Appraising the Historical and Projected Spatiotemporal Changes in Heat Index in Bangladesh

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Abstract

Climate change-derived extreme heat phenomena are one of the major concerns across the globe, including Bangladesh. The appraisal of ongoing spatiotemporal changes and possible future change in heat index (HI) is essential for developing heat stress mitigation strategies. However, the climate-health nexus is scarcely studied in Bangladesh. This study was intended to appraise historical and projected changes in HI across Bangladesh. The HI was computed from daily dry bulb temperature and relative humidity. The modified Mann-Kendal (MMK) test and linear regression were used to detect trends in HI for the observed period (1985–2015). The future change in HI was projected for the mid-century (2041–2070) for three Representative Concentration Pathway (RCP) as 2.6, 4.5, and 8.5 scenarios. The results revealed a monotonic rise in the HI and extreme caution conditions, especially in the humid summer season for most parts of Bangladesh for the observed period (1985–2015). Future projections of HI revealed a continuous rise in HI in the forthcoming period (2041–2070). A higher increase in HI was projected in the northern, western, and south-central regions, while a decrease in the northwestern region in the future. Bangladesh should take region-specific adaptation strategies to mitigate the impacts of HI.

1. Introduction

Climate change-derived heat extremes have become a matter of global concern with the rapid rise in temperature (Rajib et al. 2011; Rakib 2013; Ballester et al. 2016; Nissan et al. 2017; Rahman et al. 2019a). The climate influences public health mainly through temperature extremes. Though cold extremes are more fatal compared to heat extremes (Dixon et al., 2005), a gradual rise in earth temperature due to climate change has made heat extremes the major concern to public health throughout the globe (Field et al. 2014). According to UNISDR (2018) nearly 166 000 people died between 1998 and 2017 due to heat extremes. Global Change (2018) report estimated nearly 9300 deaths per year by 2090 due to temperature extremes. The rising temperature would cause a gradual decrease in cold extreme-related fatalities and an increase in heat extreme related health consequences. Therefore, the majority of public health implications in the near future would be due to heat extremes. Considering severe consequences of heat extremes, a large number of studies have been conducted to assess extreme heat effects on different human health aspects in recent decades (Monteiro et al. 2013; McGregor et al. 2015; Ballester et al. 2016; Pal and Eltahir 2016; Modarres et al. 2018).

Temperature-based indices are generally used to appraise human exposure to extreme heat. Heat exposure is defined as a negative function of temperature, relative humidity, solar radiation, and wind speed that human experiences (Blazejczyk et al. 2012; Nguyen and Dockery 2016). Whereas the heat index (HI) is commonly known as the apparent temperature experienced by the human body. Therefore, HI is generally used to measure human exposure to extreme heat. However, the measures of HI vary according to the local climate and vulnerability of the population. Therefore, a large number of heat indices have been developed to assess human exposure to extreme heat (de Freitas and Grigorieva, 2014). According to Modarres et al. (2018), out of 170 climate indices that have been developed to evaluate various climatic conditions so far, over 100 indices are designed to assess the nexus between meteorological parameters and heat index.

The human capability to adapt to heat is directly related to dry bulb temperature and humidity (Raymond et al., 2017). Therefore, HI based on both temperature and humidity, is most widely accepted to assess human

exposure to extreme heat (Brouillet and Joussaume, 2019). The human temperature comfort decreases with the increase of temperature and relative humidity, and vice-versa. It is also related to the evaporative cooling of the human body or physical homeostasis (Kjellstrom et al., 2009; Buzan et al., 2015). High temperature and humidity together cause human discomfort, which may lead to heatstroke. Sweating is an essential body mechanism by which the human body can transport away the metabolic heat. At a higher dry bulb temperature and relative humidity, the human body's heat exchange process is ceased, which results in accumulating excessive temperature in the human body (Budd 2008) and accelerates the rate of morbidity and mortality (Basu and Samet 2002). Therefore, HI estimated based on both dry bulb temperature and relative humidity is most widely accepted to evaluate heat extremes.

