


RESEARCH ARTICLE

Forecasting human heat stress: Insights from observations and WRF simulations during Bangladesh heatwaves

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Abstract

This study investigates the heatwave conditions in Bangladesh through the lens of thermal stress, and aims to facilitate the forecasting of thermal stress at lead times of 5–9 days using the weather prediction model, WRF. Here, the thermal stress is determined using the widely known bioclimatic index, PET (Physiologically Equivalent Temperature), and is calculated via the RayMan model. The first phase of the study involves a comprehensive analysis of observed thermal discomfort during seven major heatwave events, using data from eight divisional meteorological stations across the country. The findings reveal alarming levels of thermal strain nationwide. In the second phase, the WRF model has been used to simulate those heatwave events at 1-day lead time (D1), and its performance has been tested in predicting heat stress. The comparison of the model simulated values with the observed counterparts illustrated promising results in the employment of WRF model in predicting heat stress, particularly for the month of April. Finally, the same model configuration is used to forecast a heatwave event in April 2021 at extended lead times (D5-D9). Results indicate that the WRF model maintains commendable accuracy in simulating thermal stress even at longer forecast period.

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Introduction

Heatwave has emerged as a threat worldwide as a consequence of global warming. There has been a lot of changes in the climate mainly owing to anthropogenic reasons which is clearly demonstrated by the upward trend in mean surface air temperature over the last 100 years [1]. In their Fifth Assessment Report, the IPCC indicated a strong likelihood that heatwaves will become more frequent, last longer, and be more intense across most land areas as time goes on [2]. Bangladesh is no exception. The climatological analysis of the heat index (index defining combined effects of temperature and relative humidity) from 1961-2010 in Bangladesh has revealed

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Data availability statement: • GFS data obtained from National Centres for Environmental Prediction, National Weather Service, NOAA, U.S. Department of Commerce, 2015. NCEP GFS 0.25 Degree Global Forecast Grids Historical Archive (<http://www.ftp.ncep.noaa.gov/data/nccf/com/gfs/prod/>). • Observed data were collected from the Bangladesh Meteorological Department (bmd.gov.bd).

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significant augmentation of temperature in past 20 years [3]. Studying the pattern and variability of the frequencies of days with $T_{\max} \geq 36^{\circ}\text{C}$ across the country from 1991–2021, it has been found that the number of days with $T_{\max} \geq 36^{\circ}\text{C}$ have an increasing trend for seasonal and annual phenomena countrywide, except for very few places [4]. In another study, considering the maximum temperatures over Bangladesh during the period 1981–2016, the increasing trends of the seasonal and annual frequency of $T_{\max} \geq 38^{\circ}\text{C}$ are found to be statistically significant up to 95–99% level of significance [5]. The rise in temperature is the highest in the cities, such as Dhaka and Chattogram of Bangladesh owing to the influences of urban heat island (UHI) impacts [6], and urban regions are more exposed and vulnerable to heat compared to their surroundings [7–9].

Extreme heat proliferates the rate of mortality, with higher impacts among the elderly, children and men [10,11]. In fact, the probability of fatality due to heat-related issues during heatwave events is 146% [12]. More than 87% of all disaster casualties were due to thermogenic complications between 2000–2016 [13]. The severity of heatwaves topped during the 2003 European mega heatwave yielding fatalities of over 70000 people across Europe [14]. Heat impacts were reported for all-cause mortality, cardiovascular disease mortality, and infectious illness mortality in general. In the context of agriculture-dominated South Asian country, Bangladesh, heatwave is truly a matter of concern [15,16]. The urban population in Bangladesh is highly susceptible to climate change due to population density and limited capacity to adapt [17]. Heat related death was detected in all age categories, with substantial effects observed in the elderly above the age of 65 in Bangladesh [18]. However, there is a limited number of studies on the temperature-mortality relationship in South Asia, including Bangladesh, and the need for improved environmental and health monitoring in this region is emphasized [19]. Most of the studies are focused on the rising trend of mean annual temperature with a significant gap in policies and actions to address heat risk at spatial levels [20].

Heat related risk magnifies due to the lack of efficient adaptation strategies. The action plan for reducing heatwave impacts needs to focus on the complete assessment of outdoor thermal conditions. In this case, bioclimatic index serves as an excellent tool for quantifying thermal stress. Most importantly, the indices formulated using heat budget of human body provides better understanding of heat stress [21]. The Physiologically Equivalent Temperature (PET) is one such index which is broadly used for the assessment of thermal stress on human body [22]. The formulation of PET is based on Munich Energy-balance Model for Individual (MEMI) describing the thermal condition in a physiologically relevant way [23]. Moreover, PET encapsulates the effects of physiology and insulation as well as environment [24]. An array of activities in the field of applied climatology, such as urban and regional planning, tourism necessitate an assessment of the thermal component of various climates [25–29].

In this study, we exploit the features of PET to quantify the level of thermal strain across Bangladesh during the heatwave events in order to facilitate heat-stress-based forecasting system using WRF. The state-of-the-art software, WRF is used to simulate weather phenomena with records of simulating heatwave events in a

multitude of studies [30–34], including some case studies related to Bangladesh [35–39]. However, these studies focused primarily on investigating the associated features of heatwave through simulation. The novelty of this research is here we investigated the ability of WRF in predicting heat stress by simulating seven heatwave events at 1-day lead time. In addition, we attempted to predict the countrywide heat stress condition 5–9 days before the occurrence of heatwaves. In this era of changing climate with intense heatwave events, the findings of the study hold significant importance for Bangladesh, as these will aid in taking informed decisions for preparing for the upcoming heatwaves and thus mitigating losses.

Study area

The study leveraged data from eight meteorological stations located at the eight divisional cities of Bangladesh (Fig 1): Barishal (22.7°N, 90.4°E), Chattogram (22.7°N, 91.8°E), Dhaka (23.8°N, 90.4°E), Khulna (22.8°N, 89.5°E), Mymensingh (24.7°N, 90.4°E), Rajshahi (24.4°N, 88.7°E), Rangpur (25.7°N, 89.2°E) and Sylhet (24.9°N, 91.8°E), in order to provide a comprehensive understanding of heat stress across the country. Situated between 20°34′ and 26°38′ north latitude and 88°01′ and 92°41′ east longitude, Bangladesh experiences a tropical monsoon climate owing to surrounding geographic features. The mean temperature during summer season varies from 23 to 30°C, and the maximum temperature can reach up to 40°C in the north-western and south-western regions [40].

Data

In the Fig 2, climatological mean maximum temperatures for eight selected stations is shown, from where it can be seen that, April is the hottest month of the year, and the regions of Rajshahi, Khulna and Dhaka are warmer than other stations. In this study, we utilized daily maximum temperature (T_{max}) for characterizing heatwaves. Then particular focus was given on three weather variables, such as, temperature, relative humidity and wind speed for investigating heatwave conditions and heat stress. The aforementioned data were collected from Bangladesh Meteorological Department (BMD) which is a government organization for observing, collecting and monitoring weather data. We used data recorded at an interval of 3 hour for each of the selected heat wave episode from the BMD archive.

The initial and boundary condition to the WRF-ARW model integration, used for this study is the GFS (Global Forecasting System) data taken from the National Centre for Environmental Prediction (NCEP). The NCEP operational GFS analysis and forecasts are on a 0.25° × 0.25° global latitude-longitude grid and in the vertical, there are 127 layers. The GFS is run four times (00, 06, 12, 18 UTC) a day by US National Weather Service with a horizontal grid size of 18 miles (28 kilometers), and the analysis and projections, extending up to 16 days, are supported by the available temporal resolution [41,42]. It has been utilized for forecasting heatwaves and extreme temperatures in several studies conducted in Bangladesh and the neighboring country, India [34,35,38,43,44].

