# Exploring the Use of WRF-ARW Model for Analyzing Heatwaves in Bangladesh

**Md. Momin Islam, Pappu Paul, Saurav Dey Shuvo, Fatima Akter* and Sadiq Mubassir Khan**

Department of Meteorology, University of Dhaka, Dhaka 1000, Bangladesh

*Manuscript received: 20 February 2023; accepted for publication: 27 September 2023*

**ABSTRACT:** This study attempts to simulate heatwave events over Bangladesh using the WRF-ARW Model that could be used to implement a best practice strategy for predicting heatwaves in Bangladesh. In this research, 17 heatwave events were identified from the period between 2007 and 2022. The thresholds for heatwave events were considered when the maximum temperature from a weather station was above the 95$^{th}$ percentile for three consecutive days. After carefully identifying the events, all the events were simulated with the WRF-ARW model. Simulated temperature, relative humidity, and wind vector (direction and speed) were analyzed for this research. The synoptic conditions were synthesized for all the heatwave events. It was found that the propagation of warm temperatures corresponded to the movement of wind and was aptly supported by the presence of humidity in the region of interest. This information could be used at the operational level for predicting heatwaves.

**Keywords:** Heatwave; WRF-ARW; HEWS; NCEP FNL

## INTRODUCTION

Heatwave is a period of abnormally high temperatures that may also include high humidity. It is then measured concerning local weather norms and seasonal average temperatures (Robinson, 2001). Heatwaves, which are regular temperatures to individuals in hotter places, are referred to as such by people in cooler regions. (Meehl and Tebaldi, 2004). The World Meteorological Organization is particular in its definition by describing that a heatwave is when the daily maximum temperature for more than five consecutive days exceeds the average maximum temperature by 9 degrees (Frich, 2002). The mechanism of heatwaves is well explained by Smith et al (2014). When a system of high pressure arrives in a region and stays there for two days or longer, it draws the air in the atmosphere's upper layers toward the ground within a high-pressure system. There the air is compressed and heated upwards. This causes the upper atmosphere to be in under high pressure, and therefore heat is trapped at the ground level. This situation then increases the temperature.

Globally heatwave becomes a major weather event since the average temperature of the earth is rising. It is identified as one of the most well-known extreme weather events due to its enormous effects on people's health, society, and the environment (Gao et al., 2018).

*Corresponding Author: Fatima Akter
Email: fatima.geoenv@du.ac.bd
DOI: https://doi.org/10.3329/dujees.v12i1.70461

Bangladesh has an extremely warm summer because it is located in the subtropical part of the planet (Rasheed, 2008; Shuvo, 2021; Shuvo and Sultana, 2022). Sometimes during summer, multiple spells of heatwaves have crossed over the country. The effect of these heatwaves has been amplified increased global warming in recent years, especially during the pre-monsoon months of March to May (Rahman, 2008). Throughout this season, there are countless instances of heatwaves across the nation (Rajib et al., 2011; Shahid, 2010). One of the biggest obstacles to their predictions and analysis is the definition of heat waves. Normally, definitions of heat waves depend on the place and the period. (You et al. 2017; Perkins et al 2015; Robinson 2001). Heatwave is just one of the severe threats that climate change poses to Bangladesh (Huq, 2001). Four of the ten deadliest natural disasters are the result of a heatwave that gradually changes the climate. In Bangladesh, a few studies have been made by some authors (Karmakar, 2019; Nissan et al., 2017; Hashizume et al., 2008) but several studies have been made for India (Ratnam et al., 2016; Pai et al., 2013; Mishra et al., 2015; Panda et al., 2017; De and Mukhopadhyay, 1998; Murari et al., 2015; Ghatak et al., 2017). There are heatwaves almost everywhere in the world. However, there isn't a universally accepted criterion or threshold for what constitutes a heatwave to be considered. Different nations and organizations have different definitions of a heatwave, but there is a unanimous agreement that it is characterized by overshooting the temperature above the normal range.

As stated by Bangladesh Meteorological Department (BMD), many northern towns showed day temperatures reaching over 40 °C (104 °F), which is unusual during the summer in Bangladesh. In addition, the humidity was high. The frequency of heat waves has dramatically increased in recent decades (Nissan et al., 2017). As a result, a sizable number of individuals are both harmed and killed by heatwave events. Heat waves are normally observed during pre-monsoon and can extend up to the month of June in Bangladesh. May and June are the months with the most heatwaves.

Numerical weather prediction (NWP) models can be a useful tool in creating short-term heatwave forecasting systems that can be used operationally while taking into consideration the human bio-meteorological aspects to support the public health protection services under these future climatic circumstances (Giannaros et al., 2018).

Based on the measurement of temperature, the Bangladesh Meteorological Department (BMD) divides heatwaves into four categories. As per BMD, heatwaves are defined as those days whose temperature is more than 36º C (96.8º F) and sustained at least three days consecutively.

Another definition of a heatwave for Bangladesh is given by Nissan et al. (2017) that states -

(i) $T_{max}$>95$^{th}$ percentile.

(ii) Tmin>95$^{th}$ percentile.

(iii) Sustained consecutive 3 days at least.

In the past few decades, the temperature in Bangladesh has increased owing to the changing climate condition (Shahid et al., 2016). In recent years, people have also been experiencing greater temperatures than the normal mean temperature (Kibria et al., 2022). Heat-related illnesses have also increased significantly in all age groups of people in the country (Haque et al., 2013). It is difficult to determine the precise number of individuals who will be affected by the heatwave in Bangladesh due to a lack of health statistics. An early warning system for heatwave prediction is very essential to protect the life and livelihood of the people of this country. There are examples of previous works done on this purpose. But, all of them lack the clarity behind analyzing the events from a meteorological perspective. Jaman et al. (2022) tried to establish a method for predicting heatwaves based on the performances of different physics schemes. However, the analyses in that work are too naïve and do not really dwell on why a particular scheme is better that the others. Above that, the cases studied in the research are too few for getting a solid conclusion. Nevertheless, the research is still an optimistic try to get a best-practice manual on forecasting heatwaves in Bangladesh. Another noteworthy research on heatwaves in Bangladesh has been done by Chaki et al. (2022a). But that research is just an attempt in simulating heatwaves through WRF model. So, this research too is devoid of any structural analyses of the events. Chaki et al. .(2022b) tried to establish a forecasting manual for heatwaves in Bangladesh with some meager analysis. Hence, this research is being conceived to develop an idea about analyzing the heatwaves in Bangladesh using the WRF-ARW model. This research attempts to analyze the heatwave events from their synoptic features. The researchers feel that this is mandatory before establishing any forecasting manual. Unfortunately, no previous works deal with this common issue. Synoptic conditions were analyzed with the simulated results from WRF-ARW model. The reason behind using simulated results, but not observational data, for analyzing the heatwave events is twofold. Firstly, we don't have enough stations inside Bangladesh with great areal coverage. And secondly, not all the data are available for every synoptic hour. Again, synoptic data is available for every three hours. So, it creates a situation where the available data are to be interpolated spatially and temporarily. Both can have erroneous implications and therefore were not considered by the researchers for this research. The other option could have been using the readily available gridded dataset, for example – ERA data, NOAA data, GPCP data, GPCC data, etc. But these datasets were basically global datasets. That means they have less local information. Only the GFS and FNL datasets carry some local information which were used in this research. The analyses from this research will hopefully help the operational meteorological officers to get a general idea about which parameters to look into for predicting the heatwaves in Bangladesh.

## DATA AND METHODOLOGY

### Numerical Weather Prediction

Numerical Weather Prediction (NWP) is being used to study and also predict a wide range of weather occurrences by simulating the movement of air in space, time, and the oceans using computer algorithms (Lorenc, 1986). The model assumes that the atmosphere is made up of many grids, with corner points serving as the grid points. A more thorough simulation is indicated by a greater number of grids. Through simulation, the model creates the model atmosphere's future state from its initial state at all grid points.

There are several NWP mesoscale models, including MM5, WRF, and FSU. The meteorological processes that commonly occur between 10 km and 1000 km are examined in - Mesoscale Meteorology (Emanuel, 1986). One of the most extreme weather conditions that directly affect human lives is a heatwave (Gasparrini and Armstrong, 1986). There is still much to learn about the mechanics of heat waves. In this research, the WRF-ARW model is used for simulating a few heatwaves in Bangladesh. More details about WRF-ARW model can be found in the works of Dasari et al (2014).

## Identification of Heat Wave Events

Heatwave event is identified by using an extreme temperature criterion based on IPCC's definition of extreme temperature index TX95p (Karl et al.,1999). According to the index - TX95p, a heatwave day is determined when the daily maximum temperature exceeds the 95$^{th}$ percentile of a late twenty century reference period (1961-1990). Then heatwave events were identified when temperature persisted over the 95$^{th}$ percentile for three consecutive days. Using these criteria, 17 heatwave events are identified at 3 stations in Bangladesh during the period (2000-2020). The year of 2016 was the warmest year in Bangladesh according to this extreme temperature index. This index is calculated through the statistical software – R, and by using the package - RclimDex (Karl et al., 1999). RclimDex is a package which is designed by Expert Team on Climate Change Detection and Indices (ETCCDI). Then these events were identified:

**Table 1:** List of Selected Events based on Heatwave Thresholds from TX95p

| Event | District | Longitude | Latitude | Start Date | End Date |
|---|---|---|---|---|---|
| Event 1 | Dhaka | 90.38 | 23.77 | 01/04/2012 | 03/04/2012 |
| Event 2 | Dhaka | 90.38 | 23.77 | 16/06/2013 | 18/06/2013 |
| Event 3 | Dhaka | 90.38 | 23.77 | 29/04/2014 | 01/05/2014 |
| Event 4 | Dhaka | 90.38 | 23.77 | 19/05/2019 | 21/05/2019 |
| Event 5 | Dhaka | 90.38 | 23.77 | 09/04/2020 | 11/04/2020 |
| Event 6 | Chattogram | 91.80 | 22.22 | 16/05/2010 | 18/05/2010 |
| Event 7 | Chattogram | 91.80 | 22.22 | 11/10/2011 | 13/10/2011 |
| Event 8 | Chattogram | 91.80 | 22.22 | 10/06/2014 | 12/06/2014 |
| Event 9 | Chattogram | 91.80 | 22.22 | 28/09/2014 | 30/09/2014 |
| Event 10 | Chattogram | 91.80 | 22.22 | 03/06/2015 | 05/06/2015 |
| Event 11 | Chattogram | 91.80 | 22.22 | 13/03/2020 | 15/03/2020 |
| Event 12 | Rangpur | 89.27 | 25.73 | 01/10/2016 | 03/10/2016 |
| Event 13 | Rangpur | 89.27 | 25.73 | 17/08/2018 | 19/08/2018 |
| Event 14 | Rangpur | 89.27 | 25.73 | 19/07/2019 | 21/07/2019 |
| Event 15 | Rangpur | 89.27 | 25.73 | 05/08/2019 | 07/08/2019 |
| Event 16 | Rangpur | 89.27 | 25.73 | 07/06/2020 | 09/06/2020 |
| Event 17 | Rangpur | 89.27 | 25.73 | 02/08/2020 | 04/08/2020 |

Out of these 17 events, 5 are based on the data from Dhaka station; 6 events are for Chattogram, and a further 6 are for Rangpur station. All of these events are being simulated with the WRF-ARW model in this research for analysis. The location of the three stations in concern is shown in the country map (Fig. 1).

