Journal of Contemporary Academic Research and Methodologies

An Online Peer Reviewed / Refereed Journal
Volume 1 | Issue 7 | August 2026
ISSN: 3139-7247 (Online)
Website: www.journal.jcarm.in

Original Research Article

EXPLORING THE SUITABLE AREAS IN BANGLADESH FOR PREDICTING EXTREME TEMPERATURES USING THE WRF-ARW MODEL

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Article No: 009 | **Accepted**: 20 August 2026 | **Published**:10 September 2026

Abstract: This study examines suitable areas in Bangladesh for predicting extreme temperatures using the Advanced Weather Research and Forecasting (WRF-ARW) model during the pre-monsoon and winter seasons. Based on the Root Mean Square Error (RMSE) of the temperature at 2m height, it is established that the WRF model is highly capable of simulating extreme temperatures. The WRF model output data were compared with the ERA data from the ECMWF global model. The comparison indicates that the WRF model successfully captures the spatial distribution of extreme temperature areas across Bangladesh and demonstrates a reasonable capability for their deterministic prediction. The third objective of this study is an initial attempt to identify the causes of extreme temperature events in Bangladesh. The WRF model revealed that the Thar Desert, the Himalayan range, the Bay of Bengal, the Arabian Sea, and the region's geography play a significant role in producing extreme temperatures in the Indian subcontinent. Finally, it is concluded that the study successfully achieved its intended outcomes, as evidenced by the findings presented in this research.

Keywords: Explore, Extreme, Predict, Suitable, Temperature

INTRODUCTION

Bangladesh serves as a playground for various types of disasters, including thunderstorms/tornadoes, floods, flash floods, droughts, rainwater surges associated with tropical cyclones, extreme temperature conditions, heavy rain, and more. Heat Waves (HW) and Cold Waves (CW) are two parts of Extreme Temperature (ET), which is a rare weather phenomenon. A large number of casualties and socioeconomic losses occur every year due

 https://doi.org/10.5281/zenodo.22765937

to severe heat waves. For decreasing of agricultural land and erosion, dry soils are susceptible. No doubt about that, evaporation of water bodies is the main reason for the devastation to marine populations, because it reduces the available habitat size and the nutrients in the water. A cold wave can be the cause of death and injury to livestock and wildlife. Exposure to cold provokes animals, including humans, to increase their caloric intake, and if a cold wave is accompanied by heavy and dogged snow, grazing animals may not be able to reach necessary food and water, and die of hypothermia (Thornbrugh et al., 2007). Because of this fact, since the last century, studies and experiments on the climatology of extreme temperature conditions, both theoretically and practically, have become a major concern in scientific research. Heat waves and their associated stress occur almost every year in Bangladesh, the severity of which is more over western, northwestern, and northeastern parts of the country. These events severely affect crops, reducing crop production significantly, livelihoods, deteriorating human and animal health, as well as hampering food security greatly. In Bangladesh, the circulation of wind associated with heat and cold waves at different levels of the troposphere has not yet been studied broadly. Numerical Weather Prediction (NWP) models like the Weather Research and Forecasting (WRF) model, and the role of predicting extreme temperature conditions have not been studied fully in Bangladesh. Mamun et al. (2022) conducted a study of recent cold conditions in Bangladesh from 1990 to 2019. The frequency of CW, station-wise, monthly, yearly, decadal, and spatially, is to compute cold waves under the study. The study revealed that the Northwestern part and the Srimangal region have more cold day has found from the spatial distribution. Mamun et al. (2022) also conducted a study to investigate the response to the radiation parameter schemes for dynamic downscaling of climatic variables. The outcome of this study depicted that the New Goddard for long wave and Dudhia for short wave schemes combination is the most appropriate to simulate the winter extreme temperature. By using the Mann-Kendall test for trend analysis and Arc-GIS for spatial distribution revealed that the hottest places are Jashore, Chuadanga, Rajshahi, Ishurdi, and Satkhira, which are located spatially in the south-western and middle-western parts of Bangladesh in the pre-monsoon; a study on the heat wave conditions over Bangladesh during 1990 – 2019 has been conducted by Mamun et al. (2023). In general, extreme temperature conditions lead to short-term increases in daily mortality (Braga et al., 2001; Curriero et al., 2002; Huynen et al., 2001; McGeehin & Mirabelli, 2001; Mercer, 2003) due to extreme heat. The occurrence of heatwaves is fundamentally dependent on certain local maximum temperature limits. Maximum temperature thresholds vary by location, primarily due to differences in atmospheric conditions and geographic location (Das & Smith, 2012). Due to extreme temperature events associated with public health risk, plant growth and/or ecosystems, it has been of great concern nowadays (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 worldwide (Black et al., 2004; Fink et al., 2004; Schar et al., 2004). Especially in Europe (Dasari et al., 2014) and North America (Gershunov et al., 2009), the mechanisms and conditions of large-scale extreme temperature events have been broadly studied. A study made on increasing heat waves and warm spells in India indicates whether and to what extent they have changed since the mid-20th century, using a multi-aspect framework to accommodate a wide range of impact sectors (Panda et al., 2017). Several forecasting studies using multiple climate models and CMIP5 data show that temperature extremes in Bangladesh and India are expected to be more intense, longer-lasting, and more frequent (Murari et al., 2015). These projections also indicate that many regions of Bangladesh and India will suffer heat stress in the near future. Given the high risk of vulnerability of large population groups to heatwaves in the region, further efforts are needed to improve the predictive power of NWP models and use these predictions for disaster management. (De et al., 2005). The increased power of high-resolution computer simulations using NWP models and the availability of high-frequency data have made it fairly possible to predict extreme temperatures with very high resolution and sufficient lead time. Mesoscale models such as WRF are used by some researchers to simulate local weather conditions, including temperature extremes, in various regions, especially in Europe and North America (Bohnenstengel et al., 2011; Salamanca et al., 2012; Giannaros et al., 2013; Giovannini et al., 2013). Heatwaves in India: Heatwaves occur in northern, western, central, and central-south India during summer (NIUA, 2016). Such a situation is caused by the wind blowing from the hot and dry state of Rajasthan. A high-pressure system developing over the state will prevent disturbances from the west from penetrating the Indian subcontinent, resulting in clear skies. Note that high pressure over the 'Thar' Desert in Rajasthan brings hot winds and increases temperatures in the surrounding areas. Nissan et al. (2017) conducted a study on the definition and prediction of heat waves in Bangladesh. According to them, the paper proposes a definition of heat waves in Bangladesh that can be used to trigger preparatory actions in the early heat warning system (HEWS). and investigate climate mechanisms associated with heat waves.

