Climate change, extreme heat, and South Asian megacities: Impact of heat stress on inhabitants and their productivity

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Abstract

Of the 33 global megacities, 10 were situated in South Asia. Extreme heat waves have become an annual phenomenon due to climate change in South Asian megacities, causing severe health issues and even deaths. In this study, we evaluated 29 years (1990–2019) of historical data on heat stress in ten selected megacities (existing and prospective) —New Delhi, Dhaka, Mumbai, Kolkata, Ahmedabad, Chennai, Bengaluru, Hyderabad, Chittagong, and Pune— in India and Bangladesh. We used Heat Index (HI) and environmental stress index (ESI) analyses to evaluate stress and vulnerability. Our results showed New Delhi, Mumbai, Kolkata, Ahmedabad, and Chennai in India; Dhaka and Chittagong in Bangladesh were already experiencing an elevated number of hours of "danger" levels of heat stress, which may lead to heat cramps, exhaustion, stroke, and even death. Furthermore, the frequency of "danger" levels of heat stress and vulnerable levels of ESI has increased significantly since 2011 in the selected megacities, which elevated the heat-related vulnerability among the millions of inhabitants in terms of work hours lost for light, moderate, and heavy work due to heat stress. The vulnerable population in the studied megacities might have to reduce annual work hours by 0.25–860.6h (light work), 43–1595.9h (moderate work), and 291-2402h (heavy work) due to extreme heat in 1990–2019. We also discussed the implication of the work-hour loss on productivity, income, GDP, and SDG progress because of heat stress and its causes and suggested recommendations to reduce its impact.

Keywords: Extreme heat, Megacities, South Asia, Climate change, vulnerability.

1 Introduction

Globally, more people lived in urban than rural areas since 2007 [1]. By 2021, 56% of the total global population of 7.89 Billion [2] were living in urban areas [1] (Figure 1), which was projected to be 68% [3] when the global population would be approximately 9.8 billion by 2050 [4]. Based on the 'Degree of Urbanisation', the United Nations identified three types of settlements: Cities (population of at least 50,000 inhabitants with more than 1,500 inhabitants per km^2), Towns and semi-dense areas (population of at least 5,000 inhabitants with at least 300 inhabitants per km^2), and Rural areas (less than 300 inhabitants per km^2) [5]. Megacities were defined as cities with more than 10 million population [6]. However, in the available literature, a megacity's population size-based definition fluctuated from 5-10 million [7]. Ten of 33 global megacities were in South Asia in 2018 [6]. According to the UN, New Delhi (India) will be the largest megacity globally, with Dhaka (Bangladesh) and Mumbai (India) in the top ten megacities by 2030 (a predicted total of 43) [6].

Heatwaves — prolonged periods of abnormally high temperatures that exceed the normal range for a particular region — in the early twenty-first century have been increasing in frequency, duration, and intensity with severe impacts on health, society, ecosystems, and infrastructure. Frequent and severe heatwaves caused several recorded highest temperatures in different parts of the world in the recent past, such as 51ºC in India (Phalodi, Rajasthan) in 2016 [8], 40.3ºC in the UK (Coningsby, Lincolnshire) in 2022 [9], 43ºC in the Bangladesh (Ishwardi, Pabna) in 2023 [10]. Carbon Brief reported an analysis of 152 extreme heat events that were assessed by scientists and concluded: "*93% found that climate change made the event or trend more likely or more severe*" [11]. Moreover, the IPCC reported increased extreme heat waves due to climate change in South Asia [12], occurring several times annually. Therefore, billions of people will live with the adverse effects of extreme heat, particularly in India and Bangladesh, as 35% and 39% of the total population live in urban areas in 2021 (Figure 1).