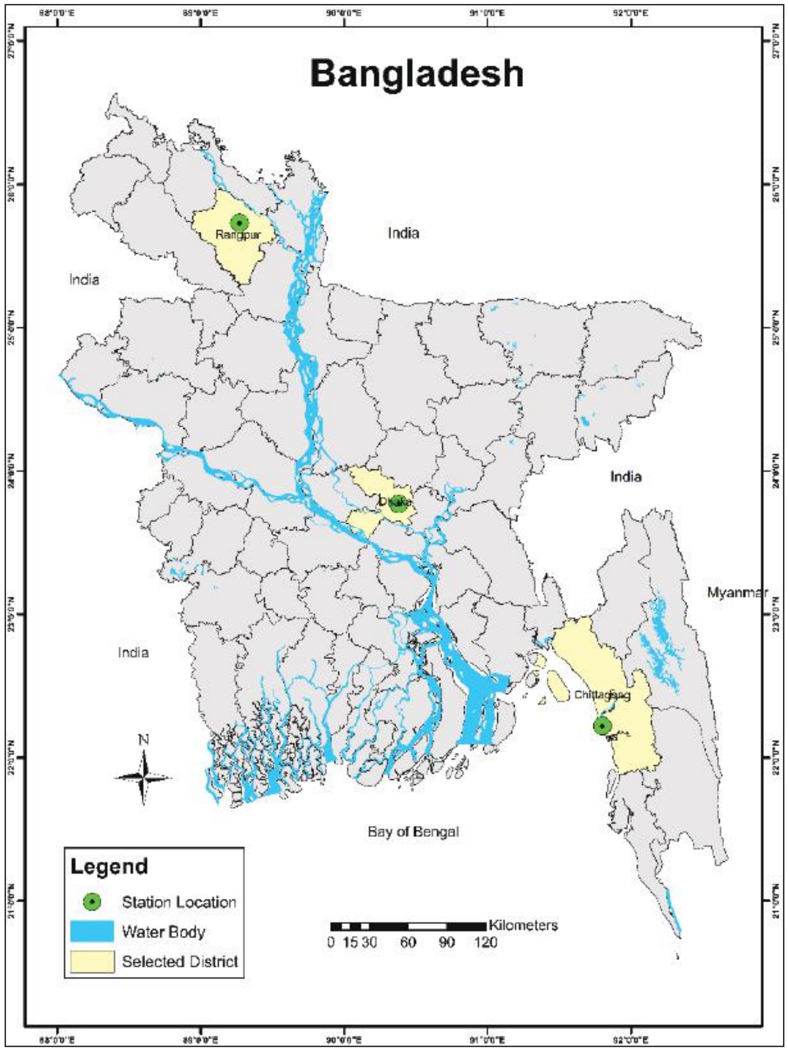


**Figure 1:** Map Showing the Locations of Weather Stations in Dhaka, Chattogram, and Rangpur Districts in Bangladesh

## Data Used in this Research

This study has been conducted in two steps. The first step involves analyzing observed data to identify the heatwave events. The second method involves using the WRF model to study the weather systems related to the extreme dates of heatwave days and then validating the model's results.

Data of maximum temperature, relative humidity, wind speed, and wind direction are gathered for 3 stations from the Bangladesh Meteorological Department (BMD) for the years 2000 to 2020. Heatwave episodes across Bangladesh are tracked using this data. The selected 3 stations, broadly covering all of Bangladesh, were chosen after studying the locations with the maximum likelihood of heatwaves in Bangladesh (Rahman, 2008; Nissan et al., 2017; Nissan et al., 2020; Raja et al., 2021). The selected stations are – Dhaka, Ambagan (Chattogram), and Rangpur.

The reason behind selection of these events has been further analyzed with anomaly for temperature, relative humidity, and wind. Temperature anomaly for the three locations were analyzed with information available from NOAA (https://psl.noaa.gov/data/). It has been found that temperature increased in all the three locations. For better contrast, the climatological period has been selected up to 2009 (from 1948). The comparison has found that the temperature increased the most during 2014 – 17 (Fig. 2b). Consequently, the temperature increased the least during 2018 – 21 (Fig. 2c). Another important finding is that the trend of temperature rise is mostly prominent in Dhaka and Rangpur. While Chattogram has experienced some rise in temperature, but the values are quite low when compared to Dhaka and Rangpur. Anomaly calculations for other variables were excluded from the analysis since they did not provide any significant ideas.

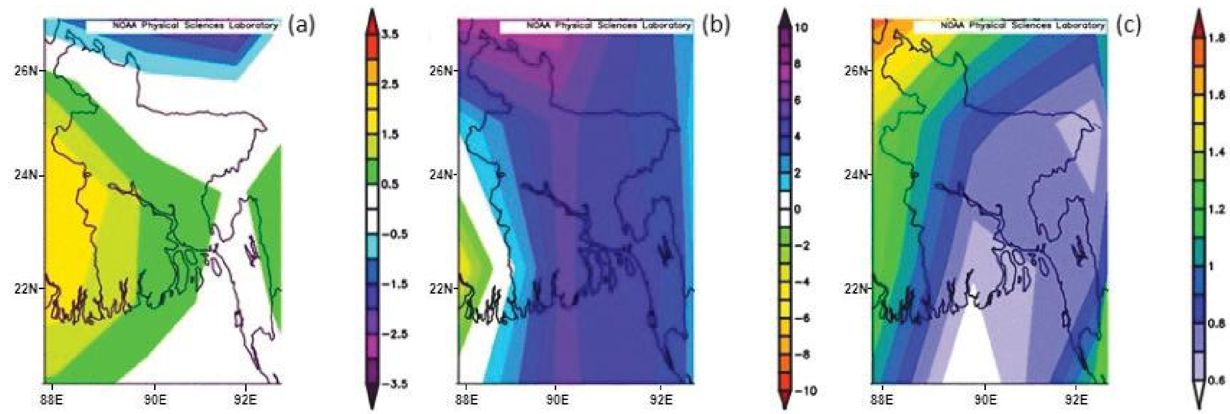


**Figure 2:** Temperature Anomaly in Bangladesh. The Climatological Mean has been Calculated for Data from 1948 to 2009. The Anomaly Calculated has been Done for Data During (a) 2010 – 2013, (b) 2014 – 2017, and (c) 2018 – 2021

The other notable feature is the directional trend of this temperature anomaly. During 2010 –2013 Fig. 2 (a), the temperature has more increased in the western portions of the country. Other regions had a more stable situation. However, anomaly could be seen more from the northern regions of Bangladesh during 2014 – 2017 Fig. 2 (b). But, almost the whole country experienced a rise in temperature during this time. The increase in temperature had a more easterly progression during 2018 – 2021 Fig. 2 (c). Again, the whole country saw a rise in temperature. So, it can be inferred that the whole country saw a rise in temperature from 2014. The majority of the heatwave events in this research are also selected from that period.

The FNL dataset (1-degree by 1-degree horizontal resolution) from NCEP has been used in simulating the events with the WRF-ARW model. There are other options for simulating weather events with WRF-ARW model. But, the choice of NCEP/NCAR FNL dataset has been made after careful consideration. The FNL dataset has been extensively used in predicting extreme weather events (Rabbani and Shuvo, 2021; Ferdaus et al., 2021; Islam et al., 2021; Sarker et al., 2021; Shuvo and Awal, 2021; Shuvo et al., 2021) around the world with much success. Therefore, the researchers have decided to use the NCEP/NCAR FNL data for simulating heatwave events.

## Experimental Setup of WRF-ARW

For this study, three regions are chosen at random. The Advanced Weather Research and Forecasting (WRF-ARW; Version 4.0) model was employed for this research. In this research, the parameterization schemes have been used following the recommendations by Jaman et al. (2022). All details about the experimental setup for this research are presented in Table 2.

**Table 2:** Overview of WRF-ARW Model Setup for this Research

| | |
|---|---|
| No. of domain | 1 (Single) |
| Domain resolution | 12 km |
| Horizontal grid system | Arakawa C-grid |
| Time integration Scheme | $3^{rd}$ order Runge-Kutta scheme |
| Cumulus physics | Kain Fritsch |
| Microphysics | WRF Single–moment 6–class Scheme |
| Planetary Boundary scheme (PBL) scheme | Yonsei University Scheme (YSU) |
| Surface Layer | MM5 Similarity Scheme |
| Land surface parameterization | Unified Noah Land SurfaceModel |
| Radiation | Dudhia Shortwave Scheme (short-wave)<br>RRTM Longwave Scheme (long-wave) |
| Simulation period | 07 (seven) days for each case<br>2020-08-02, 2020-06-07, 2020-04-09, 2020-03-13, 2019-08-05, 2019-07-19, 2019-05-19, 2018-08-17, 2016-10-01, 2015-06-03, 2014-09-28, 2014-06-10, 2014-04-29, 2013-06-16, 2012-04-1, 2011-10-11, 2010-05-16 |

## Methodology for Observed Data Analysis

Observed data from BMD are used for the determination of the heatwave events and heatwave days. The dates of the heatwaves days over Bangladesh are determined for the individual years from 2000 to 2020 using the data of maximum temperature, humidity, and wind speed & wind direction. The 95th percentile of temperature for consecutive three days per heatwave event is considered. The NCEP/NCAR reanalysis data is also used to verify the heatwave events over Bangladesh.

### Methodology for Model Data Analysis

After the simulation, post-processing is done for visualization and to get the results of the study. Then all the selected events have been simulated for further analysis and compared to the observed data.

For the comparison, several variables have been analyzed Humidity, Temperature, etc. for heatwaves on a specific point (specific latitude and longitude) is selected. For the model output analysis variables that were analyzed are Temperature, Wind speed and direction, humidity, etc. The heat index is also calculated (Anderson et al., 2013) and then compared to the model simulated results with the observations statistically.

## ANALYSIS OF RESULTS

From the five selected events based on the data from the Dhaka weather station, 4 events have identified temperatures above 35°C except for event 2 (Fig. 4). Composite analysis for temperature, wind speed, and relative humidity reveals further about these events in Dhaka. From the analysis, it is identified that temperature was increasing during this time inside the study area. Event 1 (Fig. 3) has a moderate level of temperature that keeps rising over the following 3 days. The same rising pattern is followed by the other four events.