Selection of heatwave events

There is no widely accepted definition of heatwave [45,46]. Heatwave is defined based on the generic weather pattern of any particular region, clearly because what is extreme to the inhabitants of tropical zone is not for other areas. In this study, we used the definition set by Bangladesh Meteorological Department, where a ‘mild heatwave’ is considered when the maximum temperature crosses 36°C. It goes up a category every two degrees, marking ‘moderate’ and ‘severe’, and final one is ‘extreme heatwave’ when the temperature crosses 43°C. Analyzing the maximum temperature during the pre-monsoon of 2015–2019 using statistical software R, seven heatwave events have been selected for the study (Table 1).

Methodology

The study was structured into three main phases to assess thermal stress conditions across Bangladesh and evaluate the forecasting capability of the WRF model during heatwave events.

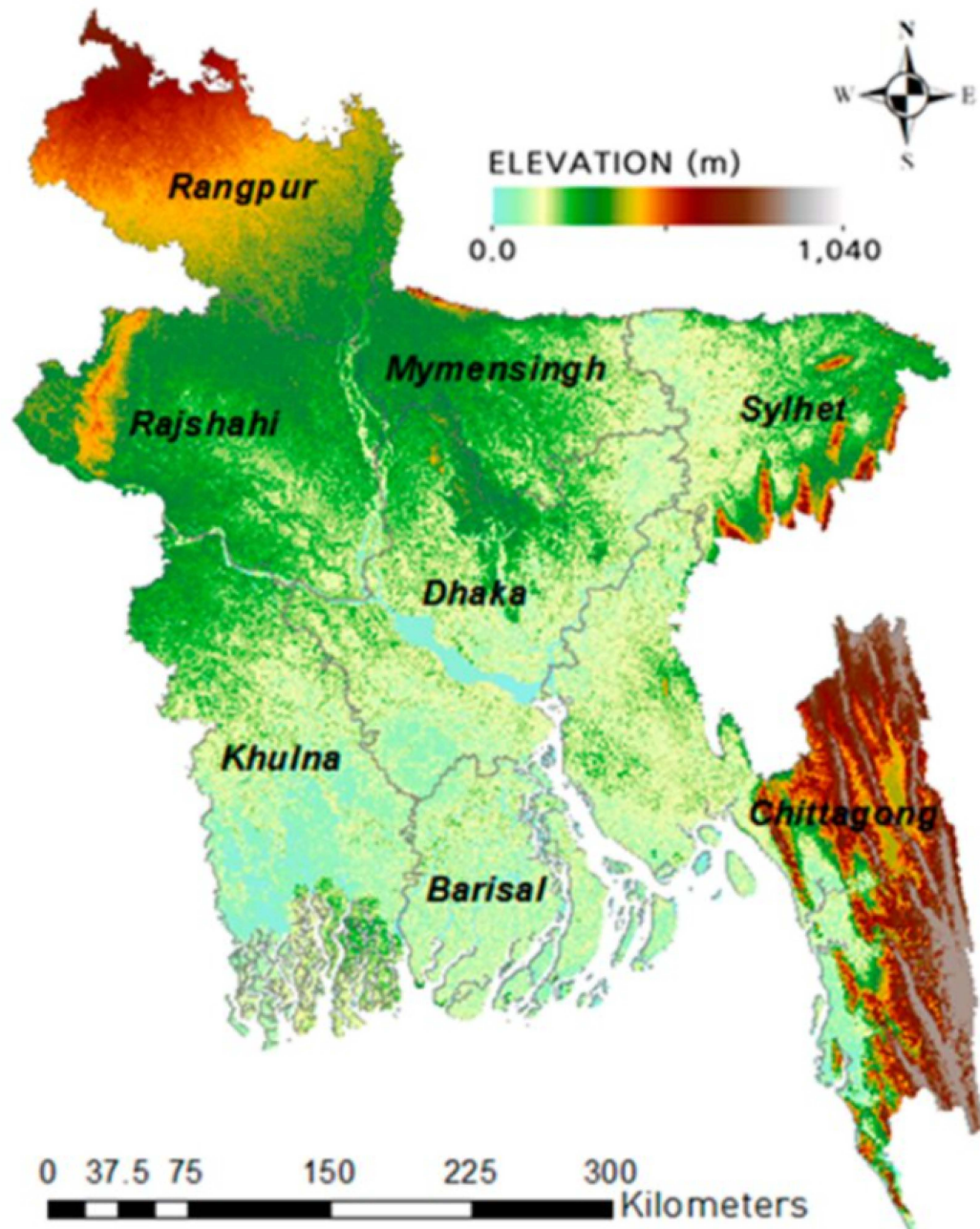


Fig 1. Study area (data source: <https://srtm.csi.cgiar.org>).

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The first phase involved analyzing human thermal stress across Bangladesh during seven major heatwave events from 2015 to 2019. Observational data, such as, air temperature, relative humidity, wind speed were collected from eight divisional weather stations. Using these values, Physiologically Equivalent Temperature (PET) was computed using the RayMan model. PET is a widely used bioclimatic index that is formulated using the heat budget equation of human body,

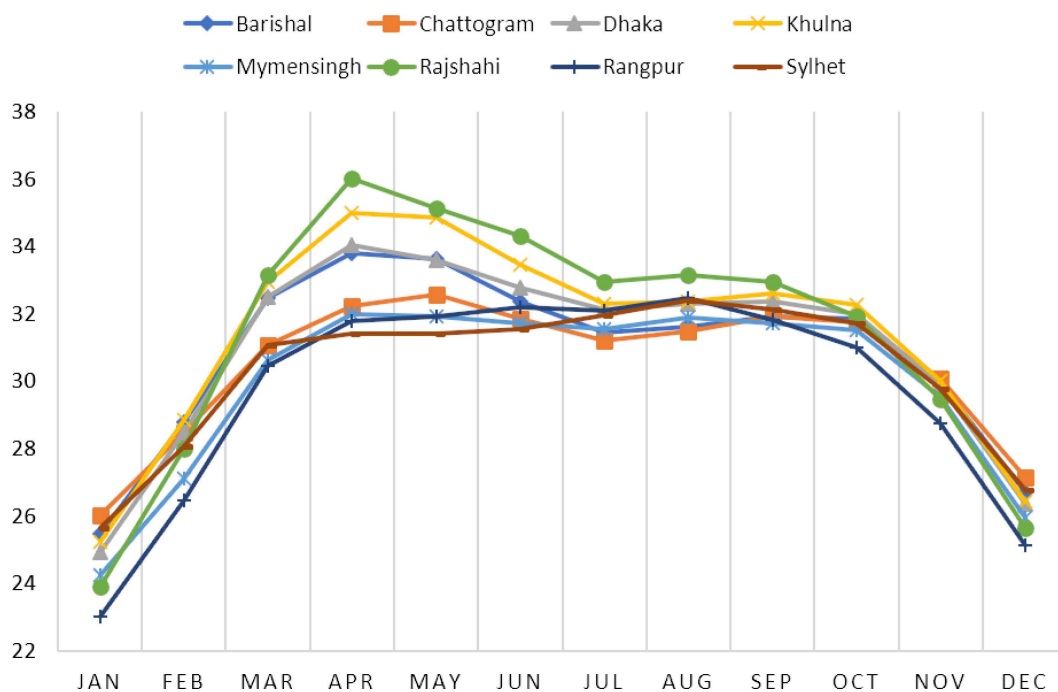


Fig 2. Climatological mean of maximum temperature for the selected stations from 1995 to 2024.

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Table 1. Heatwave events chosen for the current study.