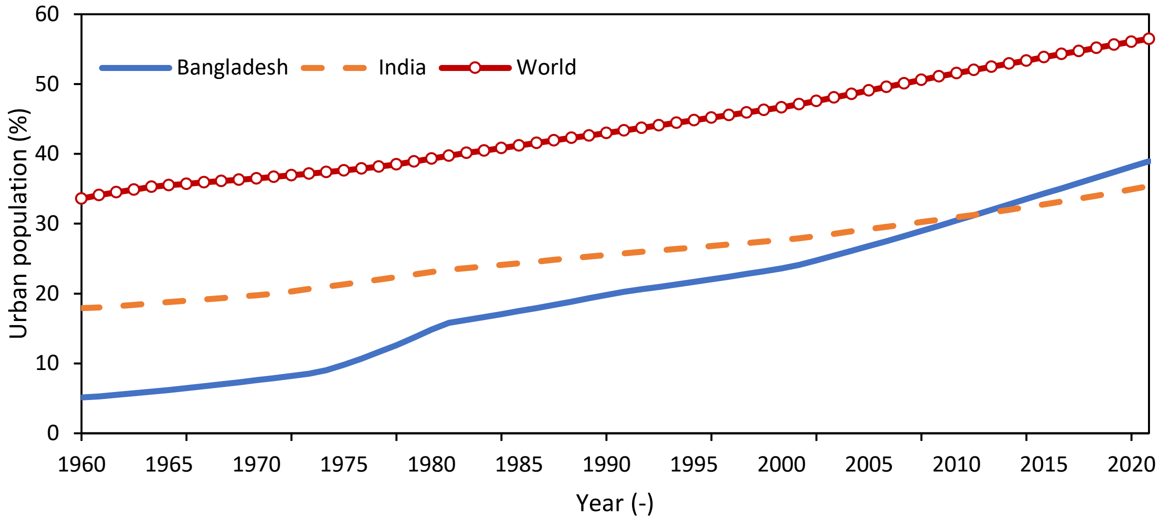


Figure 1: Urban population percentage for 1960-2021; data source: [1]

Extreme heat exposure might cause severe health issues ranging from heat exhaustion, cramps, heat stroke, and even death [13]. Extreme heat's impact on human health was often exacerbated by other factors such as age, pre-existing health conditions, and socioeconomic status [14]. One of the most significant health impacts of extreme heat could be heat stroke. This life-threatening condition might occur when the body's internal thermoregulatory system fails due to overheating [14]. Symptoms of heat stroke might include a high body temperature, confusion, seizures, and loss of consciousness [15]. Older adults, young children, and people with pre-existing health conditions such as heart disease and diabetes were particularly vulnerable to heat stroke [14].

In addition to its direct impacts on human health, extreme heat could also affect energy systems [16]. Furthermore, to live with extreme heat, people were inclined to use air conditioning, which caused elevated electricity demand for cooling, which was projected to proliferate [17]. For example, India will have 240 million A/C units by 2030, reaching 1144 million by 2050 [18], from 21.8 million in 2017 [19]. The elevated use of A/C could lead to high economic costs, particularly in urban areas where high energy demand and ageing infrastructure could exacerbate the risk of power outages. Furthermore, extreme heat events could affect energy generation [16]. Thermal power plants (dependent on cooling water from rivers or lakes) might be forced to reduce their output or shut down entirely due to high water temperatures caused by extreme heat events [20], with cascading effects on the energy supply systems, as power outages could affect critical infrastructure such as hospitals, water treatment plants, and transportation systems.

Extreme heat events, or heat waves, significantly impacted economies, particularly in emerging economies such as India and Bangladesh. Heatwaves could cause power outages, reduced agricultural yields and industry outputs, and disruptions in transportation and other critical infrastructure, causing a significant economic impact. In India, the economic impact of extreme heat was evident in the increased demand for electricity for cooling during heat waves, which can lead to power outages and increased energy costs and emissions [21]. Bangladesh suffered widespread power outages during the 2023 heat wave, where the power supply was 6.6% lower than the demand [22]. Furthermore, annual output was reduced by about 2% per degree Celsius increase in Indian factories [23].

Although various General Circulation Model (GCM) projections showed disagreements, a 4ºC temperature increase would severely impact food-grain production [24]. Also, extreme heat can significantly impact the agricultural sector, which employs many of the population in India and Bangladesh. For example, crop yield decreased by 5%, 6–8% and 10–30% in wheat, rice, and maise due to warming in India [25]. In addition to its direct impacts on the economy, extreme heat could lead to indirect costs, such as increased healthcare costs due to heat-related illnesses and lost productivity due to absenteeism.