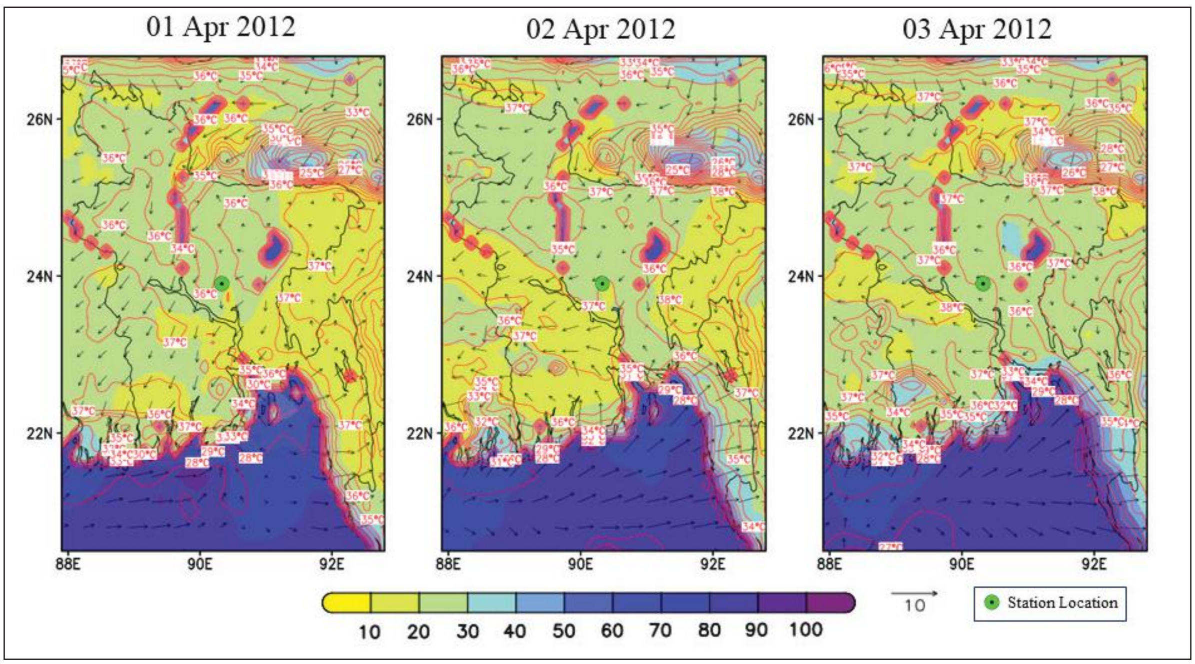


**Figure 3:** Composite Analysis for the 1st Heatwave Event in Dhaka. The Figure Shows Lines of Isotherm, Wind Direction and Speed with Arrows, and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

Event 2 (Fig. 4) has identified a more tolerable temperature across the study area. Events 3 and 4 in (Fig. 5 and Fig. 6) has identified temperature well above 40°C on the west side of Bangladesh with the study area temperature being more than 35°C. Event 5 (Fig. 7) is the highest in terms of temperature with values showing well above 37°C. In all of the events, a common pattern can be identified. The warm temperature was intruding into Bangladesh from the west. And then it was slowly covering the whole country. Another important feature to note here is the temperature distribution on the eastern side of Bangladesh. The eastern portions beside Bangladesh (in Myanmar) had already a high-temperature distribution. But interestingly, this temperature does not seemingly intrude inside the country. Rather the temperature intrusion from the west side of the country merges with the high temperature of the east. Oddly enough, this trend of temperature is only found for the heatwave events of Dhaka. Alongside that, a shift in temperature in the Bay of Bengal could also be observed from the simulations.

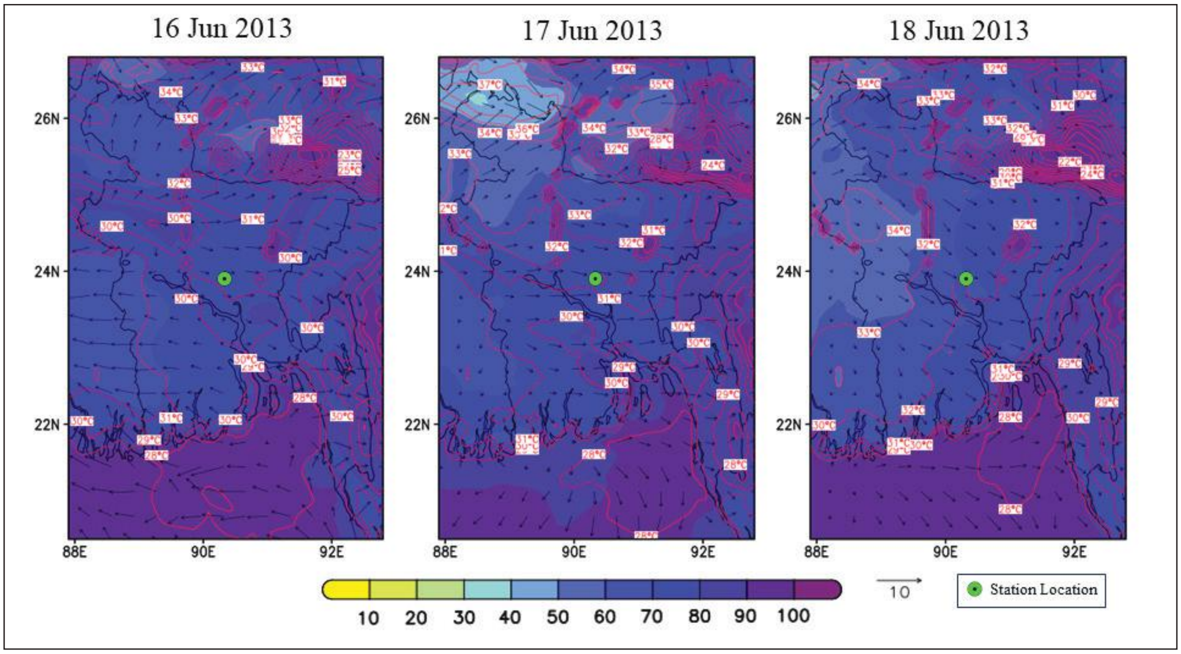


**Figure 4:** Composite Analysis for the 2nd Heatwave Event in Dhaka. The Figure Shows Lines of Isotherm, Wind Direction and Speed with Arrows, and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

The first event (Fig. 3) showed a situation where the humidity is below 50% over most parts of Bangladesh. This low relative humidity situation, along with the increase in temperature, might have resulted in extreme heatwaves. The second event (Fig. 4) was an unusual one, where the humidity stayed more than 80% over the whole country. This scenario somewhat persisted for the fourth event too (Fig. 6). The relative humidity was staying around 60% to 80% inside Bangladesh.

The remaining two events (Fig. 5 and Fig. 7) were almost similar in their characteristics. The humidity stayed between 50% to 70% within Bangladesh. Also, the distribution of humidity and its gradual progression were similar. From these simulations, it is also found that the relative humidity of Dhaka stayed mostly between 60% to 80% during the heatwave events. One exception was the first event (Fig. 3), when the relative humidity was well below 50%.

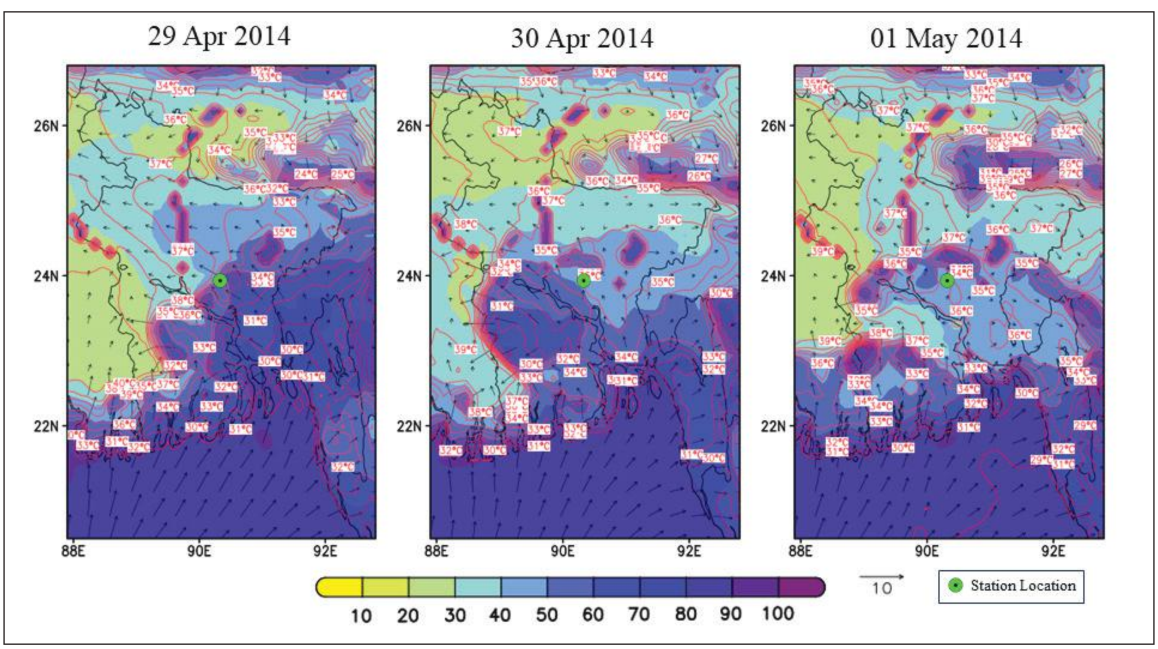


**Figure 5:** Composite Analysis for the 3rd Heatwave Event in Dhaka. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

Wind vector (wind speed and wind direction) was also analyzed in this research. Simulated surface-level wind, along with temperature and relative humidity, depicted some very important findings about heatwave events. All 17 events from Dhaka, Chattogram, and Rangpur have been simulated for analysis. In the first event (Fig. 3), southerly winds from the Bay of Bengal flew towards the north and then bifurcated into two particular streamlines – flowing towards the west and east.

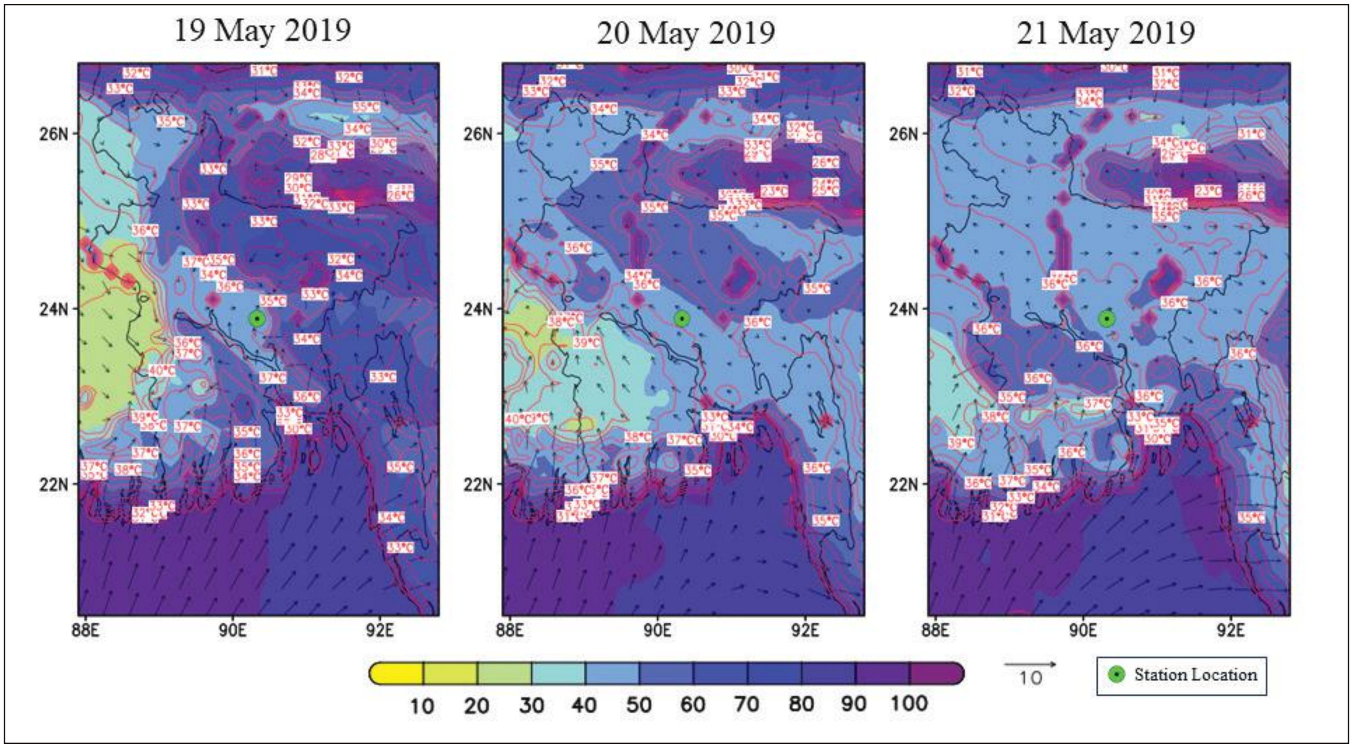


**Figure 6:** Composite Analysis for the 4th Heatwave Event in Dhaka. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