Event	Initial date (0000 UTC)	Final date (0000 UTC)	Observed Maximum Temperature (°C)	Category
1	12.05.2015	19.05.2015	37.2-38.4	mild to moderate
2	20.05.2015	27.05.2015	37-39.8	mild to moderate
3	21.04.2016	28.04.2016	39.6-41	moderate to severe
4	19.05.2017	26.05.2017	36.8-38	mild
5	26.05.2017	02.06.2017	36.8-37.8	mild
6	22.04.2019	27.04.2019	37.6-38	mild to moderate
7	26.05.2019	02.06.2019	37.5-38	mild

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and it reflects the human thermal comfort, or stress level (Table 2). PET values were classified into standard thermal stress categories to characterize the spatial distribution of heat stress during the events [22,47,48].

In the second phase, the Advanced Research WRF (version 4.2.2) model was employed to predict the heatwave periods using a single domain at lead day 01 (D1) covering the entire country. The model was run with horizontal resolution of 10 km using the Mercator map projection. In the Table 3, the physical and dynamical schemes to configure the WRF model is presented. Simulated meteorological outputs were then used to derive PET values, which were then compared with observed PET data at the eight locations. The model’s performance was assessed using the statistical indicators, such as, Root Mean Square Error (RMSE) and Index of Agreement [49].

In the final phase, a case study was conducted on the April 2021 heatwave to evaluate the WRF model’s forecasting skill. Forecasts were generated with lead times of 5–9 days (D5-D9) prior to the heatwave days. PET values were

Table 2. Grade of thermal stress corresponding to PET values [22].

PET values (°C)	Grade of thermal stress
18-23	no stress
23-29	slight
29-35	moderate
35-41	strong
>41	extreme

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Table 3. WRF setup for the study.

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

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calculated from forecasted meteorological variables and compared against observed values for the same period. The analysis assessed the WRF model’s capacity in predicting heat stress at varying lead times.

Result

Analysis of countrywide thermal stress condition during heatwave events

This section presents a detailed analysis of Physiologically Equivalent Temperature (PET) values during seven heatwave events across eight divisional stations in Bangladesh, with the aid of box plots (Fig 3), and classification table (Table 2). PET, which reflects human thermal comfort or stress, is categorized into different stress levels ranging from ‘slight’ to ‘extreme’.

Barishal (South-central region)

Analyzing the PET values at Barishal, it is found that for both heatwaves during May, 2015, the recorded minimum value for PET was above 30°C, indicating ‘moderate heat stress’. The first quartile value around 35°C implies that ‘strong heat stress’ prevailed for three-fourth time of total duration, and third quartile value shows that people suffered from ‘extreme heat stress’ (>41°C) for 25% of total span of heatwave. A similar pattern is seen for other May heatwaves. On the other hand, for heatwave events in April (2016 & 2019), PET values lay within 26–39°C marking ‘moderate’ to ‘strong’ grade of heat stress over the 7 days of heatwaves. Maximum PET values for Barishal during heatwave events (1–7) are 43°C, 44°C, 39.3°C, 43.7°C, 44.8°C, 38.3°C and 41.3°C respectively, all of them within ‘extreme heat stress’ category.

Chattogram (South-East Region)

In Chattogram, the experienced level of thermal stress is relatively lower. During the selected seven heatwave events, 75% of the time the PET values fell in the ‘slight’ to ‘moderate’ range. The maximum values of PET for the events occurring in May stood around 40°C indicating ‘strong’ stress level, while April heatwaves (event 3 and 6) had lower maxima of 34.2°C and 37.3°C respectively.

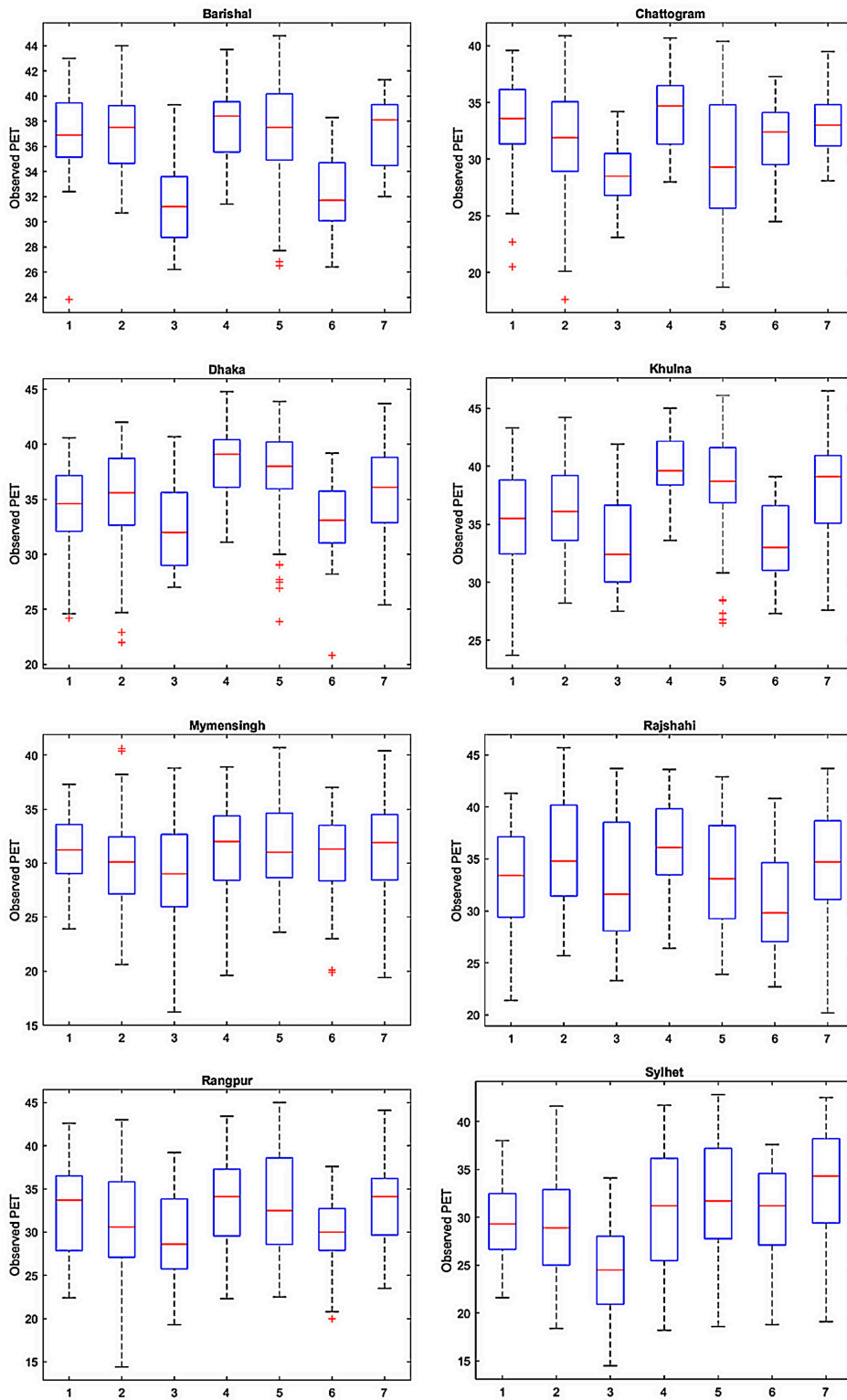


Fig 3. Boxplot of observed thermal stress condition.

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Dhaka (Central region)

Over Dhaka, 'moderate' to 'extreme' heat stress is found to prevail during the selected events. Among the seven events, the consecutive heat days during May, 2017 were the most dangerous, with PET values greater than 35°C prevailing most of the period, indicating 'strong heat stress'. The maximum value for PET reached to the height of 45°C with showing extreme stress for the 25% of the total period. Likewise, during the heatwaves in May of 2015 and 2019, the determined heat stress was quite alarming. For the heatwave occurrences in the month of April, during 2016 and 2019, moderate heat stress is obtained lying in the range 29–35°C.