There were several studies on heat exposure in cities and megacities, especially in India and Bangladesh. Azhar et al. (2017) mapped heatwave vulnerability in India with demographic, socioeconomic, and environmental vulnerability factors, combined district-level data from the census, health reports, and satellite remote sensing data, and utilised the principal component analysis (PCA) method [26]. Raja et al. (2021) investigated the spatial distribution of heatwave vulnerability in Chittagong to develop a heatwave vulnerability index with remote sensing and socioeconomic data [27]. Dewan et al. (2021) used Time series diurnal (day/night) MODIS land surface temperature (LST) data for 2000–2019 to examine the spatiotemporal variation of day and night surface urban heat island intensity in five major cities of Bangladesh [28]. Sharma et al. (2022) conducted a literature review to characterise heat waves across South Asian countries. The study pointed out that few South Asian countries had available heatwave management plans and lacked community and residential preparedness for heatwaves [29]. Tawsif et al. (2022) undertook an interview-based survey methodology to investigate the household adaptation strategies for liveable habitat to the heatwave in a regional (Rajshahi) city corporation area. They suggested three (types) of adaptation strategies: structural, non-structural, and community innovation-based. Also, the study suggested community innovation-based adaptation strategies showed high effectiveness [30]. Rashid et al. (2022) evaluated the influence of urban development on land surface temperature and ecological degradation in Narayanganj city corporation by utilising a land-use change map, vegetation coverage computation with the Normalised Difference Vegetation Index (NDVI), building coverage assessment using the Normalised Difference Built-up Index (NDBI), and Urban Thermal Field Variance Index (UTFVI) for the evaluation of an ecological index for 2011-2019. The study suggested heat action plans and toolkits for urban heat management and sustainable city development [31]. Debnath et al. (2023) used an analytical evaluation of the heat index with the Climate Vulnerability Index (CVI) to evaluate the impact of India's 2022 heatwave on adaptive livelihood capacity, food grains yield, vector-borne disease spread and urban sustainability. The study showed that heatwaves would critically hamper SDG progress at the urban scale and suggested improving extreme weather impact assessment [32].

The existing studies pointed to the urgency of adaptation and mitigation strategies for urban areas in India and Bangladesh. Although most of the existing studies focused on spatial analysis depended on remote sensing and demographic data, few studies also took meteorological data-based methodology to evaluate the impact of heatwaves and associated stress. Furthermore, the selection of cities or megacities for the existing studies was either limited or country-scale evaluations were conducted. Also, the temporal extent of the historical data analysis in the literature was constrained, and few studies were explored beyond 2000. To focus on the rapidly expanding megacities with prolonged exposure to climate change, in this study, we evaluated 29 years (1990-2019) of historical data (Temperature, relative humidity and solar radiation) on Heat Stress, Environmental Stress Index, and associated vulnerability of reduction in work hour in ten selected megacities (existing and prospected) —Dhaka, Chittagong, New Delhi, Mumbai, Kolkata, Ahmedabad, Chennai, Hyderabad, Pune, and Bengaluru— predominantly in India and Bangladesh (Figure 2).

2 Methodology

We obtained 29 years of weather data (1990-2019) from the Meteoblue database (www.meteoblue.com) for the Heat Index (HI) and Environmental Stress Index (ESI) analysis of 10 megacity climate (Figure 2) with ambient temperature, relative humidity and solar radiation. The metadata was called European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5th Generation (ERA5, ERA5T) with spatial resolution of 30 km and Hourly temporal resolution. According to Meteoblue [33]:

- "*ERA5 was produced using 4DVar data assimilation in CY41R2 of ECMWF's Integrated Forecast System (IFS), with 137 hybrid sigma/pressure (model) levels in the vertical, with the top level at 0.01 hPa.*
- *Atmospheric data are available on these levels and interpolated to 37 pressure, 16 potential temperature and one potential vorticity level(s).*
- *"Surface or single level" data are also available, containing 2D parameters such as precipitation, 2m temperature, top-of-atmosphere radiation and vertical integrals over the entire atmosphere.*
- *Due to the absence of satellite observations before 1980, the ERA5T data from 1940 to 1980 has a lower accuracy than the data from 1980 onwards*".