Though heat extreme related casualties are increasing globally, the rate of increasing health consequences is much higher in developing countries, mainly densely populated countries, due to higher exposure. South Asia is one of the most vulnerable regions in terms of public health exposure to temperature rise (Singh. 2016). Climate models projected more frequent and intense heat extremes in the region than many other regions of the globe (UN ESCAP 2015; Im et al. 2017). Bangladesh is located in South Asia, is enormously susceptible to global climate change (Huq 2001; Rahman and Islam 2019; Salam and Islam 2020). The country has experienced some recent heat extreme occurrences, which caused high mortality, especially the death of males and people older than 65 years (Burkart et al. 2014). Heat extreme related mortality rate has been reported to increase by 20% over the past decade in Bangladesh (Nissan et al., 2017). Climate change is anticipated to increase the frequency and intensity of heat exposure in the forthcoming period (Kirtman et al. 2013). Battisti and Naylor (2009) reported an increase in heat extremes in tropical and subtropical regions in the future. Future forecasts of climate change scenarios in Bangladesh demonstrated a higher occurrence of extreme heat in the future (Nissan et al. 2020). Nissan et al. (2017) reported the minimum heat exposure of consecutive three days might exceed up to ten days in Bangladesh.

Although many researchers have investigated the changes and variabilities of Bangladesh's climate at the regional and country levels (Islam et al. 2019, 2020; Salam et al., 2020), the climate-health relationship is hardly studied in Bangladesh (Rahman et al. 2019a; Nissan et al., 2020). The previous studies were mostly focused on assessment of heat index anomaly (Rajib et al. 2011), variation of extreme temperature utilizing heat index (Rakib 2013), trends in heat extreme in southwest Bangladesh (Rakib 2018), effects of heat extreme in Bangladesh (Burkart et al. 2014), mortality due to high temperature (Burkart et al. 2011), and prediction of heat waves (Nissan et al. 2017). No attempt has been taken to quantify the spatiotemporal change of historical (observed) and projected HI in different climatic regions of Bangladesh. This study intends to fill this research gap through the quantification of the spatiotemporal changes of HI in Bangladesh due to climate change. The information generated in this study can be used adaptation planning and reduction of climate change impacts on disease and death, particularly the large number of marginally poor people involved in agriculture and construction and exposed to heat extremes in the country (McGregor et al. 2015; Havenith and Fiala 2016).

2. Materials And Methods

2.1 Study area

Bangladesh, a low-lying subtropical South Asian country, has an area of 147,570 km² (Rahman and Islam 2019). Three dominant seasons are prevailing in Bangladesh, Pre-monsoon hot summer (March to May), monsoon humid summer (June to August), and post-monsoon dry winter (December to February) seasons. The annual mean rainfall is approximately 2,400 mm, of which over 75% observes in the humid summer (monsoon) season from June to September.

Long-term daily mean relative humidity, minimum temperature, maximum temperature, and evapotranspiration across Bangladesh are 80%, 21.39°C, 29.94°C, and 3.72 mm d⁻¹, respectively (Salam and Islam, 2020). January is the coldest, and April to October are the hot months in Bangladesh.

Banglapedia (2014) demarcated Bangladesh into seven climatic sub-regions based on climate, land use patterns, and hydrogeologic settings (Fig. 1). There is spatial variability in climate in Bangladesh (Ghose et al. 2021). The western zone of the country is relative drier compared to other areas (Islam et al. 2017).

2.2 Data description

Bangladesh Meteorological Department (BMD) operates only 43 weather stations throughout the country. Weather stations across the country are not uniformly distributed. They are mostly concentrated in the south-eastern and south-central regions. Many of the stations are set up after the 1990s and, therefore, do not have a long-term record (www.bmd.gov.bd). Due to these shortcomings of long-term data availability, only 20 weather stations were selected for the estimation of HI over the period 1985–2015. These selected stations encompass the seven climatic sub-regions of the country. The period between 1985 and 2015 is regarded as the warmest period on record (IPCC 2019). The rising rate of global average surface temperature reached 0.87°C during 1985–2013 relative to 1850–1900 (IPCC 2014). For that reason, the daily climate dataset for the period 1985–2015 was used as the period.

Daily dry-bulb temperature (T) (°C) and mean relative humidity (R) (%) data of 20 stations were acquired from the BMD. The missing data at all the stations were found less than 5%. The missing data were filled using the past data of the respective days or the data from the neighbouring stations after consulting with the expert of BMD. The BMD follows the World Meteorological Organization (WMO) guideline for weather dataset acquisition and record archiving. Nonetheless, a homogeneity test and autocorrelation of the dataset were performed to reveal any anomaly in the dataset (Islam et al. 2020). All of the datasets were passed the quality control test conducted by BMD staff.