Khulna (South-Western Region)

Heatwaves sweep repeatedly over the south-western region Khulna. For this station, maximum observed PET for these heat wave events are 43.3°C, 44.2°C, 41.9°C, 45°C, 46.1°C, 39.1°C and 46.5°C respectively, which are of life-threatening height. The most stressful event was heatwave of 19-26 May, 2017 as all the PET lied above 33.6°C and above 38.5°C for three-fourth of the time. Comparing with the heatwave episodes in May, the observed PET of 21-28 April, 2016 and 22-27 April, 2019 are lower, however, the ranges are 27.5-41.9°C and 27.3-39.1°C respectively, which indicate 'moderate' to 'strong' stress.

Mymensingh (North-Central Region)

Looking at the Mymensingh station, we find that the median value ranged between (29–32) °C and the maximum PET lied around 38°C, which is lower than the values of other stations. Interestingly, for this station, the level of heat stress is quite similar for both April and May events. Overall, the distribution of PET over Mymensingh indicates that, observed heat stress level was 'slight' to 'moderate'.

Rajshahi (Western Region)

Rajshahi showed a wide spread in PET distribution, suggesting varied levels of thermal stress. For instance, during the heatwave 21-28 April, 2016, the first and third quartile values are 28.1°C and 38.5°C respectively, indicating 'slight', 'moderate' and 'strong' stress. In general, the level of heat stress according to PET is 'moderate' to 'strong' in this area for most of the time. Additionally, the maximum PET for all seven events crossed the threshold of 41°C which marks 'extreme heat stress'.

Rangpur (North-Western Region)

Rangpur recorded 'moderate' to 'strong' stress levels, with median PET values of 33.7°C, 30.6°C, 28.6°C, 34.1°C, 32.5°C, 30°C and 34.1°C across the events. Maximum values of PET ranging between (39–45) °C, highlighting significant level of thermal discomfort during peak periods.

Sylhet (North-Eastern Region)

Over Sylhet, the observed thermal stress is found to be 'slight' to 'moderate', but an increase in stress is noted since 2017. Among the seven events, the most severe was the heatwave of 26 May-02 June, 2019, when the median, third quartile and maximum observed PET were recorded as 34.3°C, 38.2°C and 42.5°C respectively marking 'moderate' to 'extreme' stress for half of the time.

Performance evaluation of WRF model in simulating heatwaves

Using the model setup illustrated in the methodology section, all the seven heatwave events were simulated using WRF at lead day 01. Simulated temperature, relative humidity, wind speed values were obtained for all the events at an interval

of 3 hours, and were used to calculate the PET values. The performance of WRF in simulating heatwaves is evaluated using RMSE (root-mean-square error) and Willmott's index of agreement [49]. In Table 4, the performance of WRF model in forecasting temperature has been shown. Overall, the simulation showed reasonable agreement with the observed counterparts. Lower RMSE values are generally seen in April events indicating better performance of WRF during pre-monsoon heatwaves, while higher RMSE values appear in later May suggesting more variability in model performance as the season progressed to monsoon.

The performance metric values (d) for all the seven events are illustrated in spider diagram in the Fig 4. For station Barishal, two highest values of d are 0.85 and 0.75 for two heatwave events occurred in the month of April in 2016 and 2019 respectively. Similar pattern is noted for the other stations, for example: Dhaka (0.88 for both), Khulna (0.84 & 0.75), Mymensingh (0.86 for both), Rajshahi (0.93 & 0.91), Rangpur (0.87 & 0.89) and Sylhet (0.84 & 0.78) except for Chattogram (0.42 & 0.36). Overall, the skill of WRF in simulating heat stress is maximum for Rajshahi. The model performances for Mymensingh and Rangpur stations are sufficiently good, and for Dhaka, Khulna, Rangpur and Sylhet, model performed moderately ($d > 0.5$) for most of the cases.

Forecasting heat stress at extended lead times (Lead days D5-D9): A case study

As outlined in the methodology section, WRF model has been utilized to make predictions for the heatwave swept over the country during 24-29 April, 2021. For the domain covering the whole country, model forecasts were made at an interval of 3 hours. At 0900 UTC (1500 Bangladesh Standard Time) which typically corresponds to the daily maximum temperature, the spatial distribution of WRF simulated temperatures for lead times day 9 (D9) to day 5 (D5) are presented in Figs 5–9. These plots clearly show widespread heatwave conditions, with highest temperature surpassing 42°C in the north-western region. Notably, even at a 9-day lead time, WRF successfully indicated the onset of heatwave conditions across the region (Fig 5). The subsequent lead times depicted the intensifying extent of the event.

To evaluate the capability of WRF in predicting thermal stress during this heatwave, PET values computed from observed and simulated meteorological data were compared. While PET values derived from simulated data at D9 tend to be lower than observed values, the overall spatial and temporal pattern of heat stress is well captured by the model, with the exception of Chattogram, where deviations are more noticeable (Fig 10). Finally, Fig 11 illustrates the index of agreement between observed and simulated PET values across all lead times. The highest agreement is observed in Rajshahi, a region frequently affected by extreme heat. Additionally, the agreement index reaches 0.8 or higher for Dhaka, Khulna, Mymensingh, Rangpur, and Sylhet, indicating very good model performance. The predictive accuracy improves consistently as the forecast lead time approaches the actual event, reinforcing the potential of the WRF model for early warning and preparedness in heat-health risk management.

Table 4. RMSE of observed and WRF simulated temperature during selected heatwave events.

Event	Barishal	Chattogram	Dhaka	Khulna	Mymensingh	Rajshahi	Rangpur	Sylhet
12-19 May, 2015	2.47	2.97	2.86	2.24	2.61	3.32	3.08	2.57
20-27 May, 2015	4.12	3.31	4.05	4.67	2.80	4.95	3.29	2.19
21-28 April, 2016	1.35	3.06	2.08	2.37	2.17	2.47	2.02	2.14
19-26 May, 2017	4.70	4.81	4.80	5.08	3.72	4.28	3.83	3.54
26 May- 2 June, 2017	4.04	3.02	3.89	4.54	4.85	5.54	5.77	3.61
22-27 April, 2019	2.17	4.20	2.36	2.10	1.35	2.45	2.26	1.90
26 May- 2 June, 2019	3.97	3.73	3.46	4.26	2.86	3.56	2.34	3.30

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Fig 4. Performance metric values for observed PET and WRF forecasted PET for selected heatwave events.