The ambient temperature and relative humidity data were used to calculate the hourly heat index (HI) with the following Equation 1 adopted from [34]:

$$HI = -42.379 + 2.04901523T + 10.14333127R - 0.22475541TR - 6.83783 \times 10^{-3}T^2 - 5.481717 \times 10^{-2}R^2 + 1.22874 \times 10^{-3}T^2R + 8.5282 \times 10^{-4}TR^2 - 1.99 \times 10^{-6}T^2R^2 \dots \dots (1)$$

Where, T - Ambient dry bulb temperature (°F)
R - Relative humidity (integer percentage)

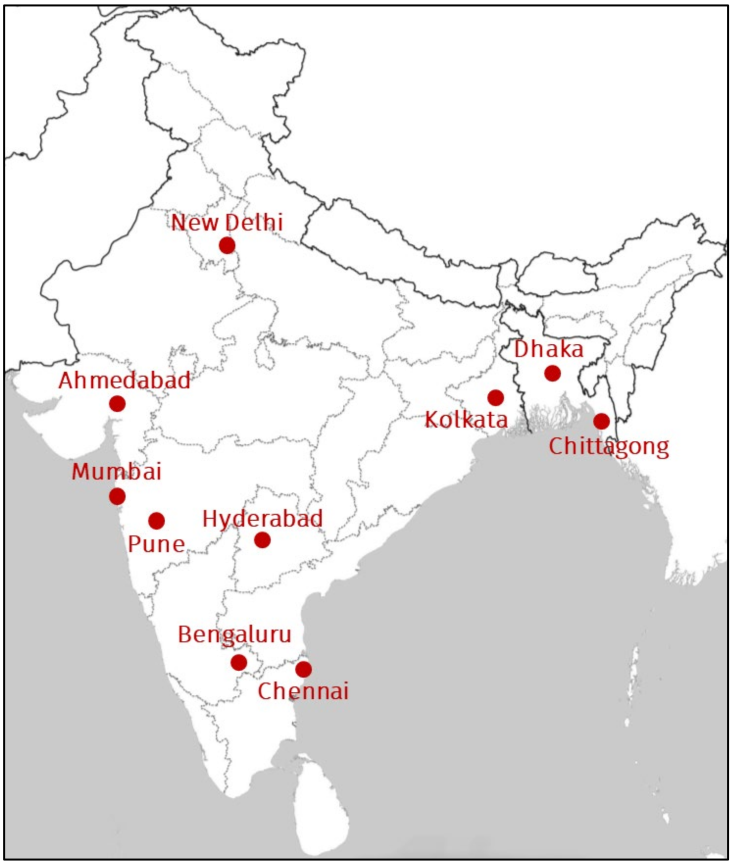


Figure 2: Selected megacities in India and Bangladesh; map source [40]

HI was selected for the study as it has been widely used in several studies to analyse the adverse effects of heat stress, such as [35, 36, 37, 38]. For the analysis in this study, we converted the ambient dry bulb temperature into °C with the following Equation 2 adopted from [39]:

$$C = 5/9\,(F - 32) \dots \dots (2)$$

Where C- Ambient dry bulb temperature (°C)

F- Ambient dry bulb temperature (°F)

Furthermore, we used the Heat Stress Index scale (**Table 1**) developed by the National Oceanic and Atmospheric Administration (NOAA) [41] to evaluate the HI for different megacities.