Twenty-six ocean-atmospheric variables of National Centers of Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) with grid resolution 2.5°×2.5° were obtained for downscaling GCM simulated Temperature and relative humidity at the station locations using Statistical Downscaling Model (SDSM) (<http://co-public.lboro.ac.uk/cocwd/SDSM/>). Historical simulation and future projections of Canadian Earth System Model Second Generation (CanESM2) for three Representative Concentration Pathway (RCP) scenarios, e.g., very low emission (RCP 2.6), medium emission (RCP 4.5), and a very high emission (RCP 8.5), with grid resolution of 2.8125°×2.8125° were downloaded from the link (<http://climate-scenarios.canada.ca/?page=pred-canesm2>). The CanESM2 model is a fully coupled earth system model which can represent intra-seasonal climate variability over south Asia sufficiently well. This model can generate a reasonable outcome in temperature extreme projection worldwide (Arora et al. 2011; Yengoh and Ando 2020). Therefore, the CanESM2

model has been used heat extreme projection in different studies conducted worldwide (Wang and Zhang 2019; Chaveillez et al. 2019; Yengoh and Ando 2020).

The NCEP/NCAR dataset was interpolated to the grid resolution of CanESM2 model. The NCEP variables were used as input and station temperature or relative humidity as output to develop the downscaling model. The downscaling model was subsequently used for projection of temperature and relative humidity for different RCP scenarios using GCM simulated variables as input.

2.3 Estimation of Heat Index

The HI is computed from relative humidity (%) and temperature (°F) using Eq. (1).

$$HI = C_1 + C_2T + C_3R + C_4TR + C_5T^2 + C_6R^2 + C_7T^2R + C_8TR^2 + C_9T^2R^2 \dots \dots \dots 1$$

Where, HI denotes heat index (in degrees Fahrenheit); T indicates ambient dry-bulb temperature (in degree Fahrenheit); R means relative humidity (percentage value between 0 and 100); and $C_1 = -42.379$; $C_2 = 2.04901523$; $C_3 = 10.14333127$; $C_4 = -0.22475541$; $C_5 = -6.83783 \times 10^{-3}$; $C_6 = -5.481717 \times 10^{-2}$; $C_7 = 1.22874 \times 10^{-3}$; $C_8 = 8.5282 \times 10^{-4}$; $C_9 = -1.99 \times 10^{-6}$

HI, used in this study, integrates bulb temperature and humidity and provides an estimate of health exposure (HE) to heat extreme (Anderson et al. 2013; Modarres et al. 2018). The HI was demarcated into four classes, e.g., caution (80–90°F), extreme caution (90–105°F), danger (105–130°F) and extreme danger (> 130°F) (Belding, 1970; Modarres et al. 2018). The HI for the historical period, 1985–2015 was estimated from observed data, while it was estimated for the future period using GCM projected data for the period 2041–2070.

To assess the trends in HI, the non-parametric Modified Mann Kendall (MMK) test was employed (Mann 1945, Kendall 1975, Islam et al. 2020, Praveen et al. 2020). Theil-Sen's slope estimation was also used to identify the magnitude of the change (Sen, 1968, Islam et al. 2019; Zinat et al. 2020). Besides, a simple linear regression method was applied to monitor the monotonic changes in observed HI in this study.

SDSM (Wilby and Dawson 2004) was used to downscale GCM simulations at the station locations. The SDSM tool, downloaded from the link <http://www.sds.org.uk>, was used in this study. In SDSM, multiple linear regression is used to create a heuristical association between regional predictors (i.e., relative humidity) and local meteorological observations (i.e., temperature). The observational datasets were divided into two portions: 70% for calibration (1985–2005) and 30% for the validation (2006–2015) of the downscaling model. Figure S1 illustrates the key steps used in this SDSM. The input of the downscaling model was selected through screening of 26 NCEP variables based on their association with the output. The coefficient of determination (R^2) was used for this purpose.

3. Results

3.1 Spatiotemporal changes of historical and projected HI

Figures 2 and 3 show the temporal changes of HI between hot summer and humid summer, respectively, in the

2 demonstrates that northern, western, south-central,

south-eastern regions, the HI value will be ranged from $88^{\circ} - 92^{\circ} F$, indicating the extreme caution HI. In the north-east, the HI value would range from $83^{\circ} - 85^{\circ} F$ that indicates caution HI. In the southwestern region, projected HI would slightly decrease than historical HI. On the contrary, in the northwestern region, HI would be considerably declined ($80^{\circ} - 84^{\circ} F$) compared to the historical ($85^{\circ} - 88^{\circ} F$) period during the hot summer (March-May). Except for the south-western region (extreme caution HI), the rest of the regions showed caution HI for the historical period as the HI less than $90^{\circ} F$. Figure 3 shows that HI would increase in the northern, northeastern and southcentral regions during humid summer (June – August). The rest of the regions would experience less HI than historical HI. Like the hot summer, the northwestern region would experience considerable declination of HI compared to historical HI. For both the hot and humid summer, the projected scenarios' ascending order in terms of increasing HI is $RCP8.5 > RCP4.5 > RCP2.6$.