This condition was also evident for the third event (Fig. 5), fourth event (Fig. 6), and fifth event (Fig. 7). But the wind velocity was higher for the fourth and fifth events than for the third event. During the second event (Fig. 4), the southerly flow created a strong circulation that propagated from west to east, becoming stronger with each passing day. In all the events, there was a presence of westerly wind (seemingly with southerly for all but four events), that perhaps aided in the transgression of temperature into Bangladesh. The passing of humid air along with the wind also made the situation favorable for heatwaves.

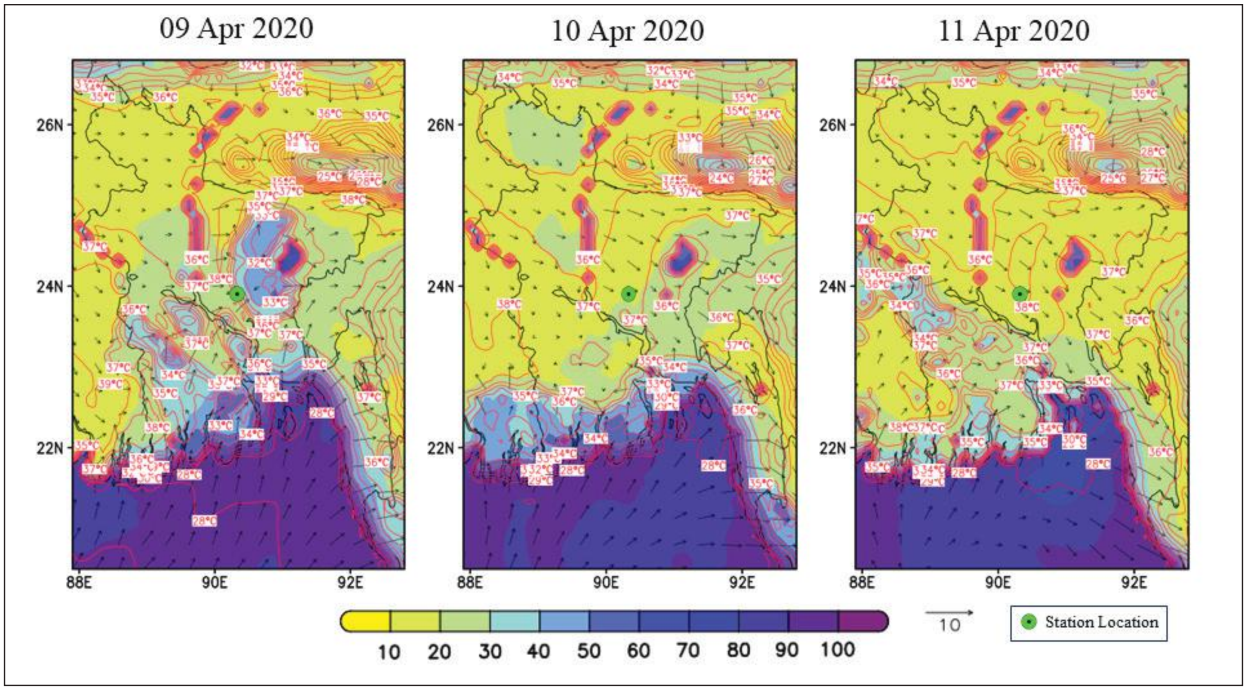


**Figure 7:** Composite Analysis for the 5th Heatwave Event in Dhaka. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

Analyses of the selected events based on the data from the Ambagan weather station of Chattogram also showed a similar pattern as described above. But there are some key differences as well. Only four events depict gradually increasing temperatures that exceed the 35°C mark. The 2nd event in Chattogram (Fig. 9) has a very unusual distribution.

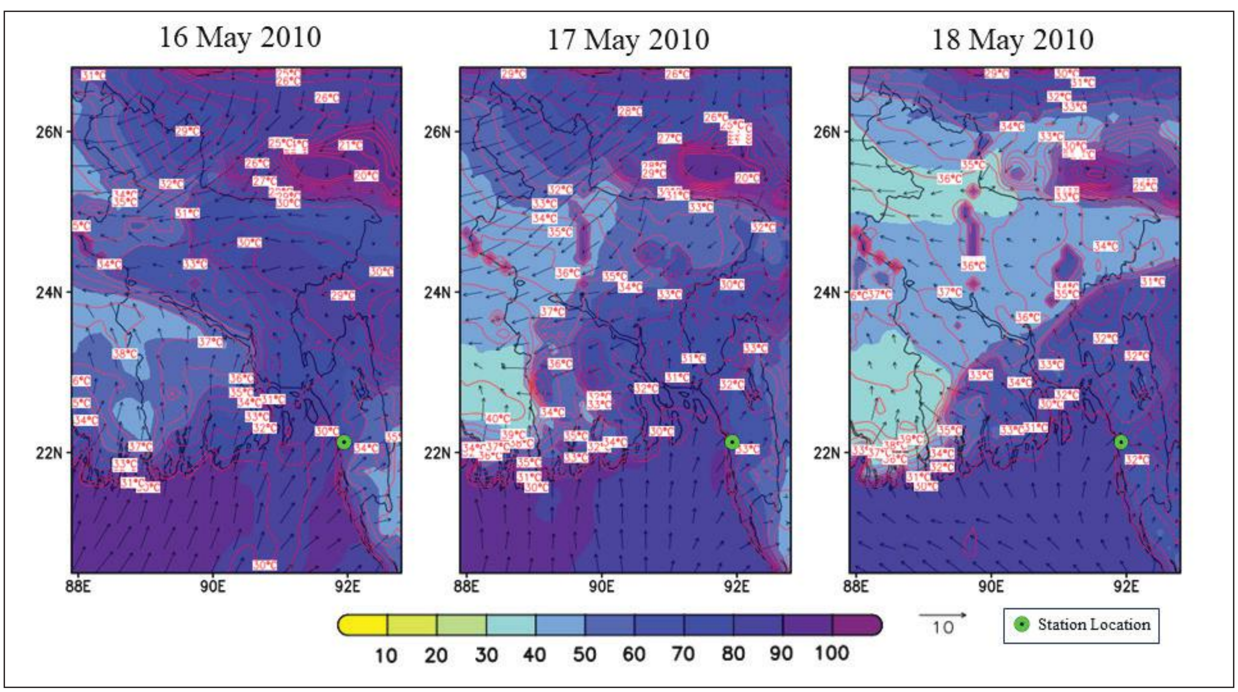


**Figure 8:** Composite Analysis for the 1st Heatwave Event in Ambagan Station in Chattogram. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

It is found that the distribution of temperatures skewed towards the northeast of Bangladesh. The eastern portions of the country (mainly Chattogram) mainly remain unaffected by this intrusion. But, a gradual increase in temperature could be visualized. Similar characteristics could also be found for the 4th event (Fig. 11). The 1st, 3rd, and 5th events (in Fig. 8, Fig. 10 and Fig.12) have some similarities to the events of Dhaka. The last event (Fig. 13) is the most interesting one of all the events described before.

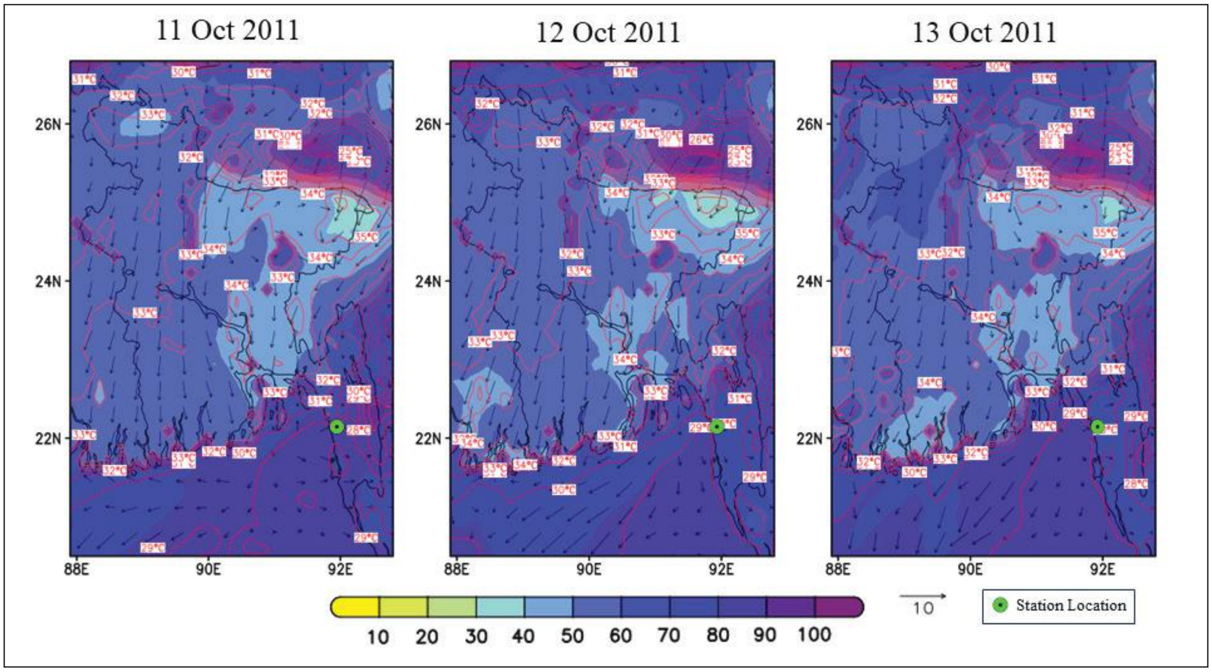


**Figure 9:** Composite Analysis for the 2nd Heatwave Event in Ambagan Station in Chattogram. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

From the above-analyzed events, it is further identified that the simulation of heatwave events has a distribution of moderate temperatures. All of the simulations have shown temperature being under 34°C except for the 1st event (Fig. 8). In that event, the temperature in the southeastern part of Bangladesh went over 34°C. There is a very small rising pattern in the temperature distribution in the simulations of these 6 events.