However, such studies are lacking in the southwest monsoon region. The Indian subcontinental experience has a general rise in the frequency of heat waves, consistent with the simultaneous increase in dry and hot extremes over several regions of the world. However, finding the distinctive spatial, temporal, and diurnal evolution of heat wave characteristics is interesting. At the global scale, the hot extremes continued to increase during the global warming pause, without any major El Niño event observed by Seneviratne et al. (2014). Since India is projected to be a global hotspot of heat stress on 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, during June to August, the year 2010 stands out clearly in terms of extreme events, with the largest summer-time warming over the Northern Hemisphere (Trenberth & Fasullo, 2012). Mamun et al. (2022) conducted a study using the WRF model, which was tested through 30 different combinations of radiation parameterization schemes to simulate regional weather over Bangladesh and to investigate the response to the radiation parameterization schemes, with other physics schemes kept constant for dynamic downscaling of weather variables. Having analyzed the RMSE results for 2-meter height air temperature at 34 stations over Bangladesh responses that the RRTM for longwave and Dudhia for shortwave combination schemes are the most appropriate to simulate the pre-monsoon extreme temperature. The increasing trend in both frequency and intensity of heat waves is often attributed to climate change (Mishra et al., 2015). The Japanese Ministry of Environment reported that the casualties due to heat stroke and heat exhaustion during the unusually hot summer in 2010 amounted to 1745 in Japan. India was also reported to have experienced deaths due to heat waves over the years. An approximate number of 1300 deaths were caused by the heat wave of 1988 (De et al., 2004), and similarly, the heat waves of 1998 and 2003 caused deaths of about 2042 people (Jenamani, 2012) and 3054 people (Bhadram, 2005), respectively. Another study is associated with the simulation of regional climate using the WRF model, which was experimented with through 30 different combinations of radiation parameterization schemes over Bangladesh. The intention was to investigate the response to the radiation schemes; the research reveals, based on Root Mean Square Error (RMSE), that the Rapid Radiative Transfer Model (RRTM) for longwave and Dudhia for shortwave schemes are the most appropriate combinations to simulate extreme temperature conditions by Mamunn et al. (2022). Analyzing climate model temperature output during 1950–2100 and the global changes in extreme temperatures by using various climate indices has been documented, as studied by Russo & Sterl (2011). The study suggested a significant increase in temperature extremes, such as warm days over the Indian region during 2001–2100. That is why, an urgent need to develop a strategy for the country for forecasting and mitigation efforts to minimize the adverse effects of heat waves. On climate change patterns, future trends, and impacts in northwest Bangladesh, Karmakar conducted a study (2018). Relative humidity has been used to calculate heat stress over the places under study, and rainfall data has been used to compute the rainless days. The dry days and heat stress trends are studied. To minimize the mass destruction of lives and property, it is very important to predict the Extreme temperature conditions for a specific time and location. Unfortunately, the improvement in the prediction of these vital weather phenomena is still handicapped for lacking of mesoscale observations and insufficient understanding.

1.1 Geographical Location of Bangladesh

Bangladesh has a latitude of 20.34 °N to 26.38 °N and a longitude of 88.01 °E to 92.1 °E. The southeastern borders Myanmar (Burma), located in western India (West Bengal), north of Meghalaya and Assam, east of Tripura and Mizoram, and northeast of northeastern Assam. It flows through the country and empties into the Bay of Bengal (BoB). Alluvial levels are part of the wider Bengal level, which is sometimes referred to as the lower level of the Ganges River. The level is less than 10 meters above sea level. To the south of the coast, the height drops to sea level. The hills southeast of Chittagong, the hills northeast of Sylhet, and the highlands in the northwest are lowlands. Chittagong Hill forms the only important hill system in the country. It changes in elevation on average between 600 and 900 m above sea level and rises sharply to a narrow ridge (average width 36 m). Between the combs on the hill, there is a valley, which usually runs north and south. To the west of Chittagong Hill is a narrow, damp coastal plain that stretches parallel to the coast. Between the combs on the hill, there is a valley, which usually runs north and south. To the west of Chittagong Hill is a narrow, damp coastal plain that stretches parallel to the coast.

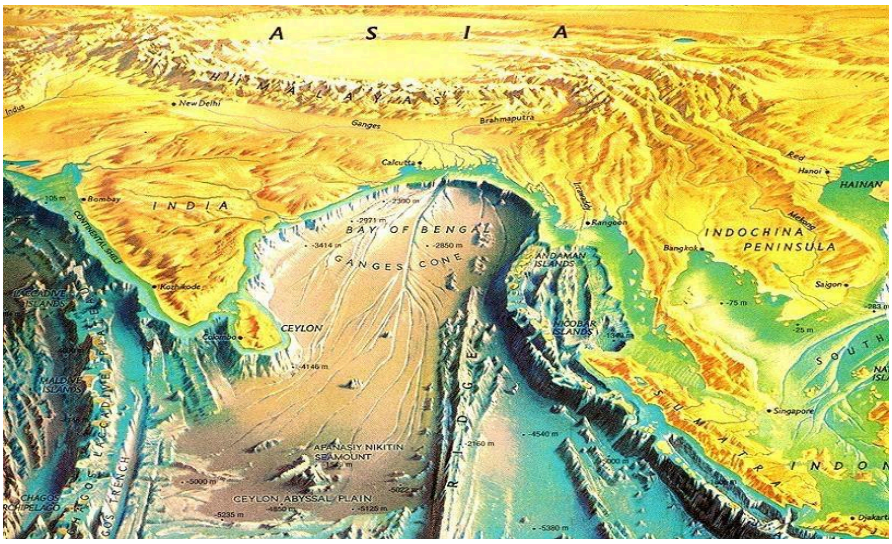

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Figure 1: A detailed map of the Indian Ocean floor (1967)

1.2 Socio-economic Impacts of the Study

Heat waves and cold waves are creating a serious threat to human life. People in tropical and temperate countries are thought to be less likely to be affected by excessive heat occurrences. Recent studies, however, refute this idea, citing significant death tolls. Continual heat waves lessen human ability to do physical jobs, as well as impact mental health. Extreme heat hampers the thermo-regulatory processes of the human body, causing thermal stress, and this ultimately reduces the ability to work. Moreover, overexposure to high temperatures gradually leads to chronic diseases. It is mainly dangerous for children, the elderly, and people exposed to sunshine for an extensive period without proper air conditioning or hydration. Bangladesh has an agriculture-based economy run with more than 65% of the peripheral community directly involved in working in the fields. It is easy to envision how deadly a heat wave is for anyone doing strenuous labor. The duration and frequency of warm days/nights have increased since 1950 according to the IPCC report (IPCC 2012), and it is anticipated that there will be more frequent hot temperatures and fewer cold temperature extremes over most of the areas of Asia. A tremendous number of the population of the nation is living below the destitution line, not having the capacity to cope with extraordinary climate events such as extreme cold waves. Older people and children are more susceptible to pneumonia, diarrhea, asthma, and other cold-related illnesses due to cold weather. Heavy fog often prevents transport and ferries from operating. To cope with such disasters, people in affected areas need external help and assistance from the government and other humanitarian organizations before disasters occur. Therefore, some precautionary measures should be taken in advance, and preparedness measures should be taken by the respective authorities to protect the affected population. In the northern town of Tetulia, which borders India, temperatures dropped to 4.5° C, the lowest ever recorded for the region. The temperature usually hovers around 8° C during this time. Although the temperature is not usually deadly cold, poor workers and their families without adequate housing and clothing are the victims of the disease. But the cold isn't the only reason for the surge in deaths. Experts say climate change is adversely affecting weather conditions in the country, leading to dense fog and the spread of disease.

1.3 Motivation

Heat and cold waves are normal weather events that occur in the pre-monsoon (March to May) and winter (December to February) over Bangladesh, which has the worst disaster impact in the western part of the country. Sometimes droughts are connected to heat waves. The combination of heat waves and drought effects leads to a major loss in the country's agriculture. Global and local warming contribute to an increase in the frequency and intensity of these disasters. The adverse effects of climate change and the increased frequency and intensity of various catastrophes have created challenges for the country's general economic development, as well as food security and livelihoods. A large number of casualties and socioeconomic losses occur every year due to severe heat waves. For decreasing of agricultural land and erosion, dry soils are susceptible. A cold wave can cause death and injury to livestock and wildlife. These events severely affect crops, reducing crop production significantly, affecting livelihoods, and deteriorating human and animal health, as well as hampering food security greatly. It is necessary to predict extreme temperature conditions for precautionary measures and for early warning and action to reduce disaster risks. So, the research is focused on extreme temperature conditions in Bangladesh's socio-economic development sustainability. To prevent the extreme temperatures' hostile impact on the life and economy of a certain region, advance information about them is very important. It is a challenging task for meteorologists and researchers to predict extreme weather events, and such predictions are useful to minimize harm and to adopt essential mitigation measures. To take necessary precautions, even a small improvement can be helpful in the skill of extended-range forecasting of extreme weather events and also in minimizing weather-related fatalities and losses, which is necessary for substantial economic benefit. This is why I was inspired to study this work.

1.4 Objectives

The purpose of this study is to use the WRF-ARW model to find out suitable areas for extreme hot and cold temperatures that occurred in Bangladesh during the pre-monsoon and winter. The specific goals of this research are

i) assessing the robustness of the WRF model's capability to simulate extreme temperatures,
ii) identifying areas affected by extreme temperatures during winter and pre-monsoon season using the WRF model, and
iii) an initial attempt to identify the causes of extreme temperature events in Bangladesh.

