Assessment of WRF model performance in simulation of heat wave events over Bangladesh

Shuchi Chaki[1], M.A. Samad[1], M.A.K. Mallik[2] and S.M. Quamrul Hassan[2]
[1]Department of Applied Mathematics, University of Dhaka,
[2]Bangladesh Meteorological Department, Agargaon, Dhaka-1207.

Abstract

Heat wave is an extended period of extreme temperature. Owing to the warming of the atmosphere, a leap in the number of heat waves has been noted across the world. Bangladesh, locating at a sub-tropical area, is at greater risk of this extreme weather event as supported by the substantial rise in heat related casualties. In order to issue heatwave alert, examining the performance of numerical weather prediction model needs to accomplished. Considering this fact, an attempt has been made to study two heat wave events that swept over Bangladesh during the April and May of 2019. For the simulation, Advanced Research WRF has been used. Both events were run with GFS (Global Forecasting System) data on 0.25°×0.25° global latitude-longitude grid as driving data. The simulated results are analyzed in details and finally, the performance of the model has been tested by comparing the temperature, relative humidity and wind speed of eight divisional stations with the BMD observed data.

Keywords: Heat Wave, Extreme Temperature, WRF, GFS

Introduction

Global warming, or the rise in mean surface air temperature over the last century is now an established fact. Particularly, in the latter half of the twentieth century, the annual magnitudes of the lowest and highest daily minimum and maximum temperatures rose throughout the world [1]. The genesis and spread of heat wave, an extreme weather event, are attributed to this upward shift in temperature [2]. In the Intergovernmental Panel on Climate Change 5th Assessment report, it has been indicated that this situation will deteriorate and there will be high probability of increase in frequency, duration and intensity of heat waves over most land areas well into the future [3]. The findings of this report had been strengthened by multitude of studies across the world. A stochastic analysis of heatwaves and temperature in Hungary using widely accepted climate change scenarios reported that heatwaves would extend in duration and strength compared to the past, in fact, geographically they would be expected to expand [4]. Investigating maximum temperature using both observation and reanalysis data indicated intense and frequent extreme weather events across Africa [5]. In a study over Southern California, it was showed that heatwaves and extreme heat events tripled over the last century and heatwaves spanning at least seven days occurred regularly after the 1970's [6].

Heat wave has become a matter of concern in the context of Bangladesh climatology. High population density, inadequate infrastructure and low adaptive capacity have made the urban population of Bangladesh highly vulnerable to climate change [7]. Though less in number, there have been studies investigating the patterns, frequency, annual and seasonal variability of heat waves in Bangladesh. The climatological analysis of the heat index (index defining combined effects of temperature and relative humidity) from 1961-2010 in Bangladesh has revealed significant augmentation of both temperature and relative humidity in past 20 years. The south-west and north-west regions of Bangladesh are most vulnerable to impacts of heat combined with humidity. Mean heat index value ranges from 42-50° C in different parts of the country in summer [8]. An upward shift in daily maximum and minimum temperature, and level of discomfort resulting from excess heat during the monsoon and pre-monsoon season has also been demonstrated over Bangladesh in another study [9].

Heat wave is emerging as a great threat worldwide. The 2003 European heat wave was the deadliest event in Europe causing fatalities of over 70000 people across Europe with France being the worst-hit [10]. Continual heat waves lessen humane ability to do physical jobs as well as impact mental health. Bangladesh undergoes a labor-based economy run with more than 61% of peripheral community directly involved in strenuous labor [11]. Consequently, research focusing on heatwave are highly important in the context of Bangladesh. This study has attempted to simulate two heat wave events occurring in the month of April and May of 2019, over the country using numerical weather prediction model, WRF. Advanced Research WRF model is the state-of-the-art numerical weather prediction model that generates high resolution meteorological data and is used to simulate different weather phenomena. Recently, WRF-ARW model has been used to simulate heat wave events in a multitude of papers [12, 13]. Analyzing the synoptic conditions related to heat waves and evaluating the performance of WRF model in simulating heat wave events over Bangladesh are two major goals of the current study. The findings will add values to the future endeavors of studying heat waves.

Synoptic conditions:

According to the Bangladesh Daily Weather Service report by BMD, on 22nd April, 2019, mild heat wave was sweeping over the regions of Rajshahi, Rangamati, Cox's Bazar, Kutubdia & Teknaf. The highest maximum temperature of 37.8°C was recorded at Rajshahi which was above normal by 2.2°C. On 23rd April, mild heat wave continued to sweep over Chattogram division and the regions of Khulna, Jashore, Patuakhali & Bhola. The temperature was above normal by (1-5)°C throughout most of the regions of the country. On the following day, the highest maximum temperature of 37.5°C was recorded at Rangamati which was above normal by 4.3°C. Severe heat wave over Rajshahi region and mild to moderate heat wave is sweeping over Khulna and the rest part of Rajshahi division and the regions of Dhaka, Tangail, Faridpur and Gopalgonj. Mild heat wave was found to sweep over the parts of the country for 25th and 26th April, 2019.