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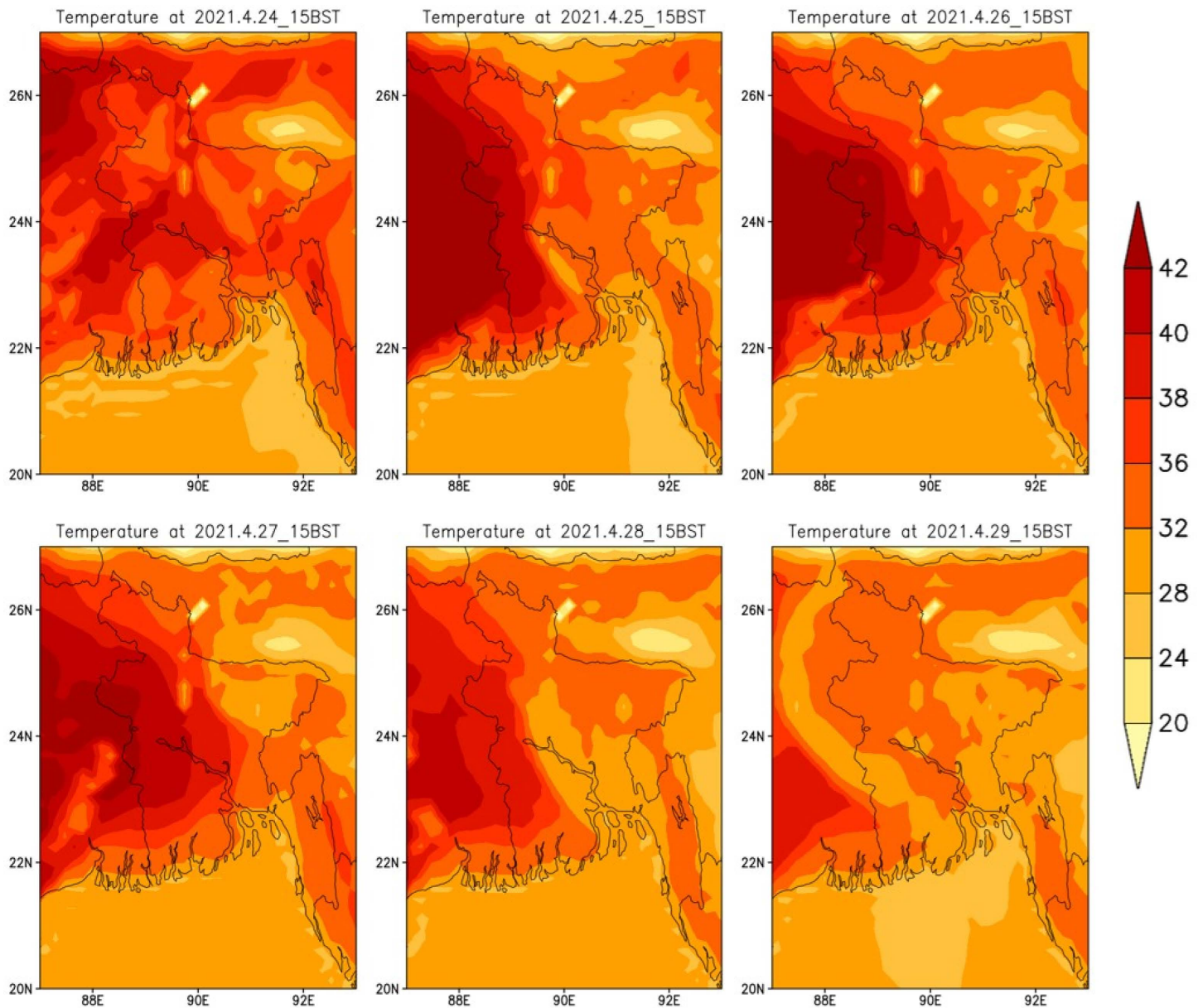


Fig 5. WRF simulated temperature at 0900 UTC (1500 BST) during 24-29 April, 2021 at D9.

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Discussion & conclusion

The elementary purpose of this research is to determine bioclimatic stress for eight divisional stations and develop real time weather forecasting of heat stress during pre-monsoon which can help the public sector and the people to reduce and minimize the repetitive losses of their properties and lives. The use of the Weather Research and Forecasting (WRF) model in simulating heatwave conditions is well-established in the scientific community. Notably, the European mega-heatwave of 2003 and the Russian heatwave event of 2010 have been extensively investigated using WRF. A total of

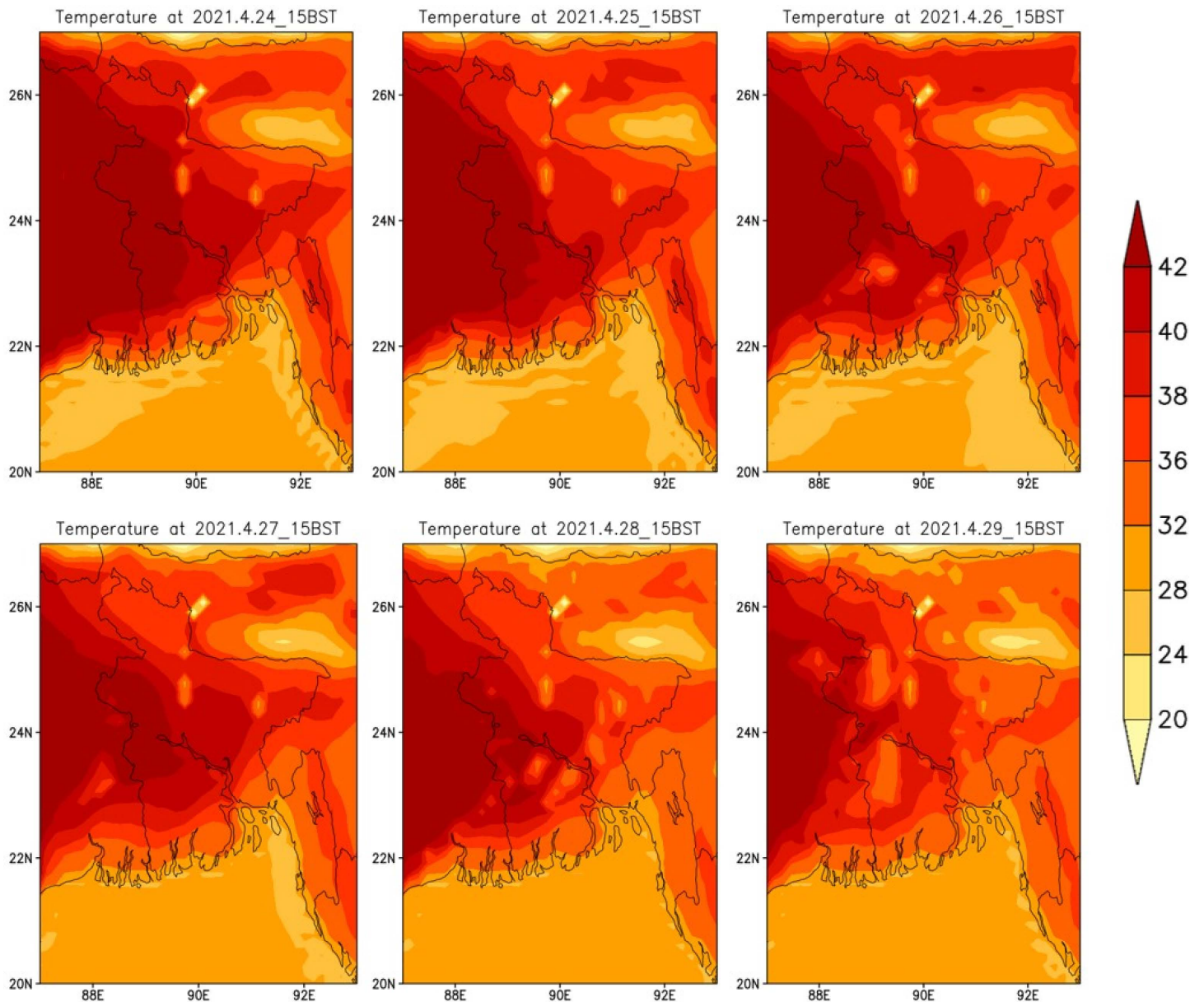


Fig 6. WRF simulated temperature at 0900 UTC (1500 BST) during 24-29 April, 2021 at D8.