2. METHODOLOGY

Model used: WRF model

Weather forecasting is always a challenging task for meteorologists. The conventional method on which the meteorological community trusts is the synoptic method. That is a subjective method, and meteorologists can show their expertise in forecasting through this method. With advances in computing capability, the objective method has advanced from Statistical to the Numerical Weather Prediction (NWP) form. Nowadays, a good number of NWP models are working around the globe. Countries advanced in science and technology have their own models, and some are working with the standard free ones. Scientists are working to improve the knowledge regarding the weather system and to enhance forecasting capability. Different scientific communities are contributing differently to the purpose. Different models have different capabilities; some are capable of forecasting the global weather, whereas others have regional capacities. Some may run for months, but some for a few days. Based on the range of forecasting, they are coined as short range/medium range/long range. Short- to medium-range forecasting (up to 14 days) is important to most of the public. With the enhancement in the capacity of calculation and storage regulation of the models has also increased. People are running regional models with less than a kilometer resolution. This super-fine grid system becomes possible through *nesting*.

In the last decade, a meso-scale model for researchers and the scientific community has emerged, and it was free, with the required data access. As a result, a lot of advances have been made through the suggestions provided by the community users. Meso-scale Model 5 (MM5), with different versions, was the last of their generation. After them, Weather Research and Forecasting (WRF) models have been released, and their varieties are in widespread use around the globe. The latest release of WRF is 4.3.0 and was released on 11 May 2021. The author is using the latest version for the research.

The WRF model has three components (as with other models): i) pre-processing, ii) Model running, and iii) post-processing. At the preprocessing stage, one has to decide/declare the date and time, the region of interest, grid spacing (in case of nested runs, parent-child ratio), map projection, etc. In this stage, the geographic data is blended with the meteorological data. The geographical data are almost static except for the land use pattern, which varies with respect to season. The meteorological data are collected from different sources; some are really free, and some require prior permission/understanding. The free data are either of two categories: reanalysis or GFS (Global Forecast System) type. Reanalysis data have to go through a four-dimensional variational analysis system, and then the data are fed to a global model for forecasting up to a certain period, mainly up to the medium range. Whereas GFS data are the output of the Global Forecast System weather forecast model run by the National Centers for Environmental Prediction (NCEP) of the USA. That model is a coupled model composed of four separate models (an atmospheric model, an ocean model, a land/soil model, and a sea-ice model) that work together to provide an accurate picture of weather conditions. Dozens of atmospheric and land-soil variables are available through this dataset, from temperatures, winds, and precipitation to soil moisture and atmospheric ozone concentration. The entire globe is covered by the GFS at a base horizontal resolution of 28km between grid points. Before blending with the geographical data, one needs to specify how many vertical levels he/she wants to calculate (either eta or pressure levels). At present, WRF can handle 38 vertical levels. After blending both the data new file is created, i.e., the data are written in a certain format suitable for the running stage.

At the running stage, one has to decide which of the different parameterization schemes will be used. Among them, radiation is the most important. In this paper, an attempt is made to check what happens when different radiation schemes are called, keeping the other physics schemes constant. Of course, this type of investigation is new and may shed new light on calling radiation parameterization schemes, but before that, researchers should know about the impact on the forecast.

To check the effect, one needs to plot the output, and that is done through the third component of WRF. It supports many different programs, of which GrADS (Grid Analysis and Display System) is being used in this study. Through GrADS, plots will be made to view the effect.

Study Objectives and Implementation

The WRF Model has been run with the best combination of physics schemes, which are selected from several research papers. Fixed physics options chosen for radiation (both longwave and shortwave), PBL, cumulus, land surface model, Surface layer, and microphysics schemes will be Rapid Radiative Transfer Model (RRTM)-Dudhia, Younsi State University (YSU), Kain-Fritsch, 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. The domain will use a 10 km 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; the integration time step will be 30 seconds. WRF will finally be 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} × 1 ^{o} resolution and 6-h time steps. Fixing the above physical parameters, the model will be run for heat waves and cold waves. From the output of the WRF Model, 3-hourly 2m temperature has 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 provides the control (ctl) file, which is converted into text (txt) format data using the Grid Analysis and Display System (GrADS). These data were 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:

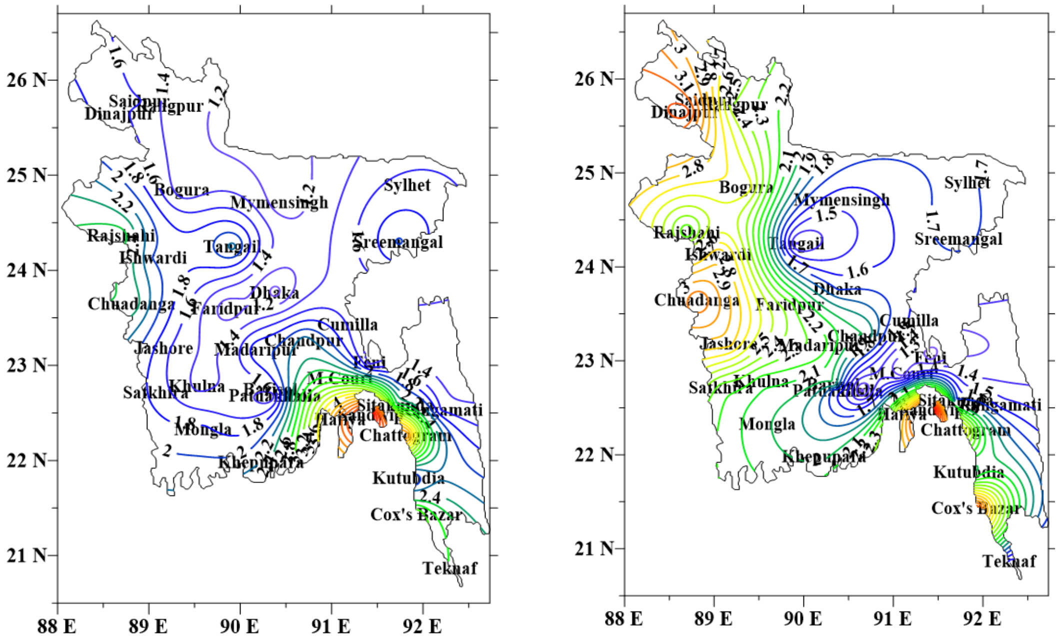
$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - y_i\right)^2}$, where n is the total number of simulated outputs, x is the model-simulated values, and y is the observed values. These RMSEs will be presented with Surfer for spatial visualization. These results have been used to assess the robustness of the model's capability to simulate extreme temperatures. Also, the WRF-ARW model-predicted data are compared with the BMD synoptic data for the verification of the model. To identify areas affected by extreme temperatures during winter and pre-monsoon using the WRF model, the WRF model output is compared spatially with the ECMWF global model's predicted ERA data. For the visualization, the Grid Analysis and Display System (GrADS) and Aeronautical Reconnaissance Coverage Geographic Information System (ArcGIS) software have been used. All figures are an attempt to identify the causes of extreme temperature events in Bangladesh.

3. RESULTS

This section has three subsections. An assessment of the robustness of the WRF model's capability to simulate extreme temperatures is discussed in subsection 3.1. Identifying areas affected by extreme temperatures during winter and the pre-monsoon using the WRF model is discussed in subsection 3.2. Finally, an initial attempt to identify the causes of extreme temperature events in Bangladesh is discussed in subsection 3.3.

3.1 Assessing the robustness of the WRF model's capability to simulate extreme temperatures.

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) is shown in Figure 1. The highest average RMSEs (above 2 °C) for the CW are found in the southeastern coastal areas of Bangladesh, as well as in other locations such as Rajshahi, Chuadanga, and Tangail (Figure 1(a)). The average RMSEs, which are reasonably acceptable (2 °C or less), are found in the rest parts of the country. The maximum average RMSE is found in Hatiya (4.76 °C), and the minimum is in Dhaka (0.92 °C). The highest average RMSEs (above 2.2 °C) for the HW are found in the southern coastal areas, the middle-western, and the northeastern parts of Bangladesh (Figure 1(b)). The average RMSEs, which are reasonably acceptable (2.2 °C or less), are found in the 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. 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.