During 26 May, 2019, mild heat wave was sweeping over the regions of Rajshahi, Pabna, Khulna, Kushtia & Mongla and it may spread. On the next day, the highest maximum temperature of 37.5°C recorded at Rajshahi & Chuadanga which was above normal by 3.1°C & 2.7°C respectively. Mild heat wave is sweeping over Khulna division and the regions of Tangail, Madaripur, Gopalgonj, Chandpur, M. Court, Rajshahi, Pabna, Badalgachhi, Dinajpur, Barishal & Patuakhali. On 28 May, 2019, day temperature was above normal by (1-5)°C over the country. Mild heat wave was sweeping over Khulna & Barishal divisions and the regions of Dhaka, Madaripur, Rangamati, Chandpur, Noakhali, Rajshahi & Pabna. On the following day, day temperature was nearly normal at Rangpur & Sayedpur and it rose by (1-4)°C elsewhere over the country. The highest maximum temperature 38°C was recorded at Khulna and Jashore which was above normal by 3.9°C and 3.5°C respectively. Mild heat wave is sweeping over Khulna & Barishal divisions and the regions of Dhaka, Tangail, Madaripur, Rangamati, M. Court, Rajshahi, Pabna, Dinajpur and it may continue. On 30th May, 2019, day temperature was above normal by (2-4)°C over the country. The highest temperature of 37.6°C was recorded at Jashore which was above normal by 3.1°C. Mild heat wave is sweeping over Khulna divisions and the regions of Rajshahi, Pabna, Dhaka, Madaripur, Rangamati, Noakhali & Barishal.

Methodology:

To identify heat wave days, we have used the definition given and followed by Bangladesh Meteorological Department (BMD). The categories of heat wave for Bangladesh are defined by Bangladesh Meteorological Department (BMD) as follows:

When maximum temperature lies between 36-38^{0}C = Mild Heat Wave
When maximum temperature lies between 38.1-40^{0}C = Moderate Heat Wave
When maximum temperature lies between 40.1-42^{0}C = Severe Heat Wave
When maximum temperature >43^{0}C = Extreme Heat Wave

The simulation of heat wave has been conducted using Advanced Research WRF model, version 4.2.2. WRF model consists of WRF software framework, ARW dynamic solver, WRF pre-processing system and WRF data assimilation. As the initial condition of simulation, 6 hourly GFS (Global Forecasting Data) has been used. The model is run with 10 km horizontal grid size and for single domain (central points of the domain 23.9°N, 90.5°E). The physics options used in this study are presented in table 1.

Table 1: Physics options used in this study

Microphysics	WRF Single-moment 6-class scheme
Cumulus Parameterization Scheme	Kain-Fritsch (KF)
PBL Parameterization	Yonsei University Scheme (YSU)
Surface Layer	Revised MM5
Land Surface Parameterization	Noah Scheme
Radiation Scheme	Rapid Radiative Transfer Model
Shortwave Radiation	Dudhia Scheme

Results & Discussion

Analysis of Temperature

Temperature is the key indicator of heat wave in Bangladesh. The model derived temperature at 0900 UTC for four days based on the initial condition of 0000 UTC of 22 April, 2019 and 0000 UTC of 26th May, 2019 are shown in the figure 1(a) and 1(b) respectively.

Mild to moderate heat wave was simulated by WRF model during 22-25 April, 2019 as displayed in the figure 1(a). Temperature across the country was found to be above 36°C while in parts of Khulna, Barishal and Chattogram region on 22nd April. On 24th of April, the major area of Bangladesh was under mild heat wave (T_{max}

> 36°C) except for north-western regions according to the simulation. The condition of heat wave found to deteriorate as temperature over south-western region crosses 38°C on the following day.