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216 simulations were performed, employing various atmospheric physics schemes in conjunction with the NOAH land surface model in order to identify the most suitable combinations of parameterization schemes for accurately representing heatwave events in the European region [32]. Studies of comparable scale and rigor are largely absent for tropical regions such as India and Bangladesh. In a related study, researchers simulated episodic heatwave events that occurred over India during 2015 and 2016 using nested domains covering northwestern and southeastern parts of the country, and applied six different atmospheric parameterization schemes. The WRF model, in this case, demonstrated an uncertainty of approximately $\pm 2^{\circ}\text{C}$ in simulating maximum temperatures across both regions [34]. Another study investigating the 2015

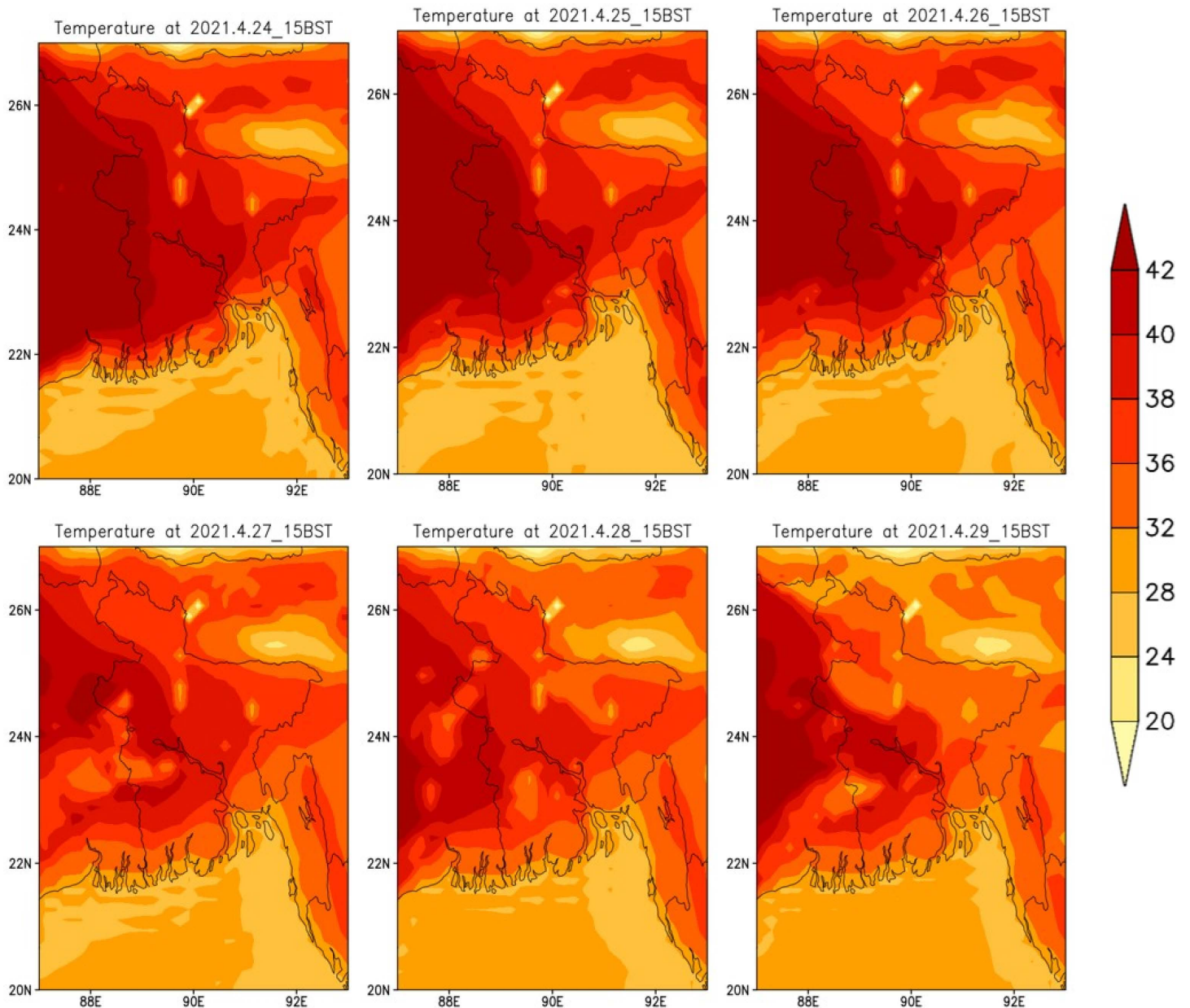


Fig 7. WRF simulated temperature at 0900 UTC (1500 BST) during 24-29 April, 2021 at D7.

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episodic heatwave event over the southeastern coast of India reported that short-range weather forecasts using the WRF model at a 3 km resolution and up to 72-hour lead times yielded root mean square error (RMSE) values ranging from 1.47 to 2.24 and with an index of agreement around 0.9 [50]. The analysis of numerically simulated extreme temperatures over the state of Odisha for the period 24–27 May 2015 demonstrated that the model effectively captured both the intensity and spatial pattern of extreme temperatures and heatwave conditions across various regions, including the western and central parts of Odisha. The RMSE for station-scale simulations of extreme temperature varied between 1.07 and 2.82, which corresponds to approximately 2.5% of the maximum observed temperature [51]. Furthermore, a detailed investigation of

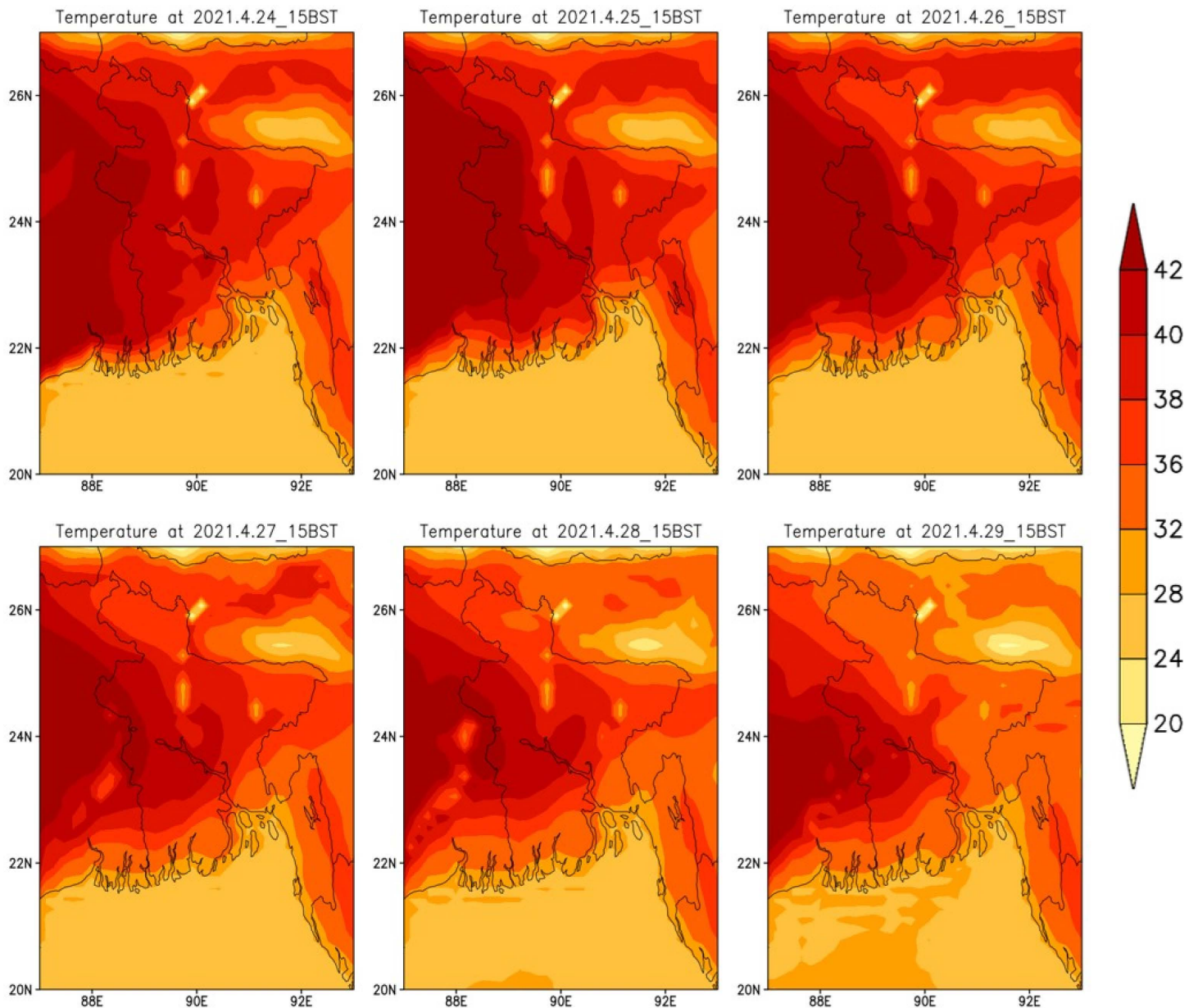


Fig 8. WRF simulated temperature at 0900 UTC (1500 BST) during 24–29 April, 2021 at D6.