(a) (b)

Figure 1: Spatial distribution of RMSE of temperature (° C) at 2m height for (a) CW and (b) 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 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) because it is an island situated on the BoB, and Feni (1.3 °C and 1.16 °C). Finally, it is noted that RMSEs are not constant, but they are variable with respect to place (station) as well as time (event).

Verification of WRF-ARW Model Performance

For the verification and validation of the WRF-ARW model performance, a comparison has been made in a combined graph. WRF model-simulated values of 2m air temperature and those of the meteorological observatory (BMD) data have been used and are presented in Figure 2.1 for CW. The stations are chosen where the temperature (observed or WRF model or both observed and WRF model) is equal to or less than 10 ^{O}C. The observations strongly revealed that the WRF model simulated values are reasonably good for predicting CW conditions, except M.court. This may be because of the coastal area.

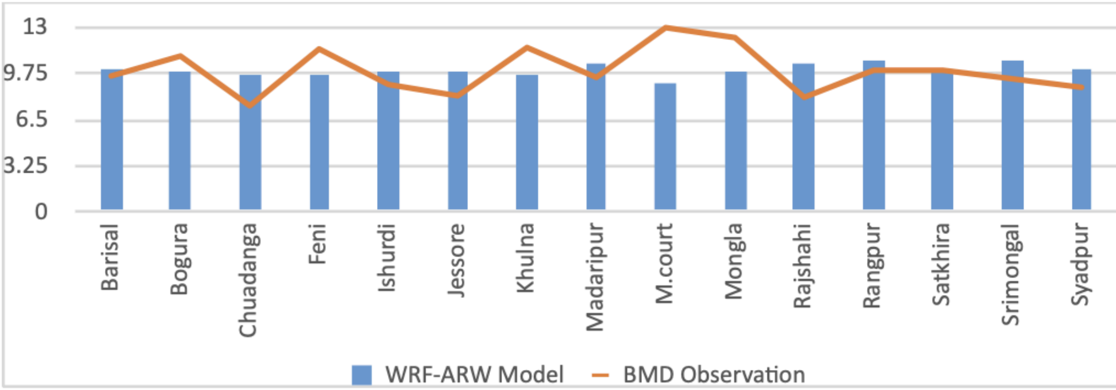


Figure 2.1: Comparison of Model-simulated Temperature (^{O}C) at 2m height and BMD observed data at 0000 UTC on 04 January 2019

Similarly, for the verification of the WRF-ARW model performance, a comparison has been made as a combined graph. WRF model-simulated values of 2m air temperature and observed has been used and are presented in Figure 2.2 for HW. The stations are chosen where the temperature (observed or WRF model or both observed and WRF model) is equal to or above 36 ^{O}C. The observations strongly revealed that the WRF model simulated values reasonably well.

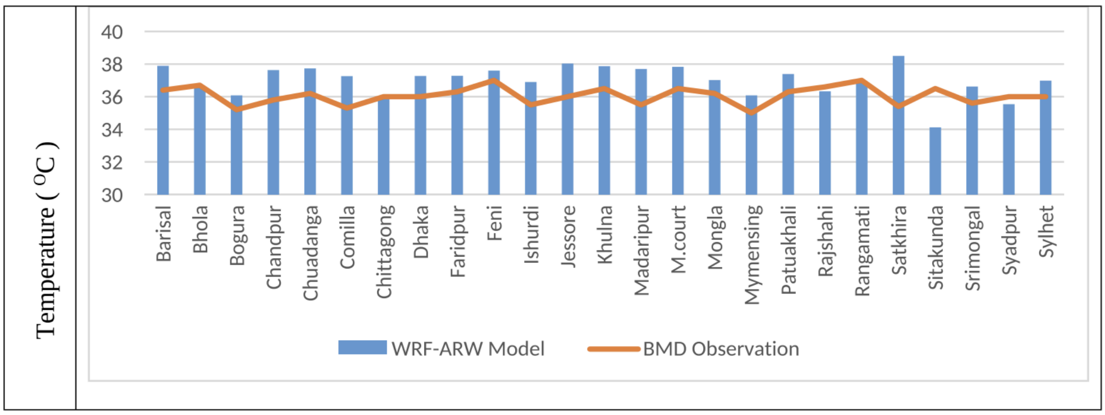


Figure 2.2: Comparison of Model-simulated 2m air Temperature with the Observation data at 0900 UTC on 24 April 2019

3.2. Identifying extreme temperature areas during winter and pre-monsoon using the WRF model.

To identify extreme temperature areas during winter and pre-monsoon, the WRF model output is compared spatially with the ECMWF global model's predicted ERA 6-hourly data. For this purpose, MSLP, the temperature at 2m height, and the wind pattern of the extreme event, both for CW and HW, are used. These parameters are related to the extreme hot and cold wave conditions.

Cold Wave Zone

The peculiar geographical location of Bangladesh, its landmass, makes it vulnerable. The landmass of Bangladesh does not produce ET. CW incurs from outside the country. Figure 3.1 shows the CW zone at 0000 UTC in winter. The WRF model simulation (Figure 3.1(a)) has shown that the cold weather comes through the foothills of the Himalaya and extends to Bangladesh, and CW also comes to the east/northeastern part of Bangladesh through Assam and Meghalaya (India). The ECMWF model's simulated data (Figure 3.1(b)) has shown a similar pattern.

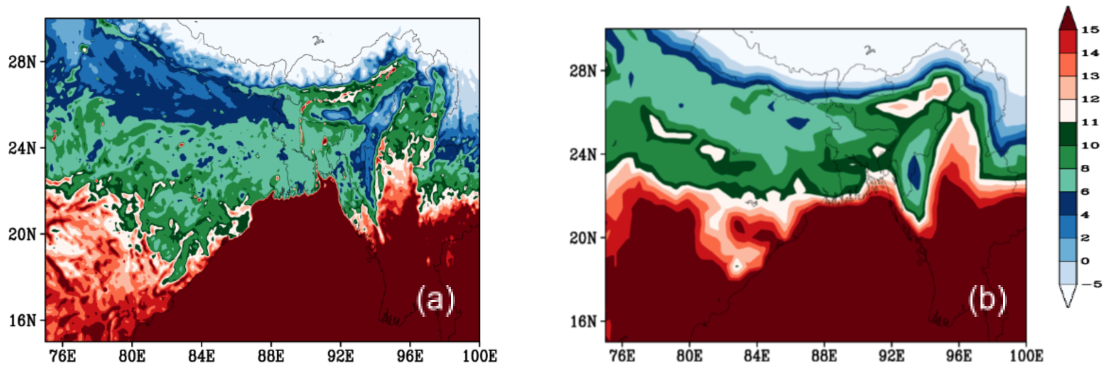


Figure 3.1: (a) WRF Model simulated temperature (° C) at 2m height and (b) ECMWF Model data at 0000 UTC on 08 January 2018.

Pressure Analysis for CW

Figure 3.2 shows the MSLP (hPa) at 0000 UTC in winter. The WRF model-simulated MSLP shows that the ridge of high pressure occurs in the 'Thar' desert (Rajasthan, India) and Muzaffarabad (Pakistan), and extends towards Bangladesh along the foothills of the Himalayas (Figure 3.2(a)). The ECMWF model predicted data indicated a similar result and pattern (Figure 3.2(b)).