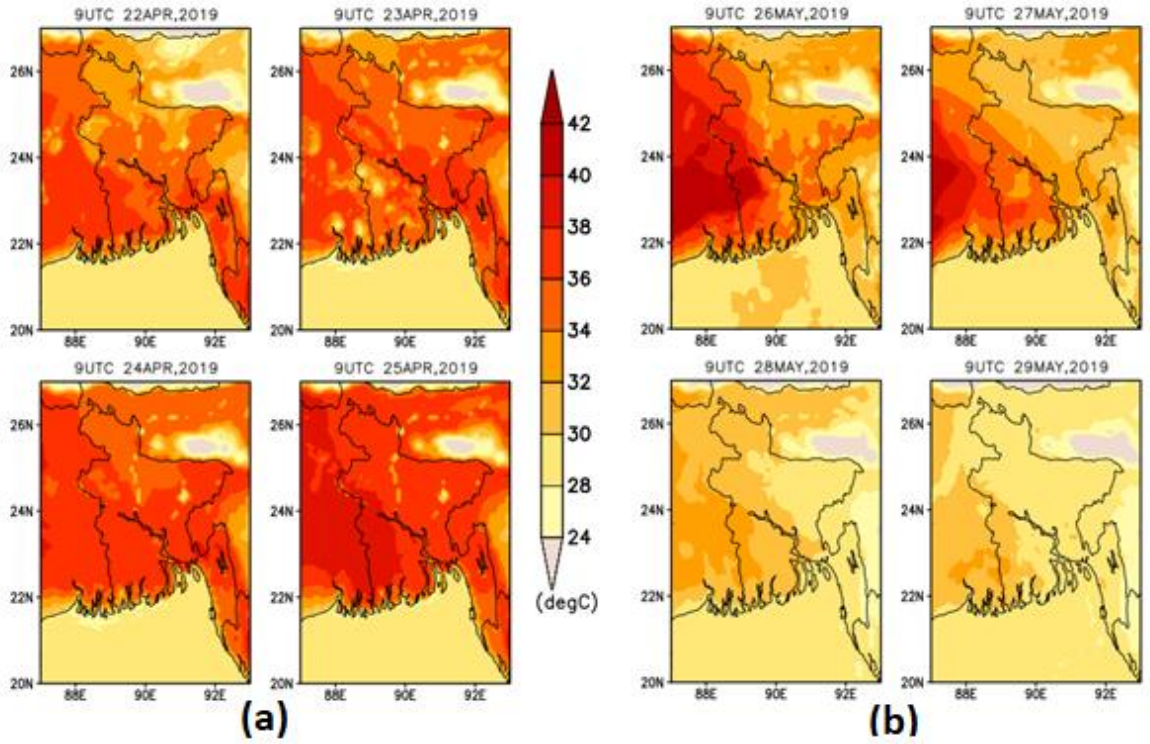

Figure 1: WRF model simulated temperature at 2-m height (a) for heat wave event 22-25 April, 2019 (b) for heat wave event 26-29 May, 2019

From the analysis of temperature at 2-meter height on 26th May, we observe that, severe heat wave was found to sweep over Jessore, Jhenaidah, Chuadanga and adjoining regions as the temperature simulated at 0900 UTC was above 40°C. Besides, temperature over parts of Rajshahi was 38°C and moderate heat wave swept over this region. The temperature elsewhere in the country was above 32°C. However, temperature was found to decrease on the northern and north-eastern parts from 27th May, and then gradually all over country from the next. No heat wave was found on these days, though there was record of heat waves.

In order to assess the performance of WRF model in simulating these two heat wave events, we compare the simulated temperature with temperature recorded by BMD at an interval of 3-hour. The comparative analysis for the heat wave event in April, 2019 as shown in figure 2(a-g) suggests that, model has nicely captured the signature trend that observed temperature followed, except for the station Chattogram. The simulated values are close to that of observed values, although an overestimation of peak values are noted. RMSE value for this event lie in the range (1-2)°C (figure 4) for stations other than Chattogram. On the other hand, from the figure 3(a-g), we observe that, for the heat wave event in May, 2019, WRF model has underestimated the temperature prominently from the third day. The RMSE value for the May heat wave is found to be greater than 3°C for all stations.

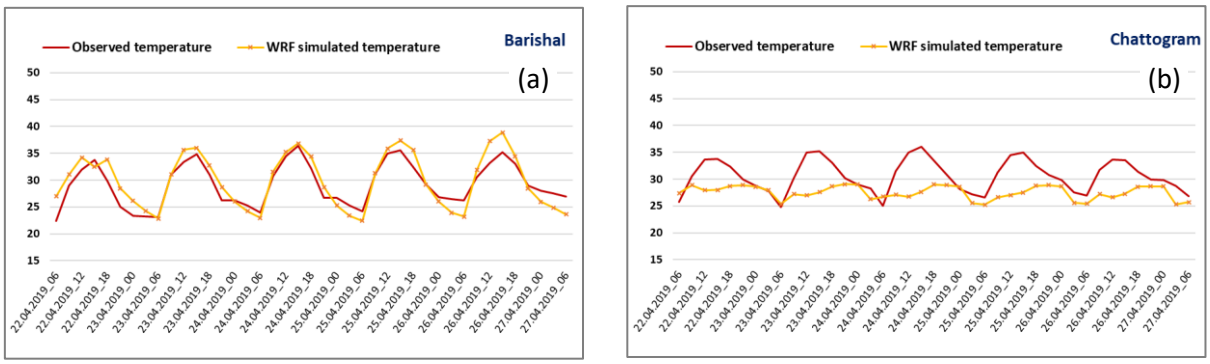

Figure 2(a-b): Division-wise comparison of WRF simulated temperature with observed temperature for 22-27 April, 2022 (a) Barishal and (b) Chattogram.

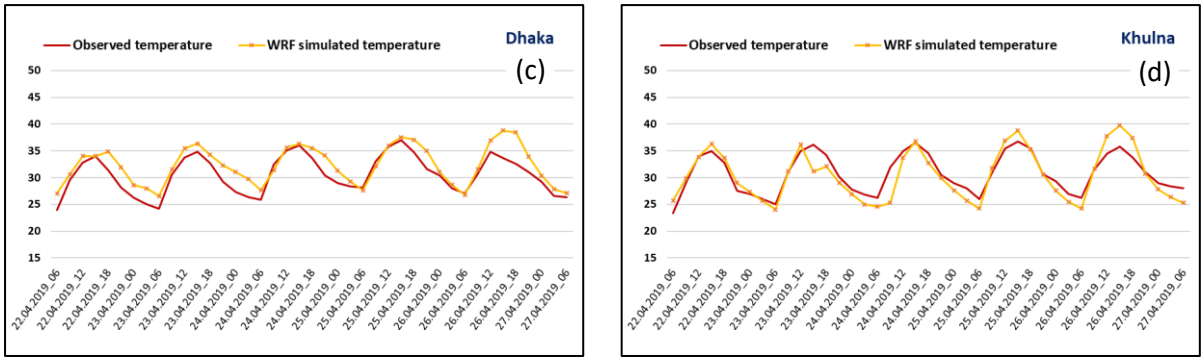

Figure 2(c-d): Division-wise comparison of WRF simulated temperature with observed temperature for 22-27 April, 2022 (c) Dhaka and (d) Khulna