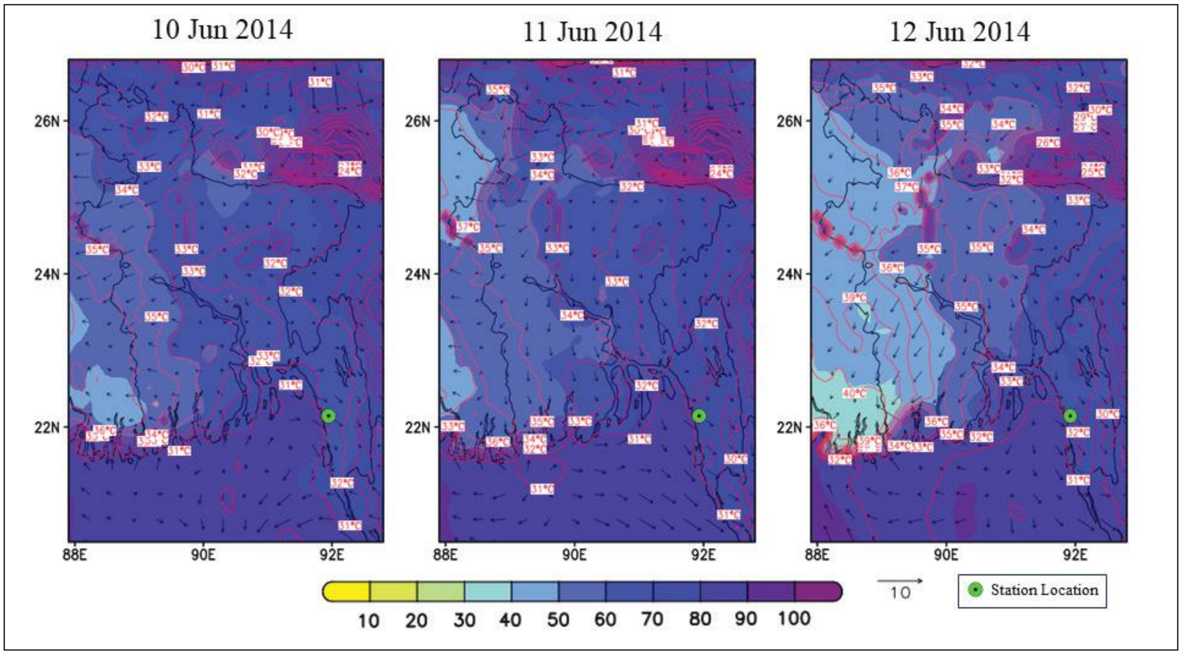


**Figure 10:** Composite Analysis for the 3rd Heatwave Event in Ambagan Station in Chattogram. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

The simulated relative humidity for the events of Chattogram portrayed a different distribution. The relative humidity was above 80% in all but two events. Relative humidity was between 50% to 70% during the first event (Fig. 8). However, the relative humidity was 20% to 50% for the sixth event (Fig. 13). Consequently, the temperature during these two events stayed very high.

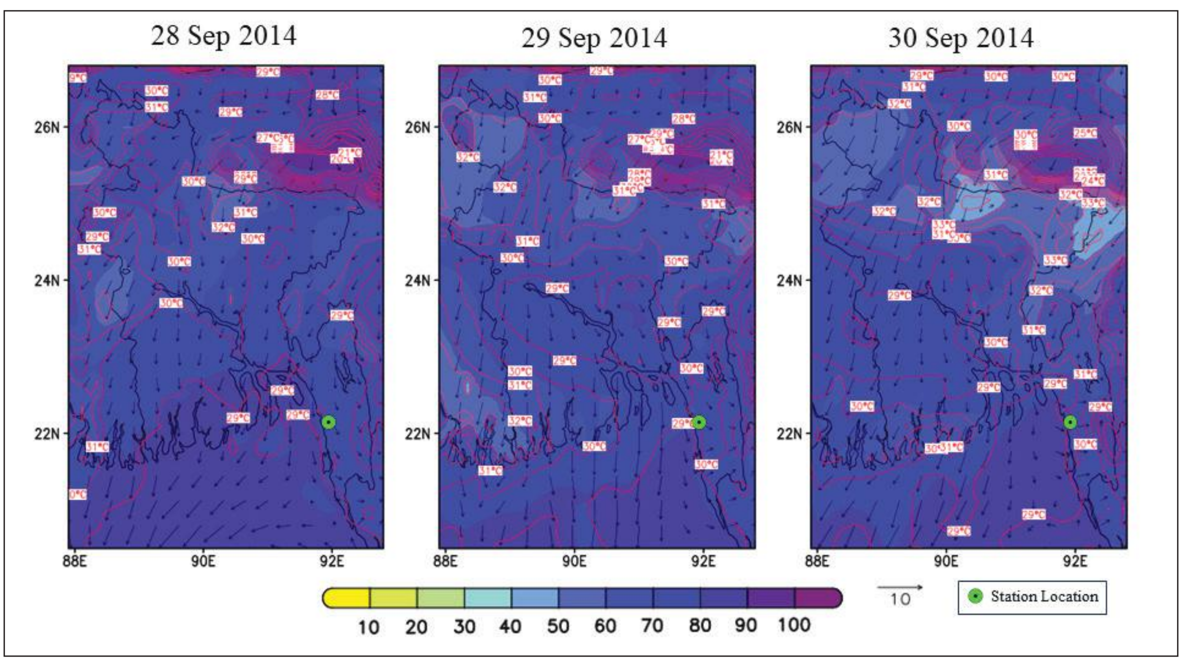


**Figure 11:** Composite Analysis for the 4th Heatwave Event in Ambagan Station in Chattogram. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and the Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

Southerly winds were also present for the heatwave events of Chattogram. During the first event (Fig. 8), that southerly flowed initially towards east and west, and then completely towards north. Similar patterns of wind movement could also be seen for the fifth event (Fig. 12).

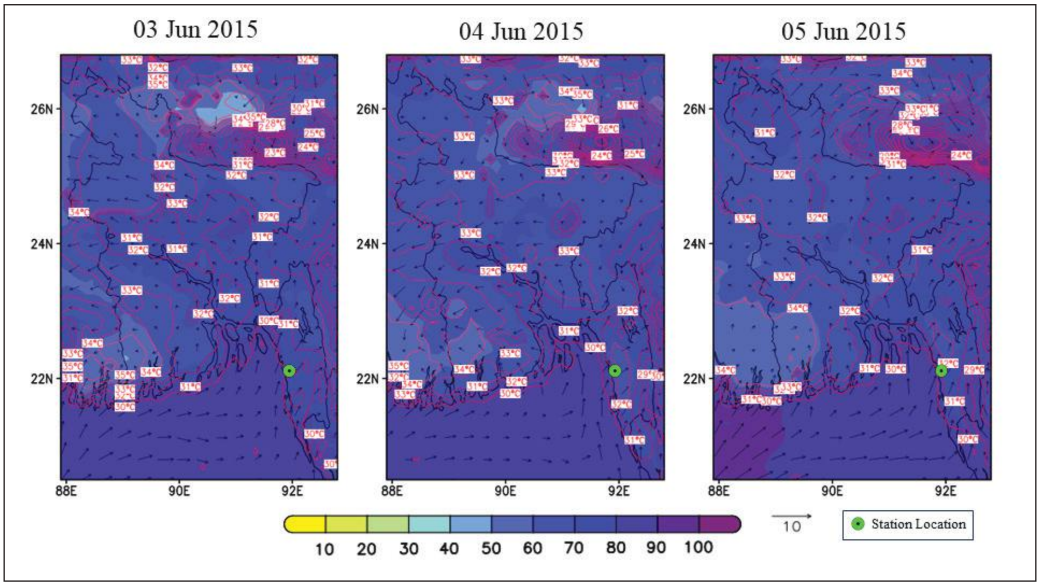


**Figure 12:** Composite Analysis for the 5th Heatwave Event in Ambagan Station in Chattogram. The Figure Shows Lines of Isotherm, Wind Direction and Speed with Arrows, and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

The southerly collided with the northerly in the second event (Fig. 9). After that, these two winds from opposite directions formed a circulation in the Bay of Bengal (Fig. 9). This condition was also seen for the third (Fig. 10) and fourth events (Fig. 11). The sixth event (Fig. 13) was completely different from the previous five. In that event, northerly wind was flowing towards south and east. After three consecutive days of wind flowing like this, the northerly was joined by westerly.

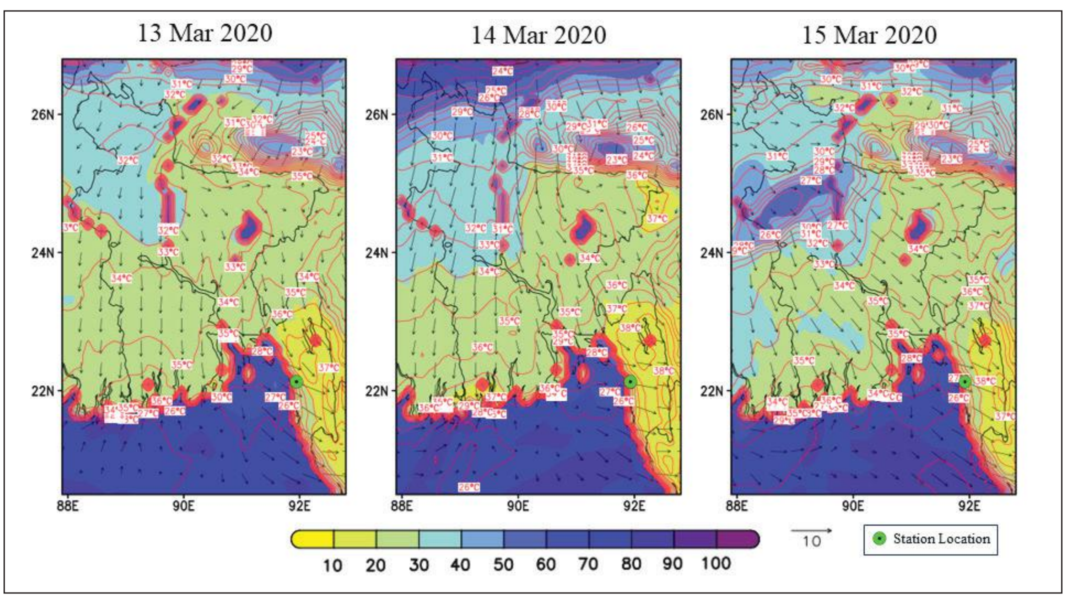


**Figure 13:** Composite Analysis for the 6th Heatwave Event in Ambagan Station in Chattogram. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

In all six simulations, the wind was flowing towards Chattogram. So, this wind was carrying the warm temperature along with it. The flow of humid air was a bit different for the events of Chattogram than it was for Dhaka. However, the situation of humidity would necessarily be influenced by the presence of the Bay of Bengal near Chattogram and hence could very well create favorable conditions for heatwaves.