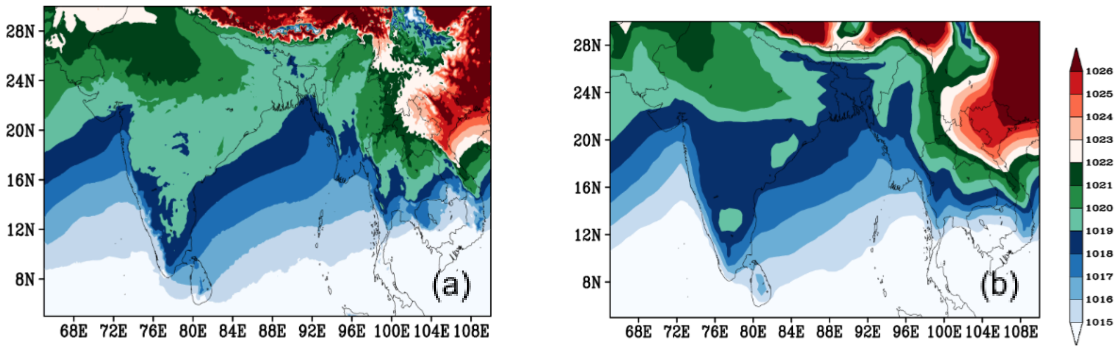


Figure 3.2: (a) WRF Model-simulated MSLP (hPa) and (b) ECMWF Model-simulated data at 0000 UTC of 03 January 2019.

Wind Pattern Analysis for CW

Figure 3.3(a-c) shows the Composite picture of 2m air temperature ^{O}C (shaded) and different-level wind direction (contour) at 0000 UTC on 03 January 2019, simulated by the WRF model at (a) 10m, (b) 850 level, and (c) ECMWF model predicted 10m height data. Figure (a) shows that the wind enters the northwestern part of the country from the foothills of the Himalaya. A small amount of wind comes from the northeasterly direction to the northern districts of Panchagarh, Dinajpur, and Rangpur. Figure (b) shows that the wind enters the entire western part of the country from the foothills of the Himalaya from a northwesterly direction. It also enters as the northeasterly monsoon wind. The ECMWF model predicted data indicated a similar pattern and direction as the WRF model.

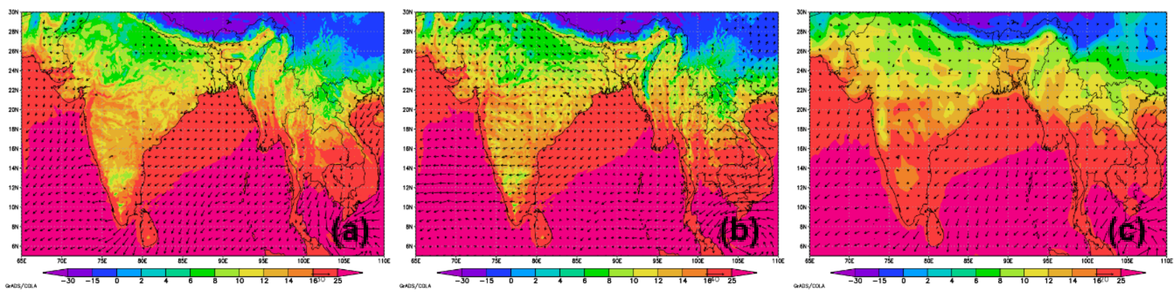


Figure 3.3: Composite picture of 2m air temperature °C (shaded) and different-level wind direction (contour) at 0000 UTC on 03 January 2019, simulated by the WRF model at (a) 10m and (b) 850 hPa level, and (c) ECMWF model predicted 10m height data.

Temperature Analysis for CW

Figure 3.4 shows the temperature analysis spatially at 0000 UTC in winter. The WRF model simulated temperature (Figure 3.4 (a)) shows that the cold weather (06-08)^{O} C produces in the foothills of the Himalaya and the northeastern side of Bangladesh and advects towards Bangladesh. Finally, the temperature $(08\text{-}10)^{O}$ C has reached the northwestern part of Bangladesh. The ECMWF model simulated data (Figure 3.4 (b)) has shown a similar pattern of producing cold weather and temperature advection range.

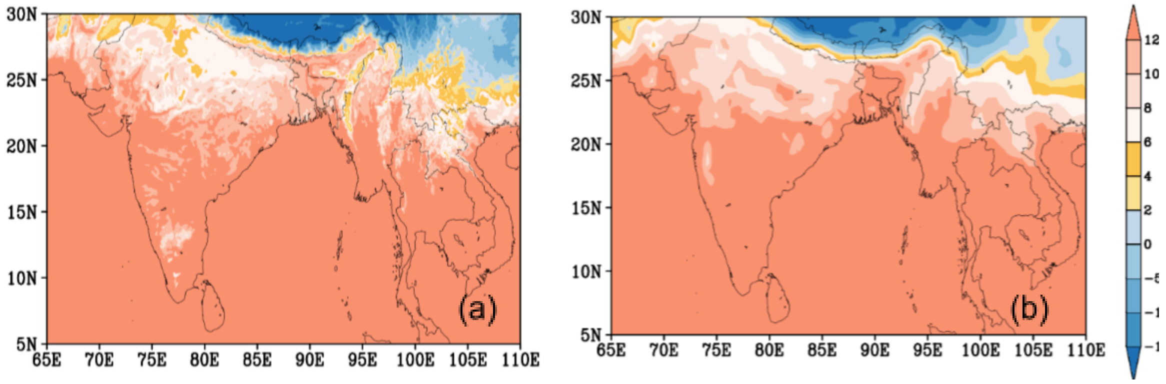


Figure 3.4: (a) WRF model-simulated 2 m air Temperature (° C) with (b) ECMWF model-predicted data at 0000 UTC on 03 January 2019.

Heat Wave Zone

The complex geographical location of Bangladesh has made it vulnerable. The landmass of Bangladesh does not produce ET. HW incurs from outside the country and sweeps over Bangladesh. Figure 4.1 shows the HW zone at 1200 UTC in the pre-monsoon. The WRF model simulation (Figure 4.1(a)) shows that warm weather comes to Bangladesh through the foothills of the Himalayas. The ECMWF model simulated data (Figure 4.1(b)) shows a similar pattern.

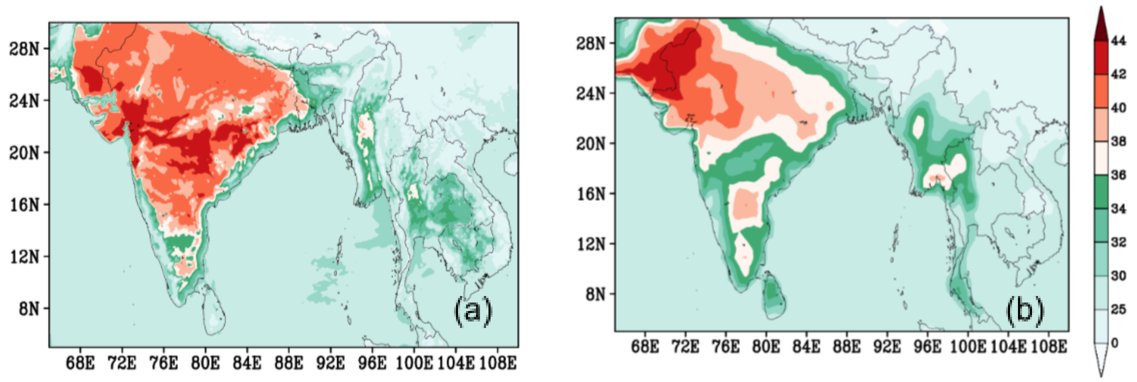


Figure 4.1: (a) WRF model-simulated 2 m air Temperature (° C) and (b) ECMWF model-predicted data at 1200 UTC on 27 April 2019.

Pressure Analysis for HW

Figure 4.2 shows the MSLP (hPa) at 0600 UTC in the pre-monsoon. The WRF model simulated MSLP shows that the trough of low pressure occurs in the 'Thar' desert (Rajasthan, India, and Sindh, Pakistan) and extends towards Bangladesh to the foothills of the Himalaya (Figure 4.2 (a)). The ECMWF model predicted data indicated a similar result and pattern (Figure 4.2(b)).