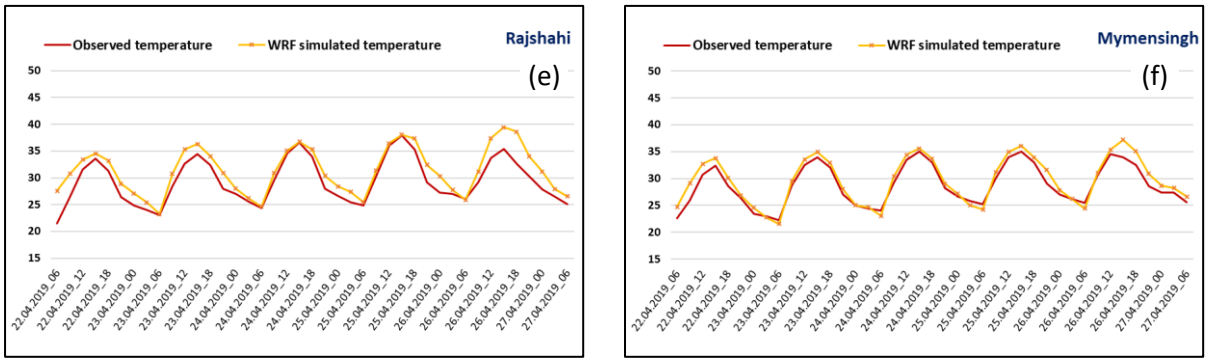

Figure 2(e-f): Division-wise comparison of WRF simulated temperature with observed temperature for 22-27 April, 2022 (e) Rajshahi and (f) Mynensingh

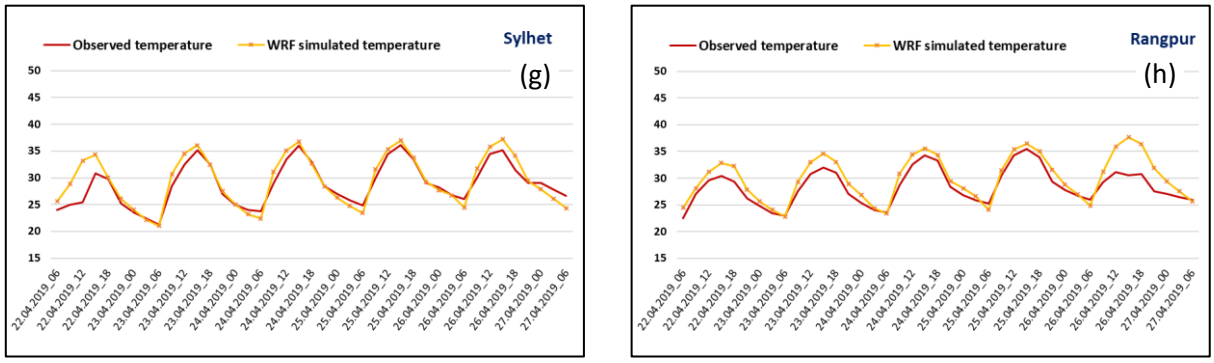

Figure 2(g-h): Division-wise comparison of WRF simulated temperature with observed temperature for 22-27 April, 2022 (g) Sylhet and (h) Rangpur

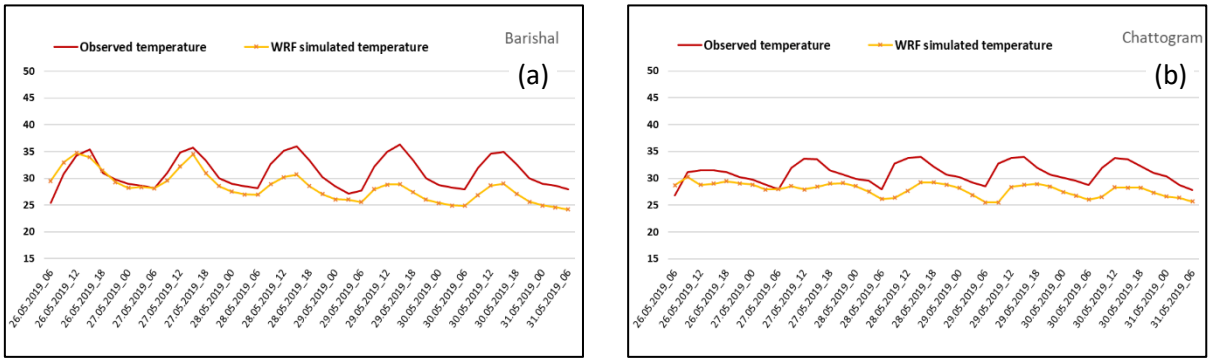

Figure 3(a-b): Division-wise comparison of WRF simulated temperature with observed temperature for 26-30 May, 2019 (a) Barishal and (b) Chattogram.

