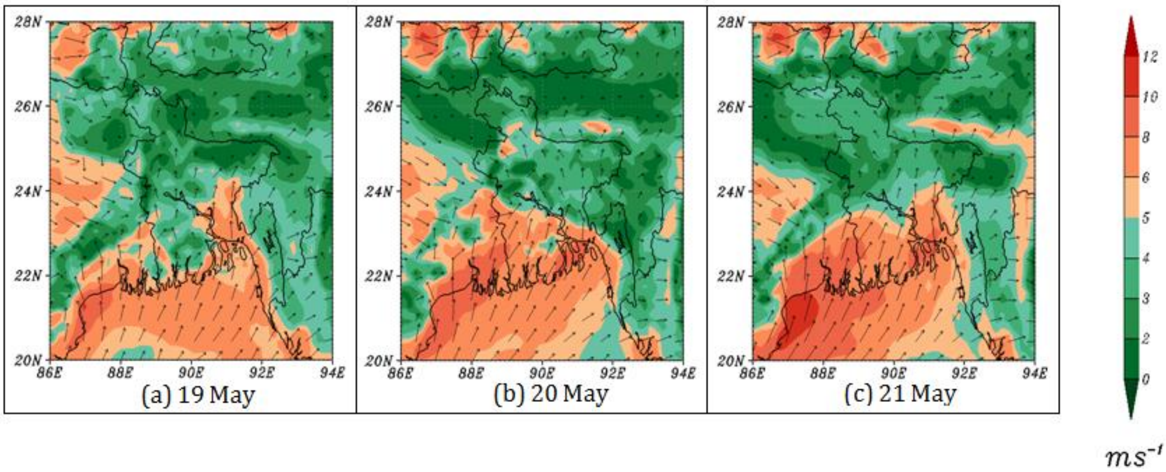
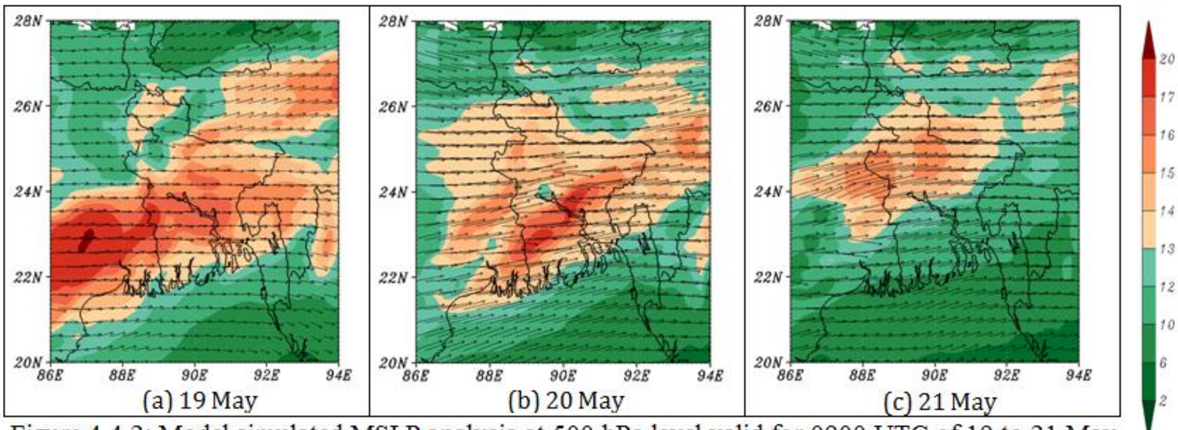

(a) 19 May
(b) 20 May
(c) 21 May

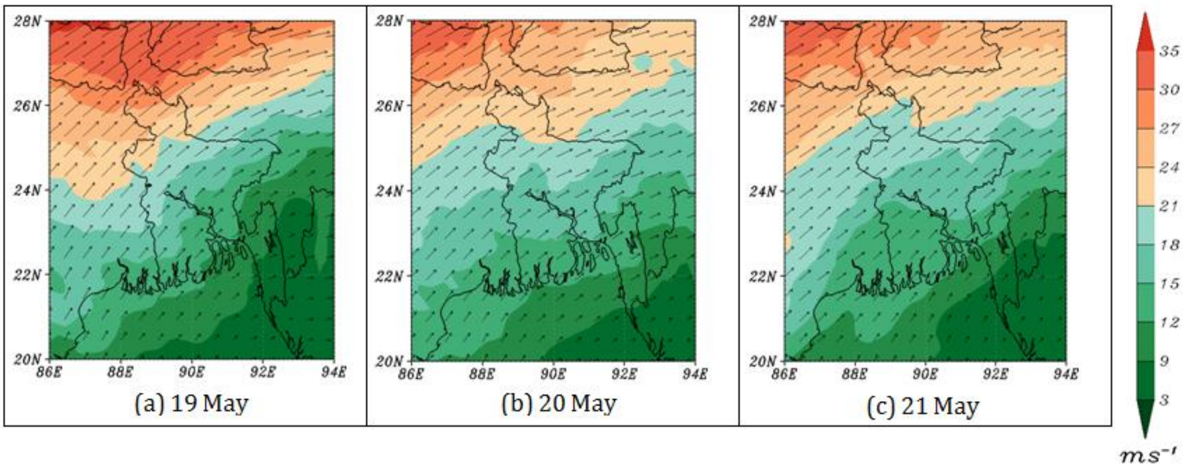
Figure 4.4.1: Model simulated MSLP analysis at 850 hPa level valid for 0900 UTC of 19 to 21 May, 2017 for 3 days respectively.