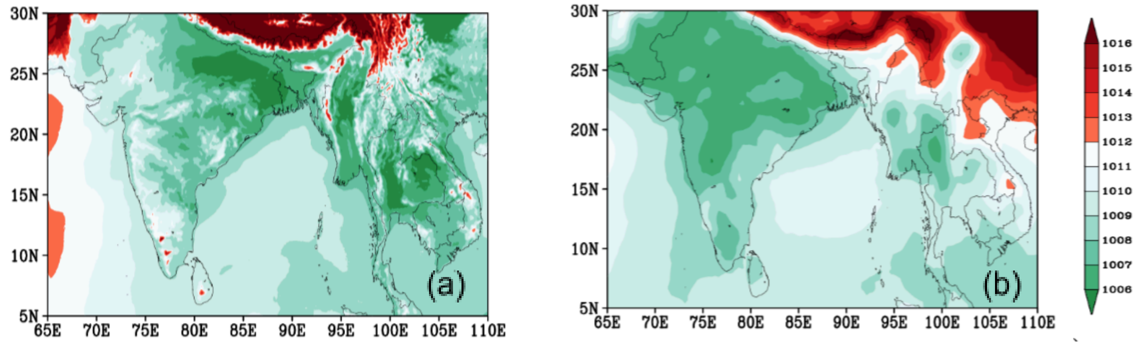


Figure 4.2: (a) WRF Model-simulated MSLP (hPa) with (b) ECMWF Model-simulated data at 0600 UTC on 26 April 2019.

Wind pattern for HW

Figure 4.3(a-c) shows the Composite picture of 2m air temperature °C and different-level wind direction at 0000 UTC on 03 January 2019, simulated by the WRF model at (a) 10m, (b) 850 hPa level, and (c) ECMWF model-predicted 10m height data. Figure (a) shows that the southwesterly wind enters the country from the Bay of Bengal (BOB). Figure (b) shows that at the 850 hPa level, the wind enters the entire western part of the country from the foothills of the Himalaya with a northwesterly direction. It also enters as a small southwesterly wind from the BOB. The ECMWF model simulated data (Figure 4.3(c)) indicated a similar pattern and direction as indicated by the WRF model.

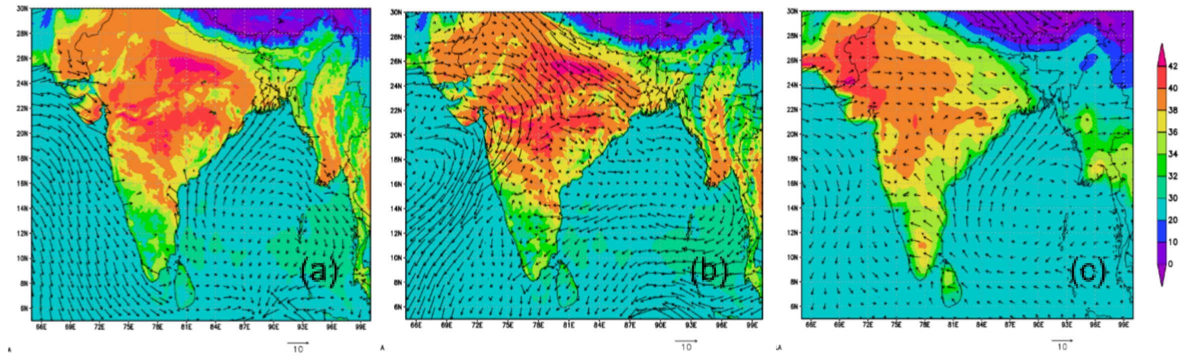


Figure 4.3: Composite picture of 2 m air temperature °C (shaded) and different-level wind direction (contour) at 0600 UTC on 26 April 2019, simulated by the WRF model at (a) 10m and (b) 850 hPa level, and (c) ECMWF model predicted 10 m height data.

Temperature Analysis for HW

Figure 4.4 shows the temperature analysis spatially at 0600 UTC in the pre-monsoon. The WRF model simulation (Figure 4.4 (a)) shows that warm weather (40-42) °C is produced over the entire India on the western side of Bangladesh and gradually decreases from west to east and advects towards Bangladesh. The ECMWF model simulated data (Figure 4.4 (b)) show that the maximum temperature (40-42) °C has been produced in the 'Thar' desert and gradually decreases to the east from the west, and finally, a temperature of 36 °C has reached the southwestern and middlewestern part of Bangladesh.

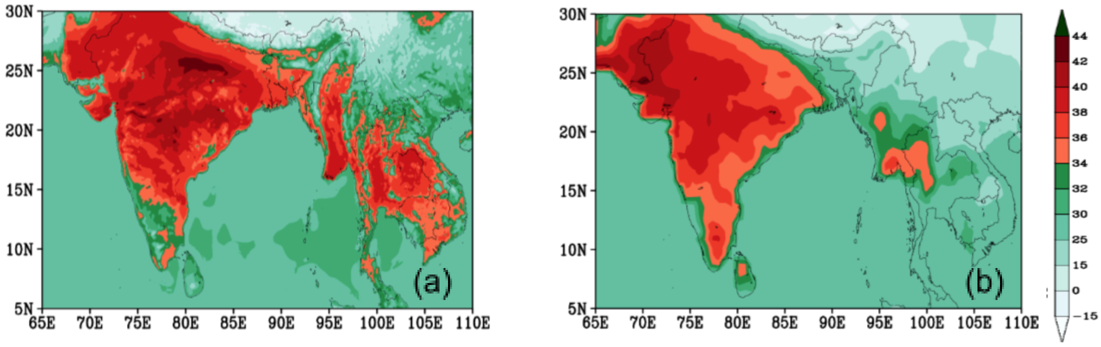


Figure 4.4: (a) WRF Model-simulated 2m air Temperature (° C) with (b) ECMWF Model predicted data at 0600 UTC on 26 April 2019.

The WRF-ARW model has been tested and verified, and found that the ARW has captured the meteorological parameters reasonably well, by which the extreme temperature events in Bangladesh can be predicted deterministically. The capability of the WRF model to predict extreme temperature areas during winter and pre-monsoon over Bangladesh is reasonably good.

3.3 Features of Extreme Temperature Conditions of Bangladesh

Bangladesh does not produce ET (both HW and CW) by itself. HW and CW sweep over Bangladesh from the west and northwest. Sometimes CW comes from the northeast in winter and HW from the southeast in pre-monsoon. The foothills of the Himalayas are warmer in pre-monsoon, and their temperature varies from 40 °C to 48 °C in parts of India; that means it is an overheated region. The sun rays drop on the 'Thar' Desert (Rajasthan, India, and Sindh, Pakistan) vertically; from the Arabian Sea, a high amount of moisture blows over this desert and occurs over the heat zone with the foothills of the Himalayas. In the foothills of the Himalayas, a trough of heat low extends to Bangladesh. There is a possibility to advect temperature towards Bangladesh. Besides, in the pre-monsoon, from the Bay of Bengal, south / Southwesterly winds carry a high amount of moisture over Bangladesh. The heat capacity of moisture is higher than that of dry air. Solar insolation, temperature advection, and moisture incursion: these three phenomena are mainly responsible for extreme heat conditions. Another factor is veering, which is associated with warm air advection and dynamic lifting. Veering is also responsible for producing severe heat waves.

In the winter season, the Sun shifts southwards, and the Indian sub-continent receives inclined solar insolation. The duration of the night is higher than that of the day. That is why the Indian sub-continent has become cooler than the southern part. The northeasterly monsoon is active. Wind enters the country from the foothills of the Himalayas. Lower solar insolation, less moisture, and a ridge of sub-continental high are mainly responsible for extreme cold conditions. Another factor is backing, which is associated with cold air advection and dynamic sinking. This backing is also responsible for producing severe and very severe cold waves.