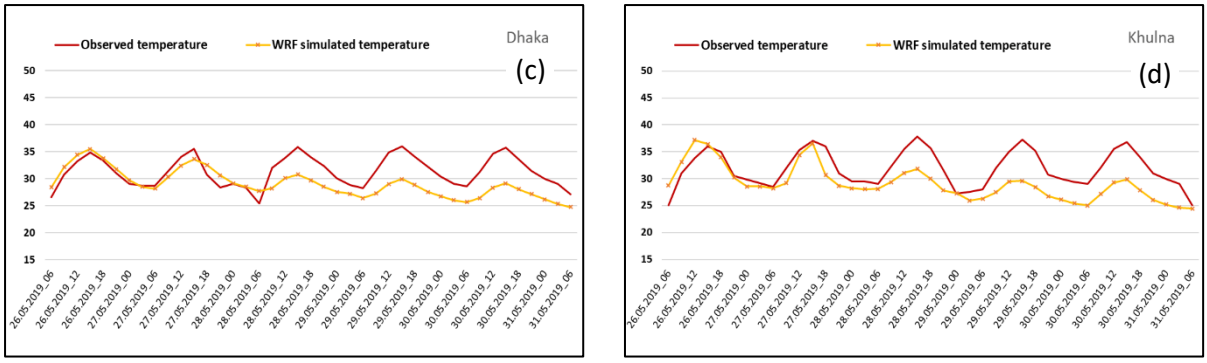

Figure 3(c-d): Division-wise comparison of WRF simulated temperature with observed temperature for 26-30 May, 2019 (c) Dhaka and (d) Khulna

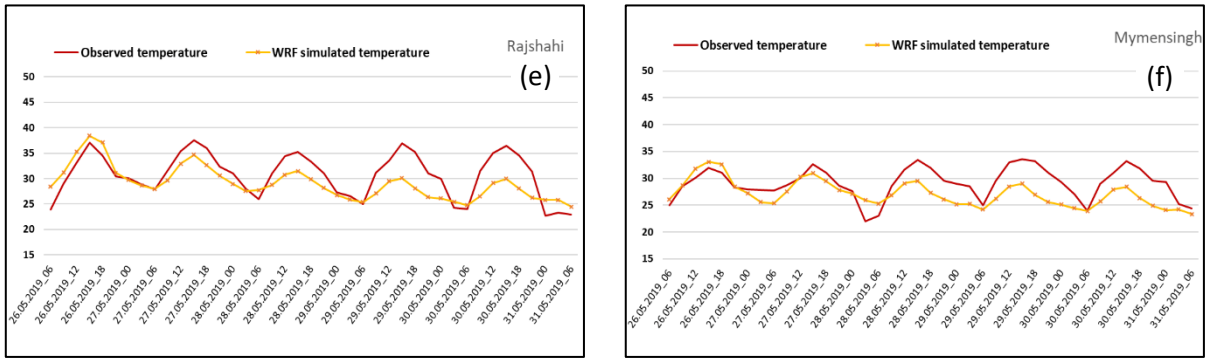

Figure 3(e-f): Division-wise comparison of WRF simulated temperature with observed temperature for 26-30 May, 2019 (e) Rajshahi and (f) Mynensingh

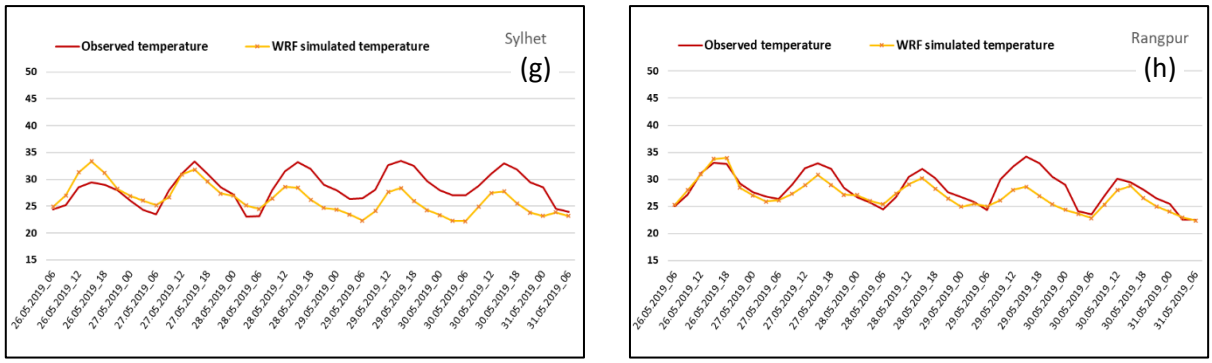

Figure 3(g-h): Division-wise comparison of WRF simulated temperature with observed temperature for 26-30 May, 2019 (g) Sylhet and (h) Rangpur