A divergence zone is seen over Rajshahi on 20 May where the wind speed is (3 − 6) ms^{-1}. On 21 May, southesterly wind is found over Rajshahi while southwesterly wind of speed (5 − 10) ms^{-1} is simulated over Khulna, Barisal, Chittagong and connecting region of Dhaka. At 500 hPa level, strong westerly wind of speed (15 − 20) ms^{-1} is simulated over West Bengal and adjoining part of Khulna division, and over Barisal, Khulna, Dhaka, Mymensingh, Sylhet and neighboring Chittagong, the wind speed is (14 − 17) ms^{-1}. On 20 May, forcible westerly and southwesterly wind of speed (15−20) ms^{-1} is found over Khulna and Dhaka division. At 200 hPa pressure level, strong westerly and southwesterly wind of speed (21 − 30) ms^{-1} is simulated over Rangpur and nearest part of Rajshahi while in Chittagong the speed is (9−15) ms^{-1}, and during the next 2 days the westerly wind is decreasing with (9 − 21) ms^{-1}.



(a) 19 May (b) 20 May (c) 21 May

Figure 4.4.2: Model simulated MSLP analysis at 500 hPa level valid for 0900 UTC of 19 to 21 May, 2017 for 3 days respectively.

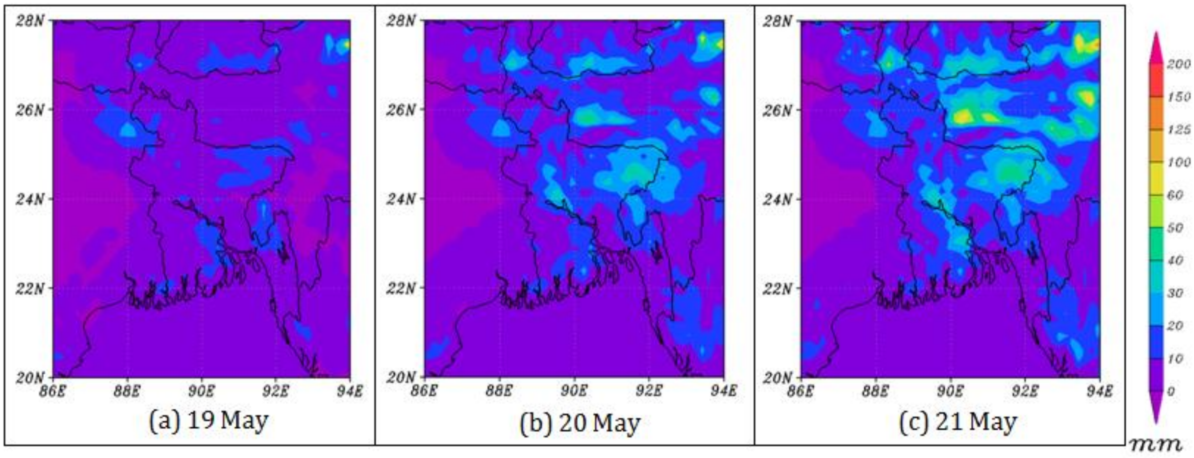


(a) 19 May (b) 20 May (c) 21 May

Figure 4.4.3: Model simulated MSLP analysis at 200 hPa level valid for 0900 UTC of 19 to 21 May, 2017 for 3 days respectively.