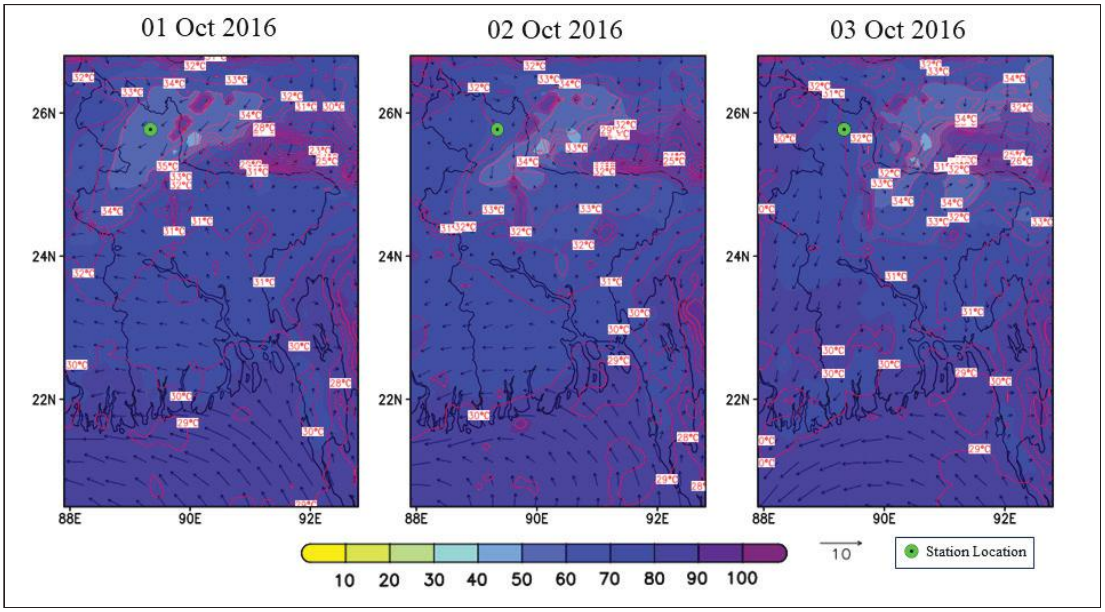


**Figure 14:** Composite Analysis for the 1st Heatwave Event in Rangpur. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows, and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

The selected events based on the data from the Rangpur weather station all have identified moderate temperatures throughout the events. These events, however, have a marked difference from all the events described before. The gradual increase in temperature is from the northern sides of Bangladesh instead of either the east or west of the country. One exception to this trend is the 5th event (Fig. 18). The intrusion of warm temperatures had been from the northwest direction of Bangladesh.

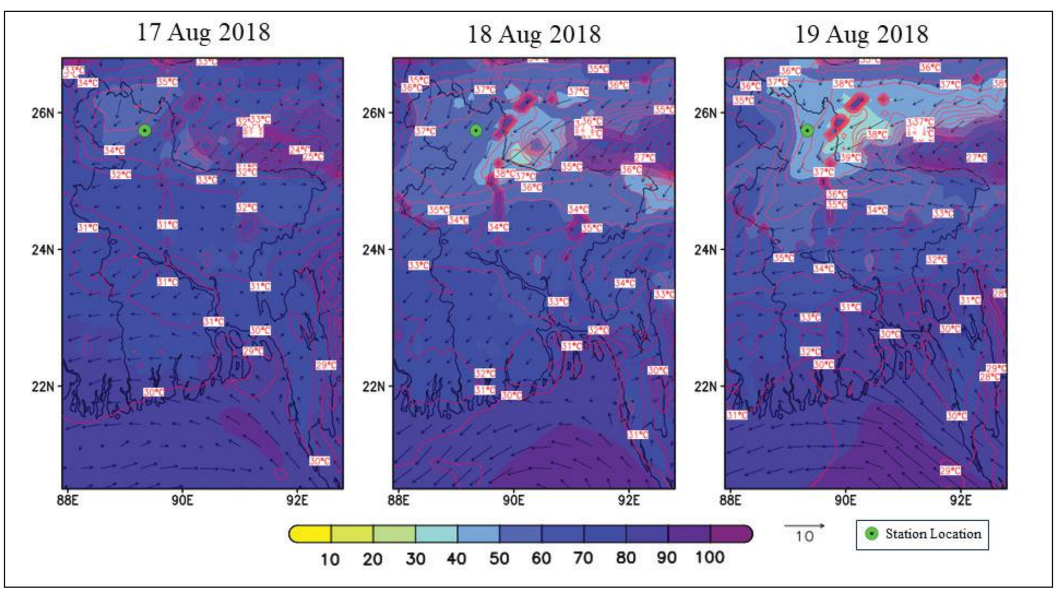


**Figure 15:** Composite Analysis for the 2nd Heatwave Event in Rangpur. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

In all the events of Rangpur, the eastern portion of the country remained less warm. Although some increase in temperature could be observed for the 5th event (Fig. 18), Bangladesh is largely unaffected by this.

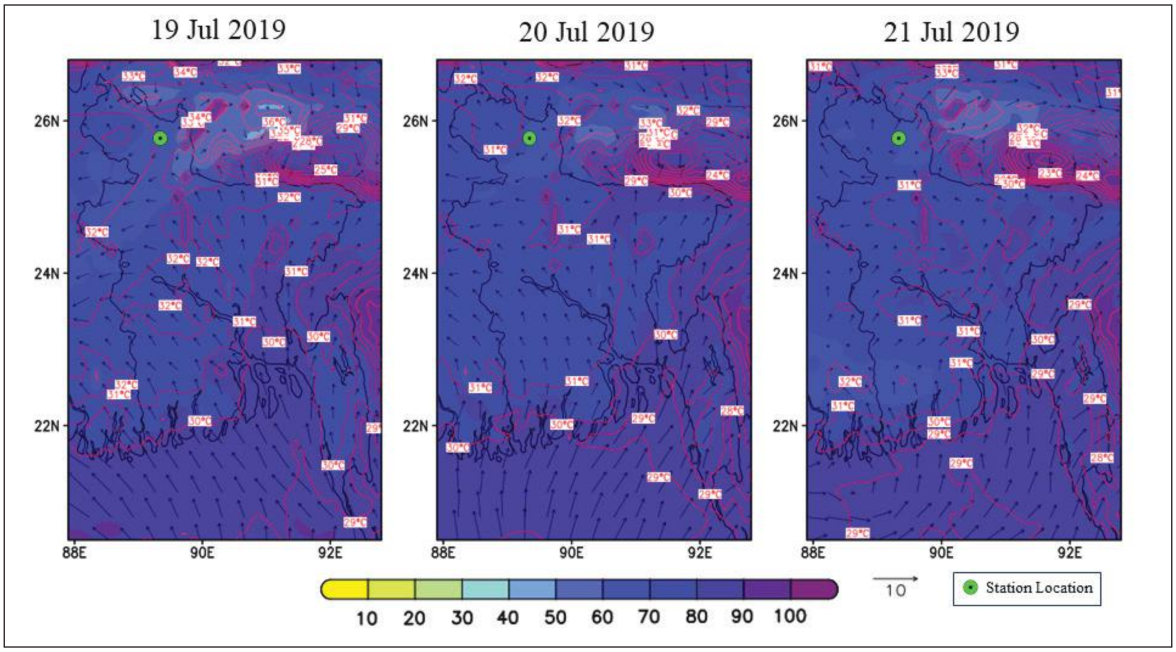


**Figure 16:** Composite Analysis for the 3rd Heatwave Event in Rangpur. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

The simulations for the heatwave events of Rangpur showed highly interesting distributions. Relative humidity was below 50% around the northern side of Bangladesh during the fifth event (Fig. 18). This was the only event that showed consistency in its distribution of relative humidity. But all the other events were highly inconsistent.

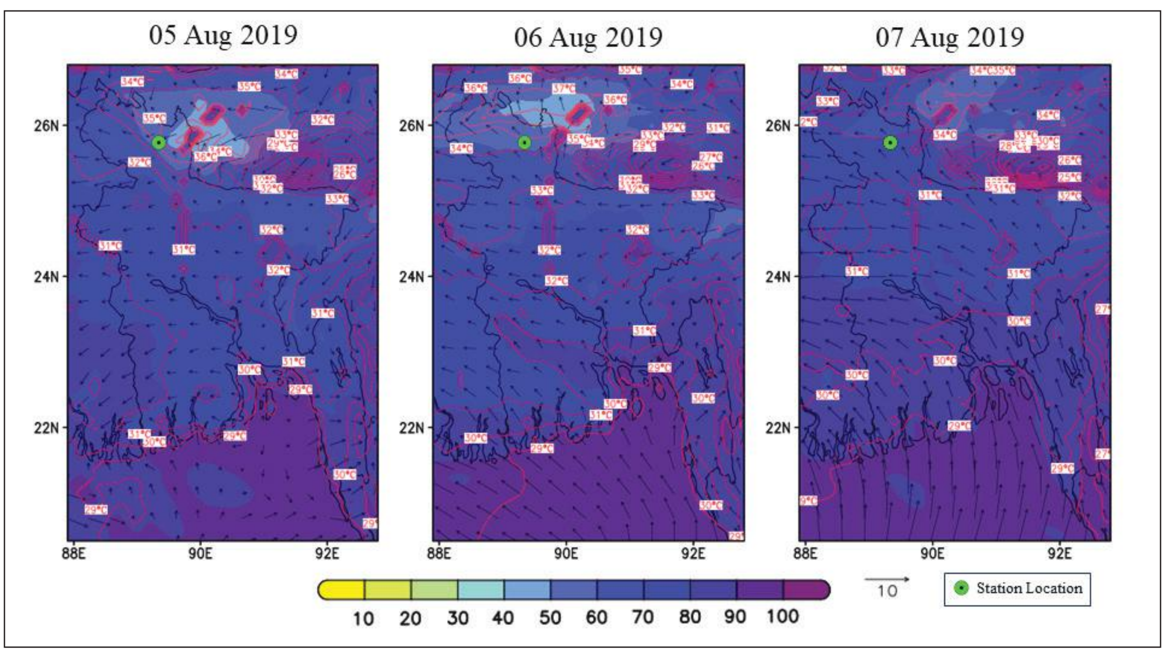


**Figure 17:** Composite Analysis for the 4th Heatwave Event in Rangpur. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

During the first event (Fig. 14), there was a gradual progression of humid air towards the south. But the humid air flowed towards west during the second event (Fig. 15). Humid air flowed towards northeast during the third event (Fig. 16). The humid air, upon entering through the northern districts, gradually covered the whole country during the fourth event (Fig. 17). The last event (Fig. 19) was the most interesting one. At first, the humid air flowed towards northeast. Then, it flowed to the west. In all the events, except for the fifth one, the relative humidity stayed between 40% to 70%.