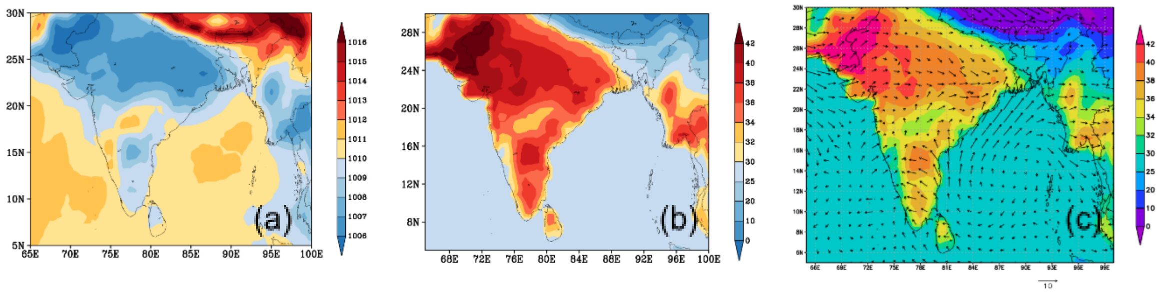


Figure 5.1: ECMWF model predicted (a) Trough of low, (b) Warm air advection, and (c) Wind pattern at 10m height at 0600 UTC on 27 April 2019.

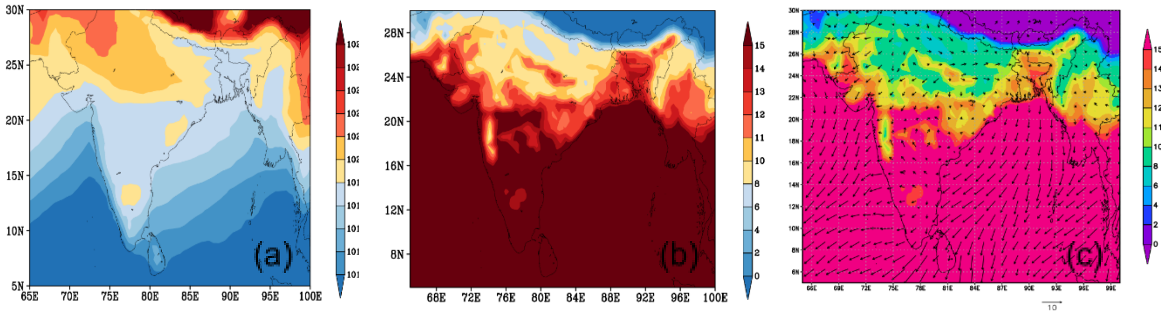


Figure 5.2: ECMWF model predicted (a) Ridge of high, (b) Cold air advection, and (c) Wind pattern at 0000 UTC of 03 January 2019.

Due to its geographical location, Bangladesh experiences HW in the pre-monsoon season and CW in winter. So, it is very important to predict these extreme temperature conditions, time, and location to minimize casualties due to these events.

Findings

The findings of the study indicate that-

i) The WRF model is highly capable of simulating extreme temperatures;

ii) The WRF model can accurately identify areas affected by extreme temperatures during the winter and pre-monsoon seasons; and

iii) An initial attempt to identify the causes of extreme temperature events in Bangladesh has been successful.

Discussions

The definition of heat waves and cold waves varies from place to place. Generally, a heat wave and a cold wave mean a certain period of abnormally high and low temperatures sweeps over a large area, and a heat and cold index. In our country context, BMD has defined that when the temperature exceeds 36 ^{O}C and plunges 10 ^{O}C at least 2 consecutive meteorological stations across the country, and continues for 2 or more days is considered a heat wave and a cold wave, respectively. There are many parameters responsible for producing HW and CW. Among them, solar insolation, temperature advection, and moisture incursion are high with height; the number of westerly disturbances is very low; there is no localized convective cloud formation; wind speed is very low; temperature is above normal by (6-8)°C; the difference of day and night temperature is reasonable; westerly/southwesterly wind is prominent; the trough of the westerly low is semi-prominent; the formation of heat traps/confined zones of heat traps in a certain region, plains, the number of low vegetation, poor water vessels, and the surface water level undergoing are the main phenomena that are responsible for extreme hot temperature conditions. Veering, which advects warm air (WAA) and dynamic lifting, is responsible for especially severe HW conditions. On the other hand, inclined solar insolation, temperature advection, the winter monsoon entering the country from the northeastern side, the duration of night is very high compared to daylight, and low moisture incursion are the main phenomena that are responsible for extreme cold temperature conditions. Backing, which advects cold air (CAA) and dynamic sinking, is also responsible for severe CW conditions. The polar ice of the northern and southern hemispheres is melting as a result of global warming. Global temperatures are steadily rising by around 1 °C every century. However, the temperature has been rising rapidly over the past few decades. According to meteorologists, this predicament is the result of man-made causes. Cars, factories, air conditioners, and refrigerators all emit CO, CO_2, CFC, and CFC_{11}, among other gases. However, urbanization, low vegetation, and a lack of water vessels are also contributing factors to global warming. This research was conducted with three objectives, which are (i) *assessing the robustness of the WRF model's capability to simulate extreme temperatures, (ii) identifying areas affected by extreme temperatures during winter and the pre-monsoon season using the WRF model, and (iii) an initial attempt to identify the causes of extreme temperature events in Bangladesh.* The study successfully achieved its intended outcomes, as evidenced by the findings presented in this research.

4. Conclusion

In this study, it has been established which areas are suitable for the ARW model to predict temperature in pre-monsoon and winter. In pre-monsoon, from the Arabian Sea, a high amount of moist air from the Arabian Sea blows over the 'Thar' desert (Sindh state of

Pakistan and Rajasthan of India). It helps to temper this region. In the trough of low pressure, this overheated air convects toward Bangladesh through the Himalayan foothills. On the other hand, from the Bay of Bengal, south/southwesterly winds carry a high amount of moisture over Bangladesh. The heat capacity of moisture is higher than that of dry air. The capacities of heat absorption and emission of 24 different categories of soil are different. As the land of Bangladesh is flat except for the eastern part, the solar insolation is very high. The vegetation and water bodies are gradually decreasing, but the emission of CO, CO_2, CFC, $CFC_{11,}$ and many more carbon related gasses emission is increasing day by day. In winter, the sun shifts southward, and the Indian sub-continent gets inclined solar insolation. This is why the Thar Desert and the foothills of the Himalayas make a cold wave zone. The cold weather is advected to Bangladesh from these areas. At the same time, the winter monsoon enters Bangladesh from the northeasterly part. Another thing is veering and backing, which are responsible for severe weather only. The study revealed that, based on RMSE of the temperature at 2m height, the south easterly coastal areas are the most biased area for the both CW and HW, after that the middle western part (Chuadanga, Ishardi, and Rajshahi) of Bangladesh for the CW and north western part (Syedpur, Dinajpur, Rangpur) of Bangladesh are the most biased area, after that the middle western part (Chuadanga, Ishardi) of Bangladesh for HW. The remaining parts of Bangladesh are suitable for predicting both HW and CW using the WRF-ARW model. The ARW model exhibited greater bias in predicting **extreme-temperature areas than non-extreme-temperature** areas, although its overall performance remained reasonably good.

References

1. Alam, M. M., Mahtab, A. S. M., Ahmed, M. R., and Hasam, Q. K. 2022. Developing a Cold-Related Mortality Database in Bangladesh. *Int. J. Environ. Res. Public Health* 2022, 19, 12175. https://doi.org/10.3390/ijerph191912175

2. Bhadram C. V. V., Amatya. B. V. S., Pant G. B. & Kumar K. K., 2005, “Heat waves over Andhra Pradesh: A case study of summer of 2003”. *Mausam*, 56, 2, pp. 385–394.

3. Black, E., Blackburn, M., Harrison, G., Hoskins, B., Methven, J., 2004. Factors contributing to the summer 2003 heat wave. *Weather* 59, 217–223. http://dx.doi.org/10.1256/wea.74.04.

4. Braga, ALF., Zanobetti, A., and Schwartz, J. - *Epidemiology*, 2001 - journals.lww.com

5. Bohnenstengel, S.I., Evans, S., Clark, P.A., Belcher, S.E., 2011. Simulations of the London urban heat island. *Q. J. R. Meteorol. Soc.* 137, 1625–1640.