4.5 Analysis of Accumulated Rainfall

The WRF model simulated daily rainfall distribution valid for 0900 UTC from 19 May to 21 May 2017, simulated for 3 days based on the initial conditions 0000 UTC of 19 May are presented in Figure 4.5.1(a-c) respectively. No significant rainfall amount is simulated over Bangladesh on 19 May, (10 − 20)mm rainfall is simulated over Sylhet during this period. In the next day, (20 − 40)mm rainfall is found over Sylhet and (10−30)mm over Dhaka and Rajshahi. On 21 May at 0900 UTC, (30 − 60)mm rainfall is simulated over Sylhet and (10 − 40)mm is found in Dhaka and adjoining part of Khulna. As very low amount of rainfall occurred over Bangladesh in the required time, so it is an important argument for HW formation.

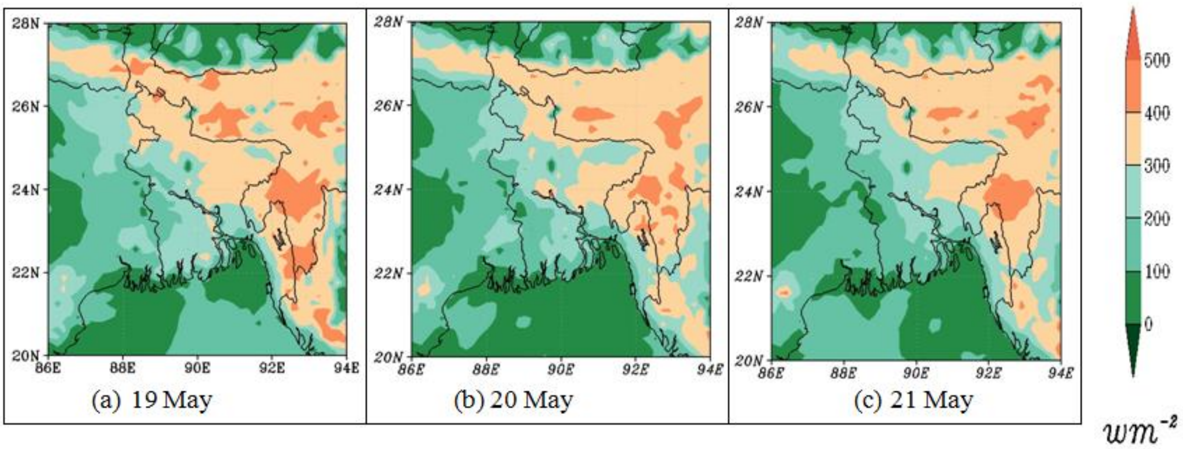


(a) 19 May (b) 20 May (c) 21 May

Figure 4.5.1: Model-simulated daily rainfall based on 0900 UTC of 19 to 21 May, 2017 for 3 days respectively.

4.6 Analysis of LH

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. Model-simulated daily LH from 19 May to 21 May 2017 at 0900 UTC based on 0000 UTC of 19 May 2017 initial conditions are shown in Figure 4.6.1(a-c). On 19 May, (300 − 400) wm^{-2} LH is simulated over Meghalya and adjoining northern and northeastern part of Bangladesh including Rangpur, Mymensingh and Sylhet divisions at 0900 UTC



(a) 19 May (b) 20 May (c) 21 May

Figure 4.6.1: Model-simulated daily latent heat at 0900 UTC of 19 to 21 May, 2017 for 3 days respectively.

Also (100 − 300) wm^{-2} is simulated over West Bengal and adjacent south and southwest part of Bangladesh that is over Rajshahi, Dhaka, Khulna and Barisal divisions. In the next day, the LH is (200 − 300) is found over Rangpur and small region of Sylhet whereas it in unchanged over other region. The next day at the same time (0900 UTC), this LH is approximately stable over Rajshahi, Dhaka, Khulna, Rangpur, Barisal and where it is found in about (100 − 300) wm^{-2}, that means HW occurred in that regions and since, LH is decreased over Sylhet, HW is not occurred here.

V. Conclusions

Heat Wave (HW) becomes significant over Bangladesh as they caused terrible damage on the live-in recent decades. Forecasting such events, especially in the pre-monsoon region is quite challenging. Therefore, this study has made an attempt to simulate HW using WRF model to predict the future events more effectively. Different radiation physics schemes that are responsible for extreme temperature 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 conclusion can be drawn:

The sensitivity test of different radiation parameterization schemes of WRF model show that the RRTM for longwave and Dudhia for shortwave option produce more or less realistic results in quantitative comparisons. Therefore, these schemes have been considered as the best for synoptic analysis and prediction of pre-monsoon heat wave over the Bangladesh.

Finally, it may be concluded that the Fifth-Generation PSU/NCAR mesoscale 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 heat wave 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 HW, its associated high impact temperature and its thermodynamic features over Bangladesh up to 72-hours advance. It is also recommended that similar study be extended for more number of cases for further refinement of the model application.

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