Table 1: Heat index and corresponding health impacts [41]

Heat Stress Index (°C)	Category	Dangers
27-32	Caution	Fatigue
32-41	Extreme caution	Sunstroke, heat cramps and heat exhaustion
41-54	Danger	Sunstroke, heat cramps, heat exhaustion, and even heat stroke
54+	Extreme danger	Heat/sunstroke

Rather than only analysing temperature and Relative Humidity as parameters to show the climate change effect in the selected cities, we also adopted the methodology of the Environmental Stress Index (ESI) as a measure for climate analysis because ESI considers the impact of climatic parameters such as ambient temperature (Ta), relative humidity (RH) and solar radiation (SR). The basic methodology of ESI was described in [42], and Equation 3 is as follows:

$$ESI = 0.63T_a - 0.03RH + 0.002SR + 0.0054(T_a \times RH) - 0.073(0.1 + SR)^{-1} \ldots\ldots (3)$$

Where T_a was the ambient temperature (°C), RH the relative humidity (%), and SR the solar radiation (Wm^{-2}), and the output unit for ESI is °C.

The work schedule reduction linked to Heat Index (HI) was used to analyse the vulnerability to extreme heat, as described in **Table 2**.

Table 2: Work schedule reduction recommendations [43, 44]

Adjusted Temperature or Heat Index (°F(°C))	Work/Rest Minutes Per Hour; Light Work (% Hourly Reduction)	Work/Rest Minutes Per Hour; Moderate Work (% Hourly Reduction)	Work/Rest Minutes Per Hour; Heavy Work (% Hourly Reduction)
94 (34.4)	Normal (0%)	Normal (0%)	Normal (0%)
95 (35)	Normal (0%)	Normal (0%)	45/15 (25%)
96 (35.6)	Normal (0%)	Normal (0%)	45/15 (25%)
97 (36.1)	Normal (0%)	Normal (0%)	40/20 (33.3%)
98 (36.7)	Normal (0%)	Normal (0%)	35/25 (41.6%)
99 (37.2)	Normal (0%)	Normal (0%)	35/25 (41.6%)
100 (37.8)	Normal (0%)	45/15 (25%)	30/30 (50%)
101 (38.3)	Normal (0%)	40/20 (33.3%)	30/30 (50%)
102 (38.8)	Normal (0%)	35/25 (41.6%)	25/35 (58.3%)
103 (39.4)	Normal (0%)	30/30 (50%)	20/40 (66.6%)
104 (40.0)	Normal (0%)	30/30 (50%)	20/40 (66.6%)
105 (40.6)	Normal (0%)	25/35 (58.3%)	15/45 (75%)
106 (41.1)	45/15 (25%)	20/40 (66.6%)	0/60 (100%)
107 (41.7)	40/20 (33.3%)	15/45 (75%)	0/60 (100%)
108 (42.2)	35/25 (41.6%)	0/60 (100%)	0/60 (100%)

109 (42.8)	30/30 (50%)	0/60 (100%)	0/60 (100%)
110 (43.3)	15/45 (75%)	0/60 (100%)	0/60 (100%)
111+ (43.9+)	0/60 (100%)	0/60 (100%)	0/60 (100%)

Based on the Work/Rest Minutes Per Hour in **Table 2**, we used the following Equation 4 (Light work), 5 (Moderate work) and 6 (Heavy work) for the estimate of the total annual per person-hours lost due to heat stress:

$$H_{Wl} = (a \times 100\%) + (b \times 75\%) + (c \times 50\%) + (d \times 41.6\%) + (e \times 33.3\%) + (f \times 25\%) + (g \times 0\%) + (h \times 0\%) + (i \times 0\%) + (j \times 0\%) + (k \times 0\%) + (l \times 0\%) + (m \times 0\%) + (n \times 0\%) + (o \times 0\%) + (p \times 0\%) + (q \times 0\%) + (r \times 0\%) \ldots\ldots (4)$$

$$H_{Wm} = (a \times 100\%) + (b \times 100\%) + (c \times 100\%) + (d \times 100\%) + (e \times 75\%) + (f \times 66.6\%) + (g \times 58.3\%) + ((h + i) \times 50\%) + (j \times 41.6\%) + (k \times 33.3\%) + (l \times 25\%) + (m \times 0\%) + (n \times 0\%) + (o \times 0\%) + (p \times 0\%) + (q \times 0\%) + (r \times 0\%) \ldots\ldots (5)$$

$$H_{Wh} = (a \times 100\%) + (b \times 100\%) + (c \times 100\%) + (d \times 100\%) + (e \times 100\%) + (f \times 100\%) + (g \times 75\%) + ((h + i) \times 66.6\%) + (j \times 58.3\%) + ((k + l) \times 50\%) + ((m + n) \times 41.6\%) + (o \times 33.3\%) + ((p + q) \times 25\%) + (r \times 0\%) \ldots\ldots (6)$$