6. Ciais, Ph., Reichstein, M., Viovy, N., Granier, A., Ogée, J. , Allard, V. , Aubinet, M., Buchmann, N., Bernhofer, Chr. Carrara, A., Chevallier, F., Noblet, N. De., Friend, A. D., Friedlingstein, P., Grünwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J. F.,

Sanz, M. J., Schulze, E. D., Vesala, T. and Valentini, R. 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* 437 (7058), 529–533. http://dx.doi.org/10.1038/nature 03972

7. Curriero, F. C., Heiner, K. S., Samet, J. M., Zeger, S. L., Strug, L., Patz, J. A., 2002. Temperature and mortality in 11 cities of the eastern United States. *Am. J. Epidemiol.* 155, 80–87.
8. Das, S., Smith, S.C., 2012. Awareness as an adaptation strategy for reducing Mortality from heat waves: Evidence from a Disaster risk management program in India. *Clim. Chang. Econ.* 03, 1250010. http://dx.doi.org/10.1142/S2010007812500108.
9. Dasari, H.P., Salgado, R., Perdigao, J., Challa, V.S., 2014. A regional climate simulation study using the WRF-ARW model over Europe and evaluation for extreme temperature weather events. *Int. J. Atmos. Sci.* 2014, 22, 704079.
10. De, U.S., Khole, M. and Dandekar, M., 2004. Natural hazards associated with meteorological extreme events. *Nat. Hazards* 31, 487–497.
11. De, U. S. and Mukhopadhyay, R. K., 1998, "Severe heat wave over Indian subcontinent in 1998 in a perspective of global climate". *Current Science*, 75, pp. 1308–1311.
12. Fink, A., Brucher, T., Kruger, A., Leckebusch, G., Pinto, J., Ulbrich, U., 2004. The European summer heat waves and drought – synoptic diagnosis and impacts. *Weather* 59, 209–216. http://dx.doi.org/10.1256/wea.73.04.
13. Gershunov, A., Cayan, D. R., Iacobellis, S. F., 2009. The great 2006 heat wave over California and Nevad Signal of an increasing trend. *J. Clim.* 22, 6181–6203. http://dx.doi.org/10.1175/2009JCLI2465.1
14. Giannaros, T.M., Melas, D., Daglis, I.A., Keramitsoglou, I., Kourtidis, K., 2013. Numerical study of the urban heat island over Athens (Greece) with the WRF model. *Atmos. Environ.* 73, 103–111.
15. Giovannini, L., Zardi, D., de Franceschi, M., Chen, F., 2013. Numerical simulations of boundary-layer processes and urban-induced alterations in an Alpine valley. *Int. J. Climatol.* 34, 1111–1131. http://dx.doi.org/10.1002/joc.3750.
16. Huynen, M.M., Martens, P., Schram, D., Weijenberg, M.P., Kunst, A.E., 2001. The impact of heat waves and cold spells on mortality rates in the Dutch population. *Environ. Health Perspect.* 109, 463–470.
17. IPCC, 2014. Summary for policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., BilirTE, Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), *Climate Change 2014, Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. IPCC, Cambridge, UK and New-York, NY, pp. 1–32.
18. Jenamani R. K., 2012, "Analysis of Ocean-Atmospheric features associated with extreme temperature variations over the east coast of India- A special emphasis to Orissa heat waves of 1998 and 2005". *Mausam*, 63, pp. 401–422.
19. Karmakar, S., 2018. Climate change patterns, future trends, and impacts in northwest Bangladesh." Abstract Book of Conference on Weather Forecasting & Advances in Physics, 11-12 May 2018, Department of Physics, Khulna University of Engineering and Technology (KUET), Bangladesh.
20. McGeehin, M.A., Mirabelli, M., 2001. The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environ. Health Perspect.* 109 (Suppl. 2), 185–189.
21. Mercer, J.B., 2003. Cold—an underrated risk factor for health. *Environ. Res.* 92, 8–13.
22. Mishra, V., Ganguly, A. R., Nijssen, B., and Lettenmaier, D. P., 2015, "Changes in observed climate extremes in global urban areas". *Environ. Res. Lett.*, 10, 2, pp.1-10, 024005; 10.1088/1748-9326/10/2/024005.
23. Murari, K.K., Ghosh, S., Patwardhan, A., Daly, E., Salvi, K., 2015. Intensification of future severe heat waves in India and their effect on heat stress and mortality. *Reg. Environ. Chang.* 15, (4), 569–579.
24. NIUA, 2016, "Heat Waves", India-Urban Climate Change Fact Sheets, prepared by National Institute of Urban Affairs (NIUA), pp. 1-4.

25. Panda, D. K., A. AghaKouchak, and S. K. Ambast, 2017. Increasing heat waves and warm spells in India, observed from a multiaspect framework. *J. Geophys. Res. Atmos.* 122, 3837 – 3858. doi:10.1002/2016JD026292

26. Peng, S., J. Huang, J. E. Sheehy, R. C. Laza, R. M. Visperas, X. Zhong, G. S. Centeno, G. S. Khush, and K. G. Cassman, 2004. Rice yields decline with higher night temperatures from global warming. *Proc. Natl. Acad. Sci. U.S.A.* 101, 9971–9975.

27. Rashid, G. M., Hossain, M. M. T., Akhter, M. A. E., and Mallik, M. A. K. 2022. Sensitivity of Radiation Schemes in the WRF-ARW Model to Predict Extreme Temperature Due to Heat Wave over Bangladesh. *IOSR Journal of Applied Physics*. E-ISSN: 2278-4861. Volume 14, Issue5, pp 21 – 33. DOI: 10.9790/4861-1405022133

28. Rashid, G. M., Akhter, M. A. E., and Mallik, M. A. K. 2022. The study of recent cold conditions in Bangladesh during 1990 to 2019. *Quest Journal of Research in Applied Mathematics*. Vol. 8 ~ Issue 11, PP: 31-37. ISSN (Online): 2394-0743 ISSN (Print): 2394-0735 www.questjournals.org

29. Rashid, G. M., Hossain, M. M. T., Akhter, M. A. E., and Mallik, M. A. K. 2022. Impact of Different Radiation Schemes on the Prediction of Extreme Cold Weather Events over Bangladesh. *American Journal of Marine Science*. Vol. 10, No. 1, 10-20. DOI: 10.12691/marine-10-1-2

30. Rashid, G. M., Hossain, M. M. T., Akhter, M. A. E., and Mallik, M. A. K. 2023. A STUDY ON THE HEAT WAVE CONDITIONS OVER BANGLADESH DURING 1990 – 2019. *Journal of Engineering Science*. 14(2), 2023, 59-67. DOI: https://10.3329/jes.v14i2.71227

31. Rashid, G. M., Hossain, M. M. T., and Akhter, M. A. E. 2025. Feasibility of Radiation Schemes to Predict Extreme Temperature Conditions over Bangladesh. *European Journal of Science, Innovation and Technology*. ISSN: 2786-4936, Vol. 5, No. 1, 18-44. www.ejsit-journal.com

32. Russo, S. and Sterl, A., 2011. Global changes in indices describing moderate temperature extremes from the daily output of a climate model. *J. Geophys. Res.*116. doi:10.1029 /2010JD014727

33. Salamanca, F., Martilli, A., et al., 2012. A numerical study of the Urban Heat Island over Madrid during the DESIREX 2008 campaign with WRF and an evaluation of simple mitigation strategies. *Int. J. Climatol.* 32, 2372–2386.

34. Schar, C., Vidale, P.L., Luthi, D., Frei, C., Haberli, C., Liniger, M.A., Appenzeller, C., 2004. The role of increasing temperature variability in European summer heat waves. *Nature* 427, 332–336. http://dx.doi.org/10.1038/nature02300.

35. Seneviratne, S. I., M. G. Donat, B. Mueller, and L. V. Alexander, 2014. No pause in the increase of hot temperature extremes. *Nat. Clim. Change* 4, 161–163. doi:10.1038/nclimate2145

36. Thornbrugh, C., Ghertner, A., McNeeley, S., Wilhelmi, O., Harriss, R., 2007. *Heat Wave Awareness Project*. National Center for Atmospheric Research.