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the heatwave over Andhra Pradesh and Telangana during 21–24 May 2013 was also conducted using WRF at 3 km resolution with lead times of 24, 48, and 72 hours, demonstrating good agreement with observed data and an RMSE of 2.24 at a three-day lead time [33]. Shahadat et al. simulated two heatwave events from 2015 over Bangladesh using seven different combinations of planetary boundary layer (PBL), surface layer, and land surface schemes within the WRF modeling framework. Among these, the YSU–MM5 scheme combined with the NOAH land surface model yielded the most accurate results [52]. In another study, 17 heatwave events occurring throughout the year between 2010 and 2020 were simulated using WRF, with the model outputs demonstrating good agreement with observed data [39]. Additional studies focusing

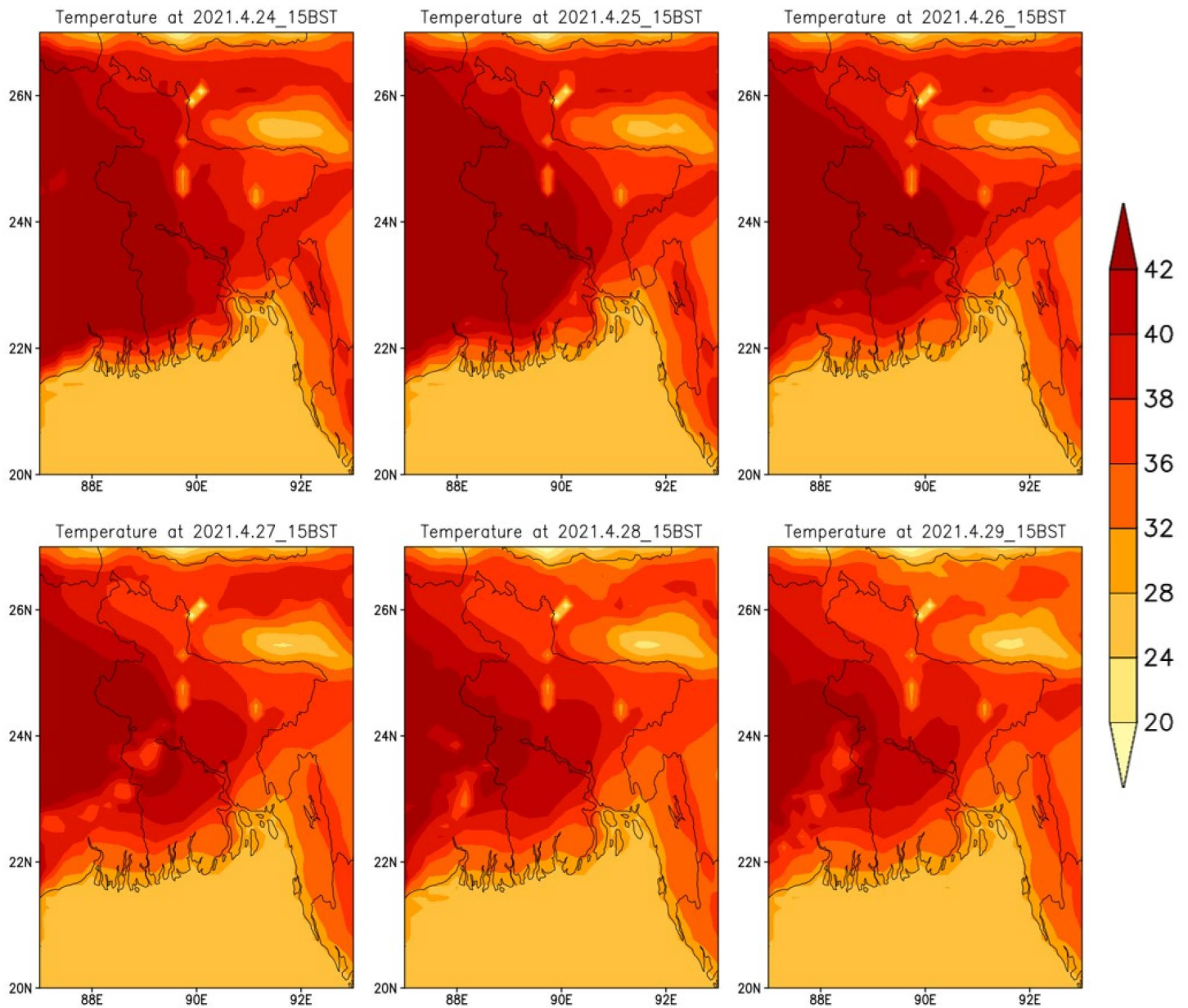


Fig 9. WRF simulated temperature at 0900 UTC (1500 BST) during 24-29 April, 2021 at D5.

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on individual heatwave events have also reported satisfactory performance of WRF in capturing heatwave characteristics over Bangladesh [35,37,38]. While previous research has mostly used simulations to understand what happens during heatwaves, this study breaks new ground by checking how well the WRF model can actually predict heat stress one day in advance for seven different heatwave events.

The comprehensive analysis of physiological stress value determined by PET for seven selected heatwave events reflects a morbid situation registering ‘moderate’ to ‘strong’ heat stress for the stations of Dhaka, Rajshahi and Khulna. Interestingly, the maximum PET of 46°C was recorded in Khulna instead of urbane Dhaka. For Barishal and Rangpur, the