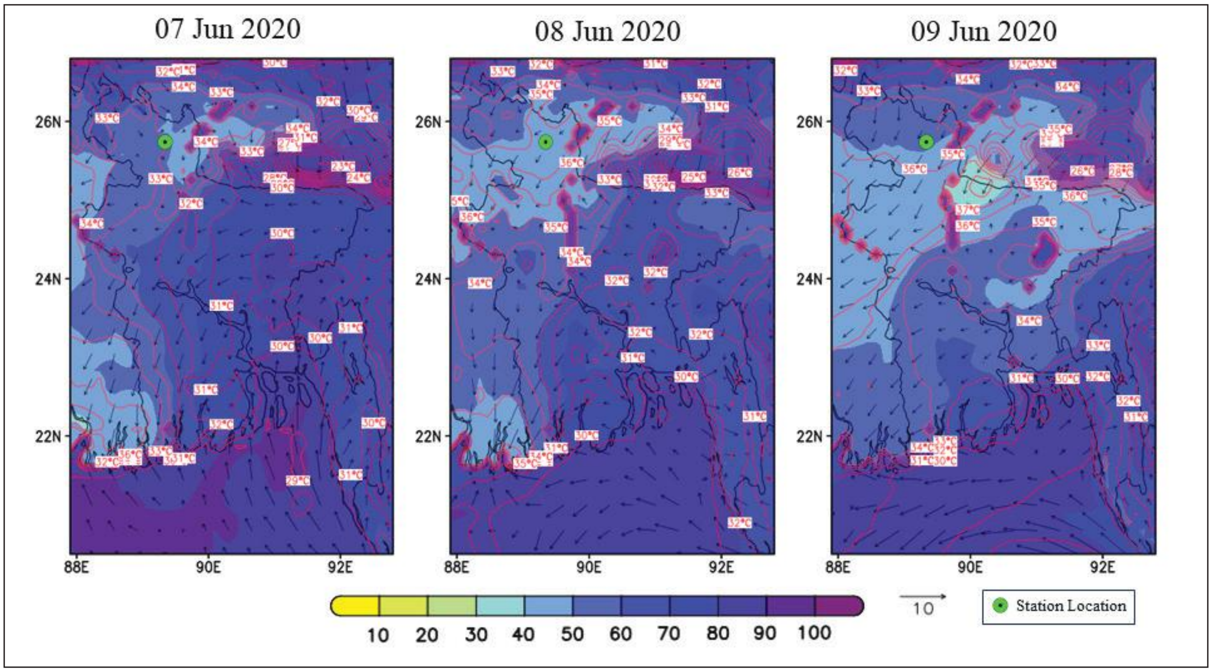


**Figure 18**: Composite Analysis for the 5th Heatwave Event in Rangpur. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

The wind was also simulated for all six events from Rangpur. In the first event (Fig. 14), a southerly wind could be seen. That southerly gradually formed a circulation over the Bay of Bengal, which initiated winds flowing towards the northeast and northwest. This condition was also observed for the second (Fig. 15) and fifth events (Fig. 18). The southerly wind temporarily formed a circulation during the third event (Fig. 16) that disappeared briefly before generating again and then moving towards southeast. The fourth (Fig. 17) and sixth events (Fig. 19) share some similarities in them.

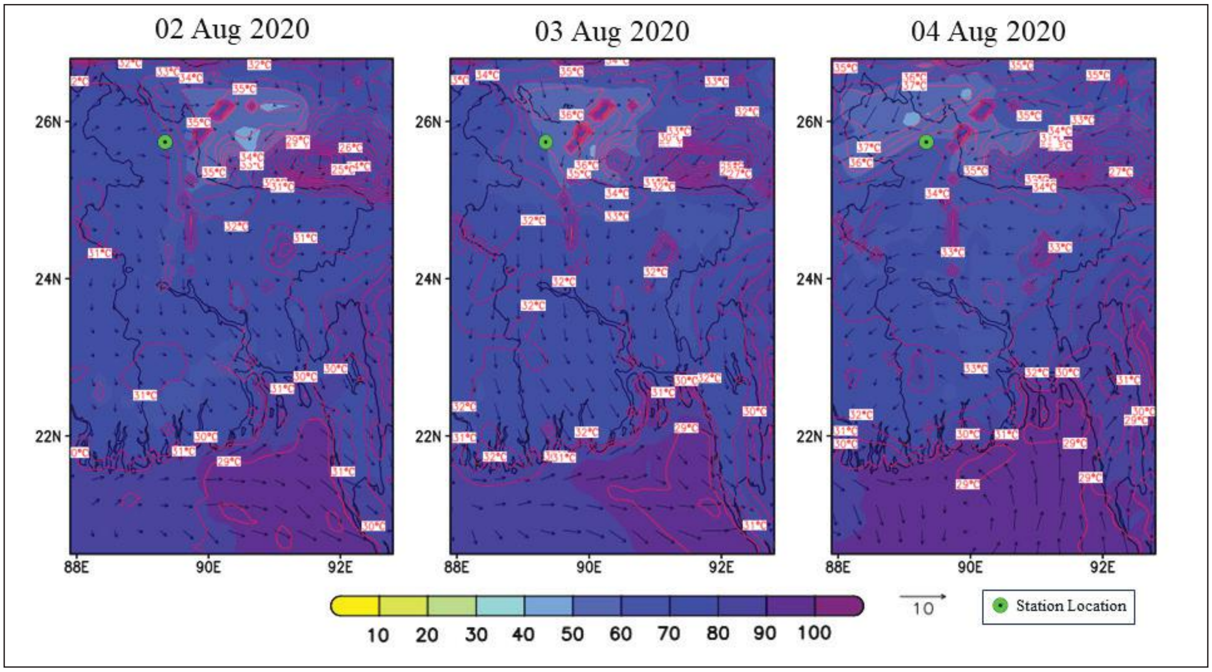


**Figure 19:** Composite Analysis for the 6th Heatwave Event in Rangpur. The Figure Shows Lines of Isotherm, Wind Direction, and Speed with Arrows and Distribution of Relative Humidity in Shades. This Information is from WRF Simulations

We found that the wind was moving toward northwest in all six simulations. Rangpur is situation in that part of Bangladesh. So, this wind was carrying the warm temperature and the moisture with it. This pattern of wind flow was actually vital for the heatwave events in Rangpur.

The analysis of temperature for all 17 events depicts a common pattern – the intrusion of temperature demarcates the location of heatwaves. We have found that the events in Dhaka were due to the intrusion from western side. The heatwaves in Chattogram are affected by the passing of warm temperatures from the east. While the events in Rangpur were caused by the warm conditions prevailing in the north of Bangladesh. It should be noted that, like most other research works (Jaman et al., 2022) on heatwaves, temperature has been given the paramount importance in this research too. The activities of temperature are better understood with the aid of relative humidity and wind. Both these variables accentuate the way temperature behaves in certain places under certain conditions. So, they have been studied in this research as well.

The 17 heatwave events in this research had clearly illustrated the intrusion of warm-air temperature in Bangladesh. In some cases, the intrusion has been from the Bay of Bengal. Bay of Bengal has this tendency to have some increase during the pre-monsoon months (Shuvo and Sultana, 2022). This increase in temperature can run through the monsoon season and can last up to post-monsoon as well (Shuvo and Awal, 2021; Shuvo, 2021). The northern and northeastern portion of Bangladesh are mostly surrounded by hills and mountains. These regions can introduce warm-air into the atmosphere through influx of moisture (Dimri, 2013; Guo et al., 2018). Basically, this is the reason for most of the heatwaves in Rangpur and Chattogram. Some events in Chattogram are influenced by the warm-air intrusion from the Bay of Bengal. The events in Dhaka can be attributed to microclimatic changes the city is long-experiencing for a while (Jabeen and Guy, 2015; Sharmin and Steemers, 2020). While the reason for heatwaves in Dhaka is not solely that, the physical essence remains the same. The sensitivity of temperatures from the warm-air intrusion has been amplified by the changes in climate in Dhaka.

## VALIDATION AND DISCUSSION OF SIMULATED RESULTS

To compare simulated data and observed data of Dhaka, Chattogram, and Rangpur station, an independent t test has been carried out. Researchers collected information on temperature, relative humidity, and wind speed on the specific event. Data for 2010/5/14, 2011/10/09, 2014/06/08, 2014/09/26, 2015/06/01, and 2020/03/11 were collected from Chattogram station. Both observed and simulated data of temperature, wind speed, and relative humidity were taken on the specific dates. Similarly, for Dhaka station, data for 2012/03/30, 2013/06/14, 2014/04/27, 2019/05/17, and 2020/04/07 were obtained (both simulated and observed). Finally, for Rangpur station, data for 2016/09/29, 2018/08/15, 2019/07/17, 2019/08/03, 2020/06/05, and 2020/07/31 were collected.

To compare the parameters of two different phenomena (simulated and observed from station), a test of hypothesis was done. It was done to check that there is no difference between observed value and the model simulated values. That's why, an independent sample t test was selected, to check their differences.

Check Temperature parameter,

Check Relative Humidity, and

Check Wind Speed

**Table 3:** Comparison between Simulated Temperature (Temp S) and Observed Temperature (Temp O)

| | observation | Mean Simulated | Mean Observed | Mean Difference | Std. Error | t value | p value |
|---|---|---|---|---|---|---|---|
| Temp O - Temp S | 17 | 33.999 | 31.912 | 2.087 | 1.163 | 1.8 | .091 |

From the results in Table 3, it can be found that the mean difference between the observed temperature and simulated temperature value has been 2.087 and the p value has been 0.091 which is statistically insignificant. That means null hypothesis could not be rejected. Note that, in this instance - the null hypothesis was that there is no difference between observed temperature value and the simulated temperature value. This null hypothesis is valid for all the tests carried out in this research. From the output, researchers concluded that there exists no difference between the observed wind speed temperature and the simulated temperature.

**Table 4:** Comparison between Simulated Relative Humidity (RH O) and Observed Relative Humidity (RH S)

| | observation | Mean Simulated | Mean Observed | Mean Difference | Std. Error | t value | p value |
|---|---|---|---|---|---|---|---|
| RH O - RH S | 17 | 75.704 | 76.718 | -1.013 | 1.12 | -.9 | .379 |

From the results of Table 4, it is seen that the absolute mean difference between the observed relative humidity and simulated relative humidity value has been 1.013 and the p value has been 0.379 which is statistically insignificant. Again, the null hypothesis could not be rejected. So, in conclusion - there exists no difference between the observed relative humidity and the simulated relative humidity.

**Table 5:** Comparison between Simulated Wind Speed (Wind S) and Observed Wind Speed (Wind O)

| | observation | Mean Simulated | Mean Observed | Mean Difference | Std. Error | t value | p value |
|---|---|---|---|---|---|---|---|
| Wind O - Wind S | 17 | 2.513 | 2.871 | -.358 | .188 | -1.9 | .074 |

From the above results in Table 5, it can be delineated that, the absolute mean difference between the observed wind speed and simulated wind speed value has been 0.358 and the p value has been 0.074 which is statistically insignificant. Thereby, the null hypothesis could not be rejected. From this output, the authors concluded that there exists no difference between the observed wind speed and the simulated wind speed.

Since all three parameters have been statistically insignificant, it can be concluded that if the above-mentioned parameters are well-known for a particular date, heatwaves from the simulated event can be predicted.

## CONCLUSIONS

In this research, 17 heatwave events were simulated with the WRF-ARW model. These events occurred in Dhaka, Chattogram, and Rangpur districts. The prevailing conditions from simulations were analyzed in this research. In this research, the three parameters the temperature, relative humidity, and wind have been analyzed for understanding the heatwave situations in Bangladesh. It has been found that intrusion of temperature (in the form of heat energy) caused heatwaves in respective regions. However, this shift in temperature is not a dramatic phenomenon. Instead, this is suitably aided by the movement of air. It has been observed that warm temperature intruded into the places (where heatwaves occurred) by flowing air. This situation was further enhanced by the presence or absence of humid air. So, it can be said that the prevailing conditions before a heatwave can be easily visualized and conceptualized if the three parameters are carefully synthesized.