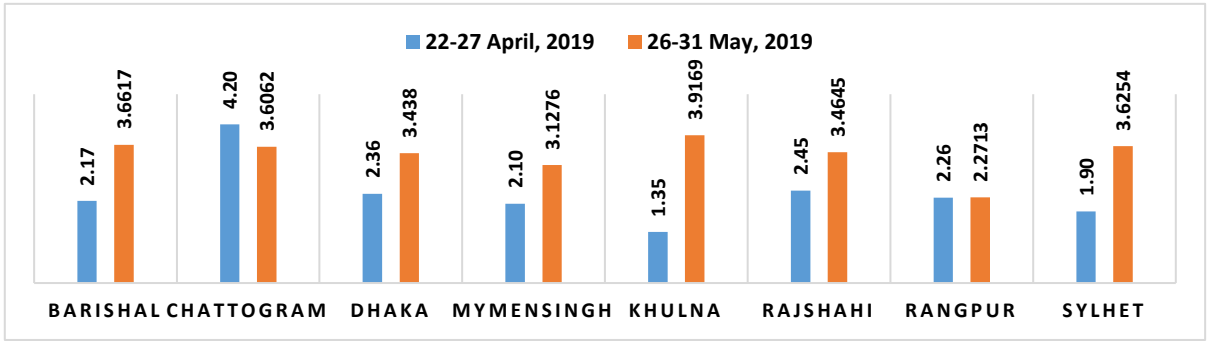

Figure 4: RMSE of observed and simulated temperature during two heat waves

Analysis of Relative Humidity & Wind Speed

Figure 5 illustrates model simulated relative humidity and wind speed for four days based on the initial condition of 0000 UTC of 22nd April, 2019. During 0900 UTC of 22-25 April, 2019, the relative humidity across the country

was found to lie in the range (30-50) %. On the right side, the model simulated values for the event 26-29 May, 2019 have been shown. On 26th May, the relative humidity was around (50-70) % across Bangladesh, except for the western region, where its value was (40-50) %. Owing to the moisture-laden air from Bay of Bengal, the relative humidity rose for the next three days and (70-90) % humidity was simulated. The wind pattern was westerly with a turning towards north over central region of the land.

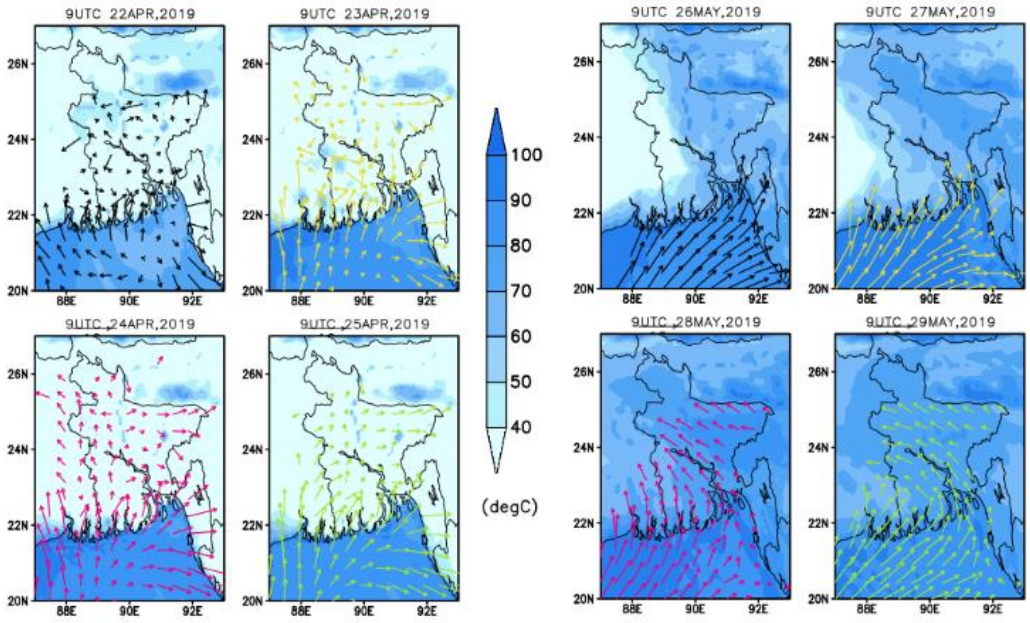

Figure 3: WRF simulated relative humidity and wind speed during 0900 UTC of 22-25 April, 2019 (left) and 26-29 May, 2019 (right)

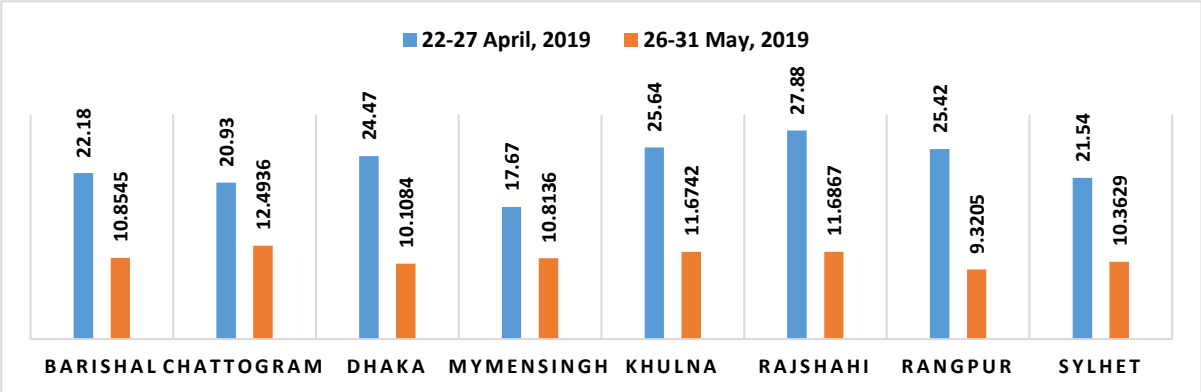

Figure 2: RMSE of observed and WRF simulated relative humidity during two heat wave events