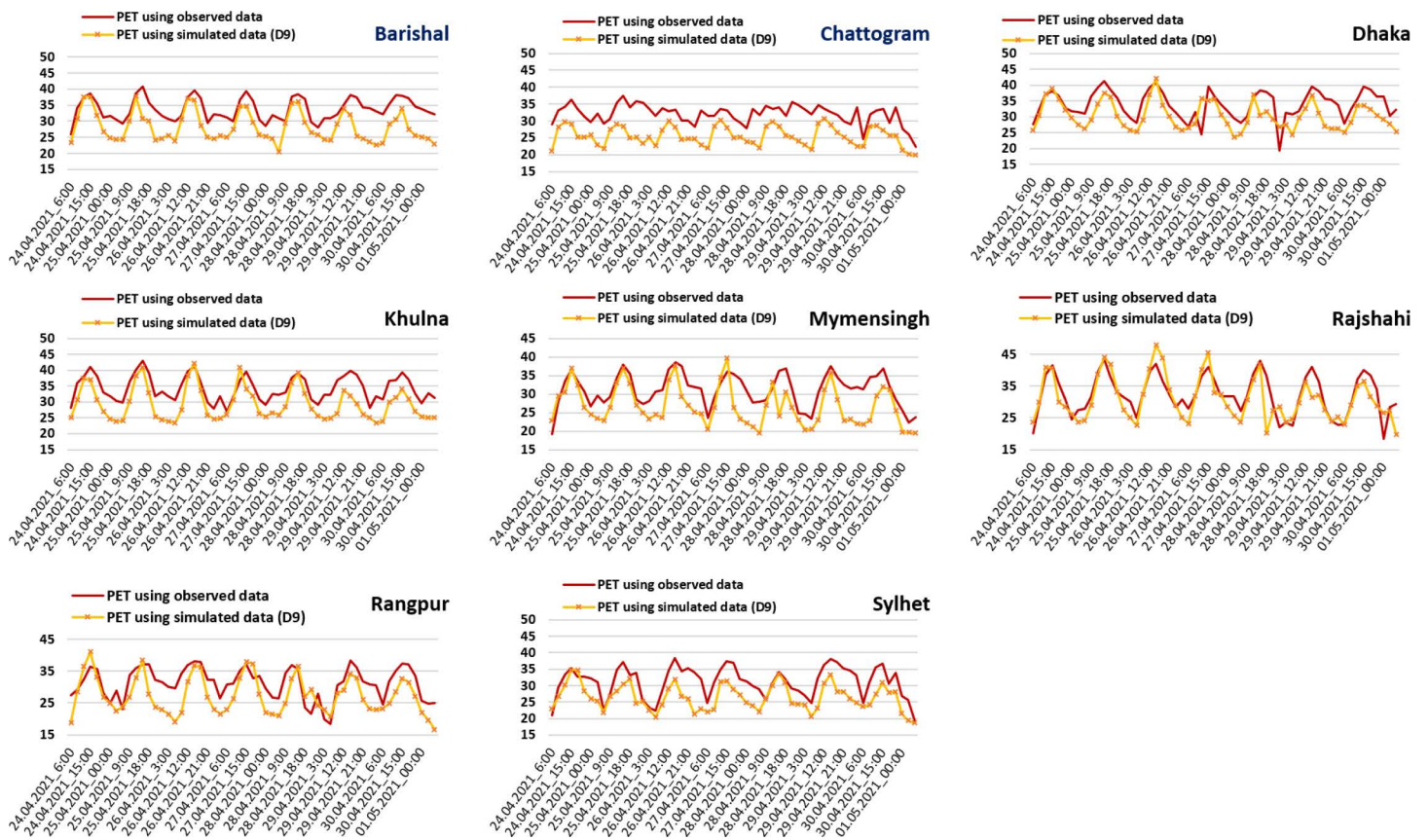


Fig 10. Comparison of observed PET and PET using WRF forecasted day at D9.

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level of heat stress is also quite alarming. However, for Mymensingh, Sylhet and Chattogram, the observed level of heat stress was slight to moderate. While this study primarily focuses on the use of PET to evaluate thermal stress conditions during heatwave events, it does not examine the underlying dynamical drivers such as atmospheric subsidence, radiative forcing, or blocking patterns. These factors may contribute significantly to heatwave development and persistence and may influence both PET variability and model biases. However, the current scope is limited to the assessment of PET behavior and its relevance to early warning and forecasting applications. Future research will aim to integrate atmospheric dynamical analyses to provide a more comprehensive understanding of the mechanisms influencing PET peaks and to improve model interpretation. Additionally, while this study demonstrates the usefulness of Physiologically Equivalent Temperature (PET) as an indicator of human thermal discomfort, we acknowledge a key limitation: the absence of health outcome data—such as heat-related illnesses, hospitalizations, or mortality—which restricts direct quantitative linkage between modeled thermal stress and public health impacts. As presented in [Table 2](#), the associated thermal stress levels corresponding to different PET values may serve as a basis for issuing public warnings. However, relying solely on maximum temperature may overlook the cumulative impact of atmospheric conditions, which PET captures more holistically. Future research should aim to integrate health metrics, including hospital admission and mortality records, to establish empirically derived PET thresholds that more accurately reflect population vulnerability and thereby enhance early warning systems and climate-health policy design.

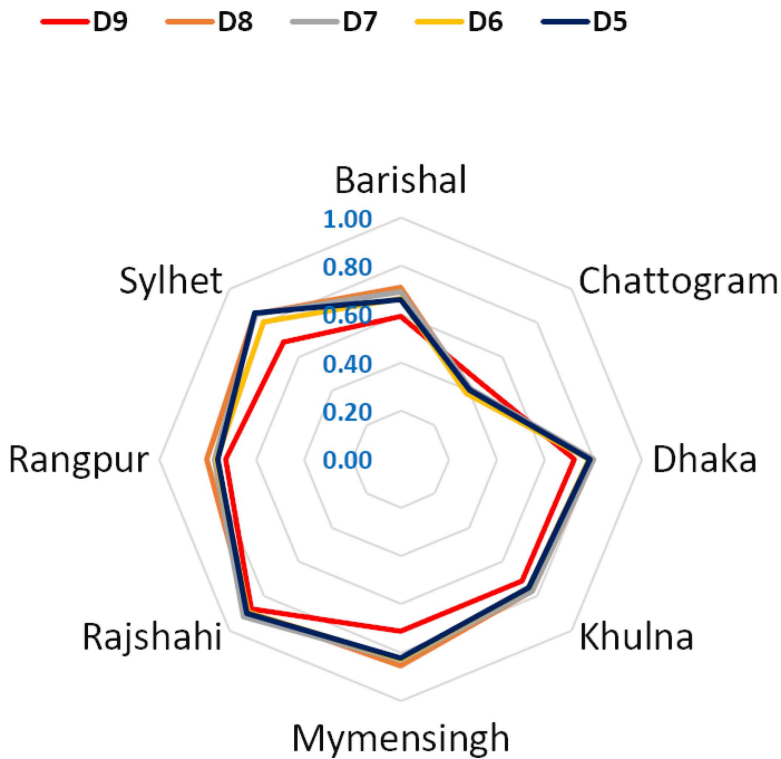


Fig 11. Performance metric (d) values for observed PET versus PET using WRF forecasted data at different lead times.

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Turning to the point of simulating heat stress for the purpose of prediction, we divided the work into two phases. Firstly, we simulated seven heatwave events from 2015–2019 using WRF to obtain the predictions one day earlier (D1). The comparative analysis of observed and WRF simulated PET indicated the potentiality of forecasting of PET using model derived data. Model performed sufficiently good for all the stations, except for Chattogram. The 10 km horizontal resolution used in this study may be inadequate for capturing finer-scale mesoscale features, particularly in coastal regions where land-sea interactions significantly influence local temperature dynamics. Additionally, this resolution may not adequately resolve urban-scale heterogeneity and land-use variations, leading to reduced forecast skill over densely populated urban areas, particularly at longer lead times. This limitation is especially relevant for urban stations where localized effects such as heat retention and urban canopy influences are not explicitly modeled. To enhance regional forecast accuracy, future studies should consider employing nested WRF domains with finer spatial resolution and explore alternative parameterization schemes to better represent local atmospheric processes. Among the simulations of selected heatwave events, the WRF model demonstrated comparatively better performance in capturing heatwave conditions in April, than in May. However, additional case analyses are required to substantiate this observation. In the following step, we targeted to extend our forecasting window to a lead time of day 9 to day 5 (D9–D5) choosing a heatwave event in April. The results obtained corroborated the result from the preceding section, and showed good agreement for the stations. While the findings from this single event are not generalizable, we believe this case study provides useful foundation for future research in long-lead forecasting of PET. In order to meet the demand of time, there is an increasing concern relating to heatwave studies in Bangladesh. The findings of this study provide critical insights into region-specific thermal stress levels during heatwave events in Bangladesh, based on PET values. These results can directly support government planning and climate adaptation efforts by identifying high-risk regions, vulnerable populations, and periods of extreme thermal discomfort. By

integrating PET-based heat stress assessments into early warning systems, disaster preparedness strategies, and public health advisories, local authorities can take proactive measures—such as issuing targeted heat alerts, enhancing access to cooling centers, adjusting work schedules for outdoor laborers, and planning emergency healthcare responses.

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