The long-term station-wise mean annual variations of HI for hot summer and humid summer are shown in supplementary Figure of S2. Both hot summer and humid summer showed nearly the same projected HI for RCP 2.6, RCP 4.5 and RCP 8.5. The projected scenarios of RCP2.6, RCP 4.5, and RCP 8.5 for HI are higher than the historical HI in all the stations except for Bogra, Faridpur, and Chittagong stations for hot summer (Figure S2a) and Bogra, Khepupara, Satkhira, and Cox's Bazar stations for humid summer (Figure S2b). It is shown in Figure S2 that Bangladesh would be faced higher HI in humid summer compared to hot summer in the future.

The probability density function (PDF) was used to investigate the mean annual historical and projected HI's probabilistic behaviour. The PDFs of the HI for the seven climatic zones of Bangladesh predicted the potentially significant changes (Fig. 4). Rightward shifting of the shape is a sign of the future-increasing trend of mean annual HI. The future-expanding pattern in HI in different zones can be ranked in decreasing order of Zone B (North-eastern), Zone C (Northern), Zone G (South-central), and Zone E (South-eastern), Zone A (Western), Zone F (South-western). Among these zones, Zone D (North-western) showed a remarkable decreasing rate of HI value for the future.

The spatial changes of HI during the historical (1985–2015) and projected period (2041–2070) for three scenarios are presented in Fig. 5. The results show that the HI values in the northern zone would increase from $81-84^{\circ}F$ to $85-86^{\circ}F$ compared to the historical (observed) HI, which means the temperature and relative humidity of the northern zone are increasing. The HI of southwestern, southcentral, and western zones also showed an increase. Surprisingly, the HI values would decrease in a few stations like Bogra, Chittagong, and Faridpur.

Figure 6 demonstrates that most regions of Bangladesh, exposed to cautious conditions ($80 < HI < 90^{\circ}F$) in the historical period, would experience a cautious condition of HI ($80 < HI < 90^{\circ}F$) in the projected period during the hot summer season. The western part of south eastern, south central and south western regions would experience more than $92^{\circ}F$ but less than $94^{\circ}F$ HI (extreme caution) for all the scenarios during the hot summer season. Like the temporal distribution, spatial distribution also depicted that humid summer would expose to higher HI than that for hot summer (Fig. 6). In the humid summer season of June, July, August month, most parts of Bangladesh exposed to extreme caution conditions $HI > 90-105^{\circ}F$ during the historical period. Unlike the historical period (HI ranged from $89-92^{\circ}F$), north eastern region would experience higher HI ($92-94^{\circ}F$) during projected periods for all scenarios. On the contrary, south eastern part of south eastern (A zone) region would expose to the same level of HI as the historical period. The most of Bangladesh that experiences extreme

condition historically would also experience extreme condition in future (94–96°F and 96–98°F) during humid summer.

The trend of HI and the rate of change of HI for the historical period of 1985–2015 are shown in Fig. 7. The figure demonstrates that HI has increased significantly ($p > 0.01, 0.05, 0.1$) in most part of the country except (insignificant decreasing trend) some part in the southwest of zone F (south western region), and northern and north eastern parts of zone G (south central region) (Fig. 7a). Northern and south eastern regions experienced the most significant ($p > 0.01$, MMK Z value ranged from 6–7) increasing trend of HI compared to other regions (Fig. 7a). The rate of change in HI was from -0.01 – 0.03 °F per decade (Fig. 7b). The same results for detecting country-wise trend were found using the linear regression model (Figure S3).

4. Discussions

Present study investigated the changes in seasonal and spatial HI for historical and projected periods across Bangladesh. This study represents a crucial step to quantify temporal and spatial changes of heat index over Bangladesh under three different future climate change scenarios. Most of the earlier works have done in Bangladesh based on the seasonal maximum temperature (T_{max}) and minimum temperature (T_{min}) change, the temporal pattern of extreme temperature condition, heatwave, etc. (Rakib 2013; Fahad et al. 2018; Khan et al. 2019; Nissan et al. 2020). Although Fahad et al. (2018) used a statistical downscaling model to project exposure to rising Temperature in Bangladesh. They found northern Bangladesh will be more affected due to heat extremes. The present study also found that the northern region would be more vulnerable to HI during the hot summer season due to an increase in temperature and precipitation (high rate of precipitation accelerates the percentage of relative humidity in the air), which is consistent with the results of this study. Rajib et al. (2011) showed increases in HI in the southwest and northwest regions in Bangladesh from 1961–2010. This study reported increasing HI in northern (contrary to Rajib et al. 2011) and southern regions (consisted with Rajib et al. 2011) of the country during the observational period (1985–2015).