The idea behind this research was to support both the identification and prediction of heatwave events. The forecasters can take the information from this research to generate a system of best practices so that a heatwave event can be predicted before its eventual occurrence. The findings from this research could help in identifying the heatwave events. In this regard, the results of this research could be utilized by the people in operational meteorological agencies.

## ACKNOWLEDGEMENTS

For providing the necessary technical support during the study, the authors express their sincere gratitude to the Department of Meteorology at the University of Dhaka. The authors additionally thank the University of Dhaka's Centennial Research Grant (CRG) for funding this research project.

## REFERENCES

Anderson, G. B., Bell, M. L., Peng, R. D., 2013. Methods to calculate the heat index as an exposure metric in environmental health research. Environmental Health Perspectives 121(10), 1111-1119.

Dasari, H. P., Salgado, R., Perdigao, J., Challa, V. S., 2014. A regional climate simulation study using WRF-ARW model over Europe and evaluation for extreme temperature weather events. International Journal of Atmospheric Sciences.

De, U. S., Mukhopadhyay, R. K., 1998. Severe heatwave over the Indian subcontinent in 1998, in perspective of global climate. Current science 75(12), 1308-1311.

Emanuel, K.A., 1986. Overview and definition of mesoscale Meteorology. In: Ray, P.S. (eds.) Mesoscale Meteorology and Forecasting. American Meteorological Society, Boston, MA. doi: https://doi.org/10.1007/978-1-935704-20-1_1

Ferdaus, J., Quadir, D. A., Alam, M. S., Panda, S. K., Das, S., Ahasan, M. N., Rabbani, K. M. G., Shuvo, S. D., 2021. Prediction of thunderstorms based on atmospheric instability indices over Bangladesh using WRF-ARW Model. Jalawaayu 1(2), 21–37. https://doi.org/10.3126/jalawaayu.v1i2.41008

Frich, P.A.L.V., Alexander, L.V., Della-Marta, P., Gleason, B., Haylock, M., Tank, A.K., Peterson, T., 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. Climate research, 19(3), 193-212.

Gao, M., Wang, B., Yang, J., Dong, W., 2018. Are peak summer sultry heatwave days over the Yangtze–Huaihe River basin predictable? Journal of Climate 31(6), 2185-2196.

Gasparrini, A., Armstrong, B., 2011. The impact of heat waves on mortality. Epidemiology (Cambridge, Mass.) 22(1), 68.

Gaughan, J. B., Mader, T. L., Gebremedhin, K. G., 2012. Rethinking heat index tools for livestock. Environmental physiology of Livestock, 243-265.

Ghatak, D., Zaitchik, B., Hain, C., Anderson, M., 2017. The role of local heating in the 2015 Indian Heat Wave. Scientific reports 7(1), 1-8.

Haque, M. A., Budi, A., Azam Malik, A., Suzanne Yamamoto, S., Louis, V. R., Sauerborn, R., 2013. Health coping strategies of the people vulnerable to climate change in a resource-poor rural setting in Bangladesh. BMC public health 13(1), 1-11.

Hashizume, M., Armstrong, B., Hajat, S., Wagatsuma, Y., Faruque, A. S., Hayashi, T., Sack, D. A., 2008. The effect of rainfall on the incidence of cholera in Bangladesh. Epidemiology 19(1), 103-110.

Hass, A. L., Ellis, K. N., Reyes Mason, L., Hathaway, J. M., Howe, D. A., 2016. Heat and humidity in the city: neighborhood heat index variability in a mid-sized city in the southeastern United States. International journal of environmental research and public health 13(1), 117.

Huq, S., 2001. Climate change and Bangladesh. Science, 294(5547), 1617-1618.

Islam, M. A., Meandad, J., Shuvo, S. D., Kabir, A., 2021. Modeling of lightning events using WRF-derived microphysical parameters. The Dhaka University Journal of Earth and Environmental Sciences 8(2), 41-50. doi: https://doi.org/10.3329/dujees.v8i2.54838

Jaman, S., Islam, M. J., Imran, A., Kamruzzaman, M., Mallik, M. A. K., Paul, P., Syed, I. M., 2022. Sensitivity of different physics schemes in the simulation of heat wave events over Bangladesh Using WRF-ARW Model. Dhaka University Journal of Science 70(1), 70-78.

Karmakar, S., 2019. Patterns of climate change and its impacts in northwestern Bangladesh. Journal of Engineering science 10(20), 33-48.

Kibria, G., Pavel, H. R., Miah, M. R., Islam, M. R., 2022. Impacts of climate change in Bangladesh and its consequences on public health. Journal of Sustainability and Environmental Management 1(3), 359-370.

Kim, H., Ha, J. S., Park, J., 2006. High temperature, heat index, and mortality in 6 major cities in South Korea. Archives of environmental and occupational health 61(6), 265-270.

Lorenc, A. C., 1986. Analysis methods for numerical weather prediction. Quarterly Journal of the Royal Meteorological Society 112(474), 1177-1194.

Meehl, G. A., Tebaldi, C., 2004. More intense, more frequent, and longer lasting heatwaves in the 21st century. Science 305(5686), 994-997.

Mishra, V., Ganguly, A. R., Nijssen, B., Lettenmaier, D. P., 2015. Changes in observed climate extremes in global urban areas. Environmental Research Letters 10(2), 024005.

Murari, K. K., Ghosh, S., Patwardhan, A., Daly, E., Salvi, K., 2015. Intensification of future severe heatwaves in India and their effect on heat stress and mortality. Regional Environmental Change 15(4), 569-579.

Nissan, H., Burkart, K., Coughlan de Perez, E., Van Aalst, M., Mason, S., 2017. Defining and predicting heat waves in Bangladesh. Journal of Applied Meteorology and Climatology 56(10), 2653-2670.

Nissan, H., Muñoz, Á. G., Mason, S. J., 2020. Targeted model evaluations for climate services: a case study on heat waves in Bangladesh. Climate Risk Management 28, 100213.

Pai, D. S., NAIR, S., Ramanathan, A. N., 2013. Long term climatology and trends of heatwaves over India during the recent 50 years (1961-2010). Mausam 64(4), 585- 604.

Panda, D. K., AghaKouchak, A., Ambast, S. K., 2017. Increasing heatwaves and warm spells in India, observed from a multiaspect framework. Journal of Geophysical Research: Atmospheres 122(7), 3837-3858.

Perkins, S. E., Argüeso, D., White, C. J., 2015. Relationships between climate variability, soil moisture, and Australian heatwaves. Journal of Geophysical Research: Atmospheres 120(16), 8144-8164.

Rabbani, K. M. G., Shuvo, S. D., 2021, August 01 – 06. Application of WRF-Chem for Monitoring Suspended Hydrometeors Available on Atmosphere [Poster presentation]. AOGS 2021, Thailand. https://www.asiaoceania.org/aogs2021/public.asp?page=home.html

Rahman, A., 2008. Climate change and its impact on health in Bangladesh. Regional Health Forum (12)1, 16-26.

Raja, D. R., Hredoy, M. S. N., Islam, M. K., Islam, K. A., Adnan, M. S. G., 2021. Spatial distribution of heatwave vulnerability in a coastal city of Bangladesh. Environmental Challenges 4, 100122.

Rajib, M. A., Mortuza, M. R., Selmi, S., Ankur, A. K., Rahman, M. M., 2011. Increase of heat index over Bangladesh: Impact of climate change. International Journal of Civil and Environmental Engineering

5(10), 434-437.

Rasheed, K. S., 2008. Bangladesh: Resource and environmental profile. AH Development Publishing House.

Ratnam, J. V., Behera, S. K., Ratna, S. B., Rajeevan, M., Yamagata, T., 2016. Anatomy of Indian heatwaves. Scientific reports 6(1), 1-11.

Ravagnolo, O., Misztal, I., Hoogenboom, G., 2000. Genetic component of heat stress in dairy cattle, development of heat index function. Journal of dairy science 83(9), 2120-2125.

Robinson, P. J., 2001. On the definition of a heatwave. Journal of Applied Meteorology and Climatology 40(4), 762-775.

Sarker, M., Quadir, D., Rashid, T., Ahasan, M., Shuvo, S. D., Meandad, J., Rabbani, K., Fariha, T. R., 2021. Simulation of structure, intensity and track of super cyclone amphan using high resolution WRF-ARW Model. The Dhaka University Journal of Earth and Environmental Sciences 8(2), 17–23. https://doi.org/10.3329/dujees.v8i2.54835

Shahid, S., 2010. Probable impacts of climate change on public health in Bangladesh. Asia Pacific Journal of Public Health 22(3), 310-319.

Shahid, S., Wang, X. J., Harun, S. B., Shamsudin, S. B., Ismail, T., Minhans, A., 2016. Climate variability and changes in the major cities of Bangladesh: observations, possible impacts and adaptation. Regional Environmental Change 16, 459-471.

Shuvo, S. D., 2021. Climatology of Frequency, Life period, energy and speed for tropical disturbances and cyclones over the Bay of Bengal. The Dhaka University Journal of Earth and Environmental Sciences 10(1), 23–31. https://doi.org/10.3329/dujees.v10i1.56277

Shuvo, S. D., Awal, M. R., 2021. Assessing Atmospheric Instability over the Bay of Bengal during October and November months between 2007–2018. The Dhaka University Journal of Earth and Environmental Sciences 9(2), 45-54. doi: https://doi.org/10.3329/dujees.v9i2.55089

Shuvo, S. D., Sultana, S. S., 2022. Assessing the climatology and synoptic conditions of tropical cyclone recurvature over the Bay of Bengal, Bangladesh. The Dhaka University Journal of Earth and Environmental Sciences 10(3), 131–141. https://doi.org/10.3329/dujees.v10i3.59079

Shuvo, S. D., Rashid, T., Panda, S. K., Das, S., Quadir, D. A., 2021. Forecasting of pre-monsoon flash flood events in the northeastern Bangladesh using coupled hydrometeorological NWP modelling system. Meteorology and Atmospheric Physics 133, 1603-1625. doi: https://doi.org/10.1007/s00703-021-00831-z

Smith, K. R., Coauthors, 2014: Human health: Impacts, adaptation, and co-benefits. climate change 2014: Impacts, adaptation, and vulnerability, Part A: Global and Sectoral Aspects, C. B. Field et al., Eds., Cambridge University Press, 709–754.

You, Q., Jiang, Z., Kong, L., Wu, Z., Bao, Y., Kang, S., Pepin, N., 2017. A comparison of heatwave climatologies and trends in China based on multiple definitions. Climate Dynamics 48(11), 3975-3989.

Dimri, A. P., 2013. Intraseasonal oscillation associated with the Indian winter monsoon. Journal of Geophysical Research: Atmospheres 118(3), 1189-1198.

Guo, L., Klingaman, N. P., Demory, M. E., Vidale, P. L., Turner, A. G., Stephan, C. C., 2018. The contributions of local and remote atmospheric moisture fluxes to East Asian precipitation and its variability. Climate Dynamics 51, 4139-4156.

Jabeen, H., Guy, S., 2015. Fluid engagements: responding to the co-evolution of poverty and climate change in Dhaka, Bangladesh. Habitat International 47, 307-314.

Sharmin, T., Steemers, K., 2020. Effects of microclimate and human parameters on outdoor thermal sensation in the high-density tropical context of Dhaka. International journal of biometeorology 64(2), 187-203.