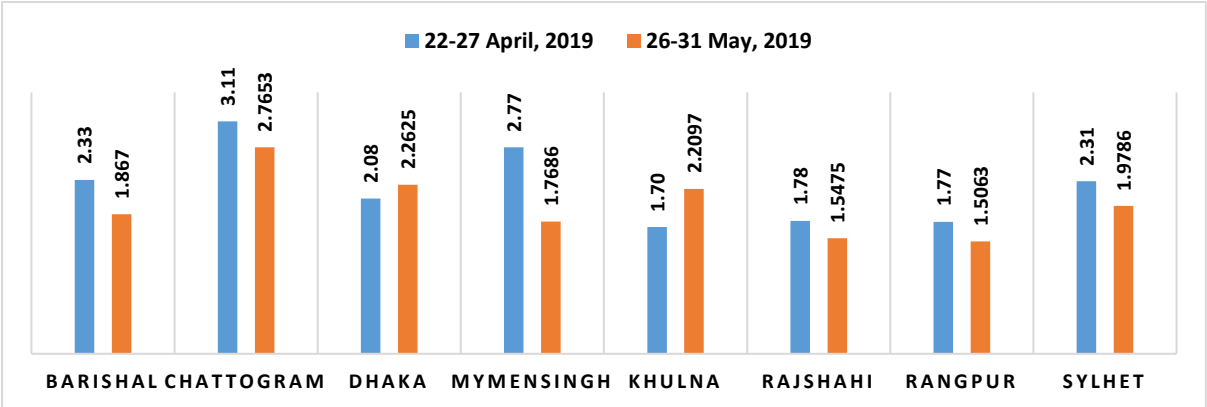

Figure 7: RMSE of observed and WRF simulated wind speed during two heat wave events

Coming to the validation of WRF simulated values, we note that, the RMSE for relative humidity during April heat wave event lies above 22 for most of the stations (figure 6). This error is highest for Rajshahi (RMSE=27.88) and lowest for Mymensingh (RMSE=17.67). In contrast, for May heat wave event, the RMSE score lies within 9-12, which is almost half of values of April heat wave during 2019. In terms of wind speed, the RMSE scores are close for both heat waves and for all stations.

Analysis of Surface Level Pressure

Model simulated results for surface level pressure for four days based on the initial condition of 0000 UTC of 22 April, 2019 are presented in the figure 8 (left). For all the four days, a zone of high pressure, ranging from 1008-1013 hPa was simulated to lie over north-eastern part of Sylhet division. During 0900 UTC of 22 April, the pressure across the country was simulated to be 1005-1006 hPa. During the same time of following days, relatively higher pressure (1007-1008 hPa) was found with less variation over the land. However, a high pressure zone (1009 hPa) was simulated over the Bay of Bengal.

Model simulated result for surface level pressure for six days at 0900 UTC based on the initial condition of 0000 UTC of 26 May, 2019 has been depicted in the picture 8 (right). During 0900 UTC of 26 May, a trough of low pressure (1001 hPa) was simulated by WRF that extended across Bangladesh except the southern and south-eastern regions. On 27 May, five isobaric lines were found to lie over the country with values ranging between 1001-1005 hPa. A gradual rise in pressure from 28 May is evident from the figure.