The shift to the right in the PDFs suggests that the onset of an increasing trend in HI mean and an extreme and rare heatwave in the future (Modarres et al. 2018). This study revealed that the North-eastern and Northern regions have the highest probability of increasing heat index while North-western might experience a decreasing rate of heat index in the future period. The reason for the increasing heat index is that unfavourable climatic conditions, environmental pollution, and the abatement and irregularity of rainfall caused a clear rising trend of humidity in the north-west, central and eastern regions (Rajib et al. 2011). In this study, a remarkable change of HI is detected in Barisal during the humid summer for three different future scenarios. In the far future, the HI value may turn into a dangerous condition in Barishal. Besides this, the study also identified that the HI would increase at an alarming rate at Rangpur, Chandpur, Comilla, and Rajshahi. While surprisingly, HI would decrease at Bogra, Chittagong, and Faridpur in the future period.

Rakib (2013) demonstrated that HI values are within a comfortable limit during the dry season. But it increases rapidly during summer, which is similar to this work. For example, in the case of hot summer, Rangpur would experience a change in heat index at least 10% during the future period compared to the historical period. By contrast, in the case of humid summer, Barisal will show the highest HI as it is located very near to the sea. The

high humidity is the cause of elevated HI value at Barishal. Prolonged exposure to such HI conditions may result in epidemiological problems such as human health hazards (Hansen et al. 2008).

Although the physiology of human body may be adapted to a long-term change in climate (Hondula 2015; Kjellstrom et al. 2016), the outcomes recommend an urgent requirement for health care system guideline by policymakers to develop robust early warning scheme and healthcare plans to cope with the rising temperature. The results imply that such an HI situation may lead to death of children and older people (Bouler et al. 2005; Fisher et al. 2012; Hansen et al. 2012; Buzan et al. 2015; Li et al. 2018; Pal and Eltahir 2016), elevated risk of novel infectious diseases like Coronavirus (Sammi et al. 2020), increasing demand for air conditioners, rising human errors in the workplace, and the rising number of accident. Attention should be provided to shift work hours to avoid severely circumstances (Kjellstrom et al. 2016; Mora et al. 2017; Bodrud-Doza et al. 2020).

5. Conclusion

The present study was intended to show ongoing and future spatiotemporal changes in HI in seven climatic regions of Bangladesh. The results reveal that the risk of heat extreme in Bangladesh is much serious during humid summer than that of the hot summer season at both the temporal and spatial scales. The HI in Bangladesh varies at the seasonal scale and among the climatic zones. This study identified hotspots, particularly in the northern, north-eastern, and southern zones of the country. Thus, the outcomes obtained in this study by considering temperature with relative humidity can be used for emerging emergency management strategy planning and early warning schemes. The results can help identify the heat index hot spot to help in early preparedness and adaptation strategy for future climate change. These results are very important for policymakers to take some initiatives for coping with this alarming risk by preparing region-wise and season-specific different contingency plans. In the future, a quantitative risk assessment based on HI in various climatic zones of Bangladesh at the regional and global scales should be performed, considering various demographic information. It is recommended that performances of the various downscaling tools and climatic models will be tested to compare the outcomes with those obtained in this study. A vital suggestion for further research is to use CMIP6 models for forecasting HI variations in Bangladesh or elsewhere in similar regions on the globe.

Declarations

Supplementary Information

Information is available in the supplementary file

Authors' contributions

ARMTI conceptualized the study; MBR analyzed the data; MBR performed the GIS-based mapping; ARMTI, AT, SMI & ZH interpreted the results; MBR & AT searched the relevant literatures and drafted the initial manuscript; First extensive review and edits were performed by UH; All authors subsequent reviewed and edited for its clarity; Besides, a critical review was done by UH, ZH, SS & ARMTI; Final version was approved by all the authors.

Ethical approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Data availability

The time series datasets supporting the conclusions of this article will be made available upon request on the corresponding author

Conflict of interest

The authors of the research work do not have any conflict of interest

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Figures

Figure 1

Map showing location of the study area and meteorological stations along with climatic zones in Bangladesh

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Figure 2

Temporal variation of hot summer for the seven climatic regions of Bangladesh Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 3

Temporal variation of humid summer for the seven climatic regions of Bangladesh Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Probability density function of mean annual HI for the seven climatic zones of Bangladesh Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Spatial changes of HI during the observed (1985-2015) and projected period (2041-2070) under three different scenarios over Bangladesh Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 7

Modified MK test Z value (a) and Sen's slope trend (b) of historical HI Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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