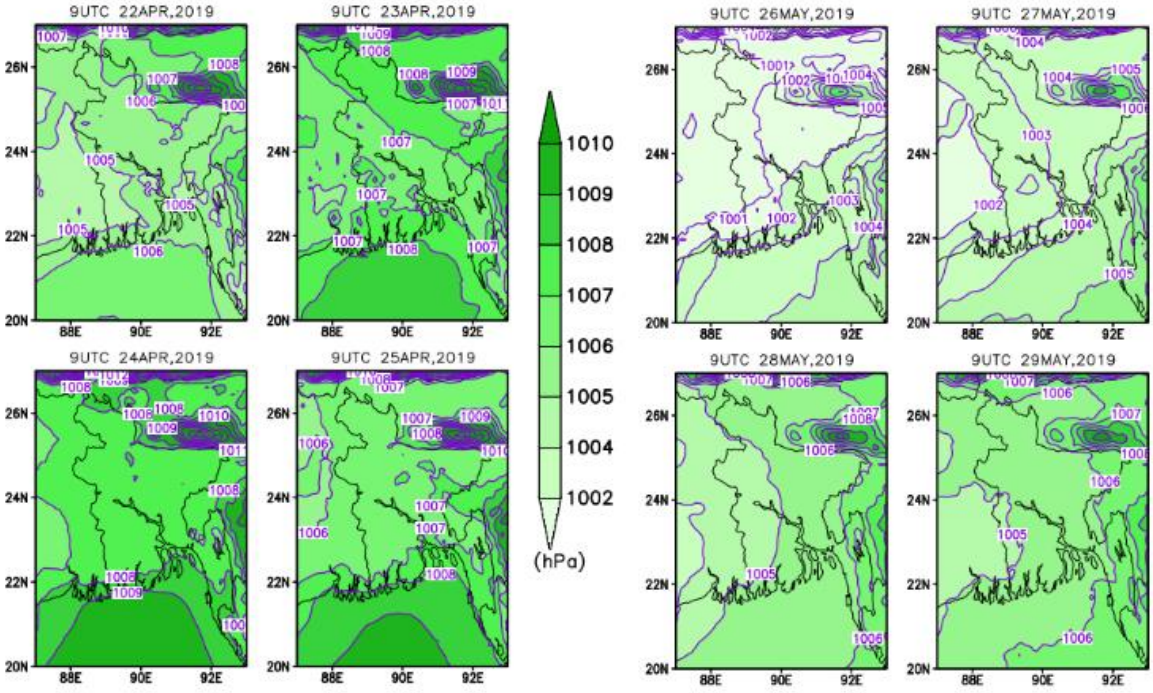

Figure 8: WRF simulated surface level pressure during 0900 UTC of 22-25 April, 2019 (left) and 26-29 May, 2019 (right)

Conclusion

This study investigates the performance of numerical weather prediction model, WRF in simulating two heat wave events. Analysis shows that WRF underestimates the temperature during May heat wave, while the overestimation of temperature is found during heat wave in April. The RMSE score of temperature for the April heat wave event is lower than that of May, however, both values indicate close simulation. Similar results have been found for wind speed simulation, with RMSE lying in (1-3). In addition, WRF simulated low pressure zone over West Bengal and adjoining western parts of Bangladesh which matches with the observed synoptic conditions. In terms of simulating relative humidity during these two heat waves, WRF model showed relatively poor performance with the current parameterization and schemes. For the future prospects, other parameterization schemes may be employed to simulate heat wave events.

References

[1] Alexander, Lisa Victoria et al. (2006). "Global observed changes in daily climate extremes of temperature and precipitation". In: Journal of Geophysical Research: Atmospheres 111.D5.

[2] Rahmstorf, Stefan and Dim Coumou (2011). “Increase of extreme events in a warming world”. In: Proceedings of the National Academy of Sciences 108.44, pp. 17905–17909.

[3] Stocker, Thomas (2014). Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge university press.

[4] Révész, A. (2008). Stochastic behaviour of heat waves and temperature in Hungary. *Appl Ecol Environ Res*, *6*(4), 85-100.

[5] Ceccherini, G., Russo, S., Ameztoy, I., Marchese, A. F., & Carmona-Moreno, C. (2017). Heat waves in Africa 1981–2015, observations and reanalysis. *Natural Hazards and Earth System Sciences*, *17*(1), 115-125.

[6] Tamrazian, A., LaDochy, S., Willis, J., & Patzert, W. C. (2008). Heat waves in Southern California: are they becoming more frequent and longer lasting? *Yearbook of the Association of Pacific Coast Geographers*, *70*(1), 59-69.

[7] Shahid, Shamsuddin et al. (2016). “Climate variability and changes in the major cities of Bangladesh: observations, possible impacts and adaptation”. In: Regional Environmental Change 16.2, pp. 459–471.

[8] Rajib, Mohammad Adnan et al. (2011). “Increase of heat index over Bangladesh: impact of climate change”. In: World Acad Sci Eng Technol 58, pp. 402–405.

[9] Rakib, Zubayed Bin (2013). “Extreme temperature climatology and evaluation of heat index in Bangladesh during 1981-2010”. In: J. Pres. Univ. B 2, pp. 84–95.

[10] Robine, Jean-Marie et al. (2008). “Death toll exceeded 70,000 in Europe during the summer of 2003”. In: Comptes rendus biologies 331.2, pp. 171–178.

[11] Wikipedia contributors. (2022, April 2). Economy of Bangladesh. In *Wikipedia*, *The Free Encyclopedia*. Retrieved, 10:30, April 6,2022, from https://en.wikipedia.org/w/index.php?title=Economy_of_Bangladesh&oldid=1080692298

[12] Ramamurthy, P., Li, D., & Bou-Zeid, E. (2017). High-resolution simulation of heatwave events in New York City. *Theoretical and applied climatology*, *128*(1), 89-102.

[13] Chen, F., Yang, X., & Zhu, W. (2014). WRF simulations of urban heat island under hot-weather synoptic conditions: The case study of Hangzhou City, China. *Atmospheric research*, *138*, 364-377.

[14] Wang, W., Bruyére, C., Duda, M., Dudhia, J., Gill, D., Kavulich, M., ... & Wolff, J. (2014). ARW Version 3 Modeling System User’s Guide January 2014. *National Center for Atmospheric Research, Boulder, CO, http://www2. mmm. ucar. edu/wrf/users/docs/user_guide_V3*, *5*.

[15] Karmakar, S. and Mohan Kumar Das (2020). “On the heat waves in Bangladesh, their trends and associated large scale tropospheric conditions”. In: Journal of Engineering Science 11.1, pp. 19–36.