Where H_{Wl} were the hours reduced in light work (h), H_{Wm} were the hours reduced in moderate work (h), H_{Wh} were the hours reduced in heavy work (h), a is the hours with HI of 43.9°C (and higher), $b, c, d, e, f, g, h, j, k, l, m, n, o, p, q, r$ is the hours at HI of 43.3-43.8, 42.8-43.2, 42.2-42.7, 41.7-42.1, 41.1-41.6, 40.6-41.0, 40.0-40.5, 39.4-39.9, 38.8-39.3, 38.3-38.7, 37.8-38.2, 37.2-37.7, 36.7-37.1, 36.1-36.6, 35.6-36.0, 35.0-35.5, and 34.4-35.0°C, respectively.

Limitation: The hourly megacity-wise climate data resolution was 30km. For example, Dhaka, one of the biggest megacities, had an area of about 306.38 km^2. Therefore, our data was only sufficient for the whole megacity scale, not for spatial variability between neighbourhoods with different characteristics or geography in the megacities, such as New Delhi, Dhaka, and Mumbai. Also, the ECMWF Reanalysis 5th Generation dataset was used for the HI, ESI and work schedule reduction estimation had assumptions, inaccuracies, and uncertainties (described in [45, 46]) which might influence the results. Furthermore, mean radiant temperature might significantly impact people's ability to work under heat stress during the daytime. Due to the lack of mean radiant temperature data in the selected megacities, we focused on the HI-related workhour loss where only ambient temperature and relative humidity were considered.

3 Results

3.1 Heat Stress Index (HI)

In the case of Dhaka (Bangladesh), the HI was 49.68°C in 2015. The maximum HI was 51.94°C in 2019, the highest in the past 29 years; 2.3°C and 3.37°C higher than the highest in 2015 and 2011. Dhaka's average HI was 30.36°C in 2019 and 29.53°C in 2015. Only 69 hours (h) in 2015, they had HI in the danger level, which increased 3.39 times by 2019 (234h) (Figure 3A).

For the port city of Chittagong (Bangladesh), the HI was at a danger level of 789h in 2019, 410h in 2015 and 235h in 2011 (Figure 3B). Therefore, the danger level exposure was elevated by 1.7 times in 2019 than in 2011. Similarly, the HI was at an extreme caution level for 3073h in 2019, 1.3 times higher than in 2011 (2444h). The highest HI was 49.40°C in 2019, about 2°C higher than in 2015 and 2011. Furthermore, the average HI increased to 30.33°C from 29.15°C in 2015 and 28.68°C in 2011.

In the case of the capital city, New Delhi (India), the maximum HI was 51.92°C in 2019, the highest in the past 29 years, 1.8°C and 2°C higher than in 2015 and 2011, respectively. New Delhi's average HI was 30.60°C in 2019 and 29.60°C in 2015 (Figure 4A). Only 58h in 2015 had HI in the danger level, which increased 4.43 times by 2019 (257h). In Mumbai, the HI was at a danger level of 277h in 2019 and only 86h in 2011 (Figure 4B). Therefore, HI at danger level in Mumbai elevated 3.22 times in 8 years. In 2015, the HI was 329h at the danger level. The highest HI was 48.11°C in 2019, about

2.3°C and 4°C higher than in 2015 and 2011. The average HI increased to 30.03°C in 2019 from 28.96°C in 2011. The HI was at a danger level of 1342h in Kolkata in 2019, 1065h in 2015 and 619h in 2011 (Figure 4C). The danger level of HI exposure elevated by 2.2 times by 2019 than in 2011. The highest HI was 53.48°C in 2019, about 1.3°C and 4°C higher than in 2015 and 2011.

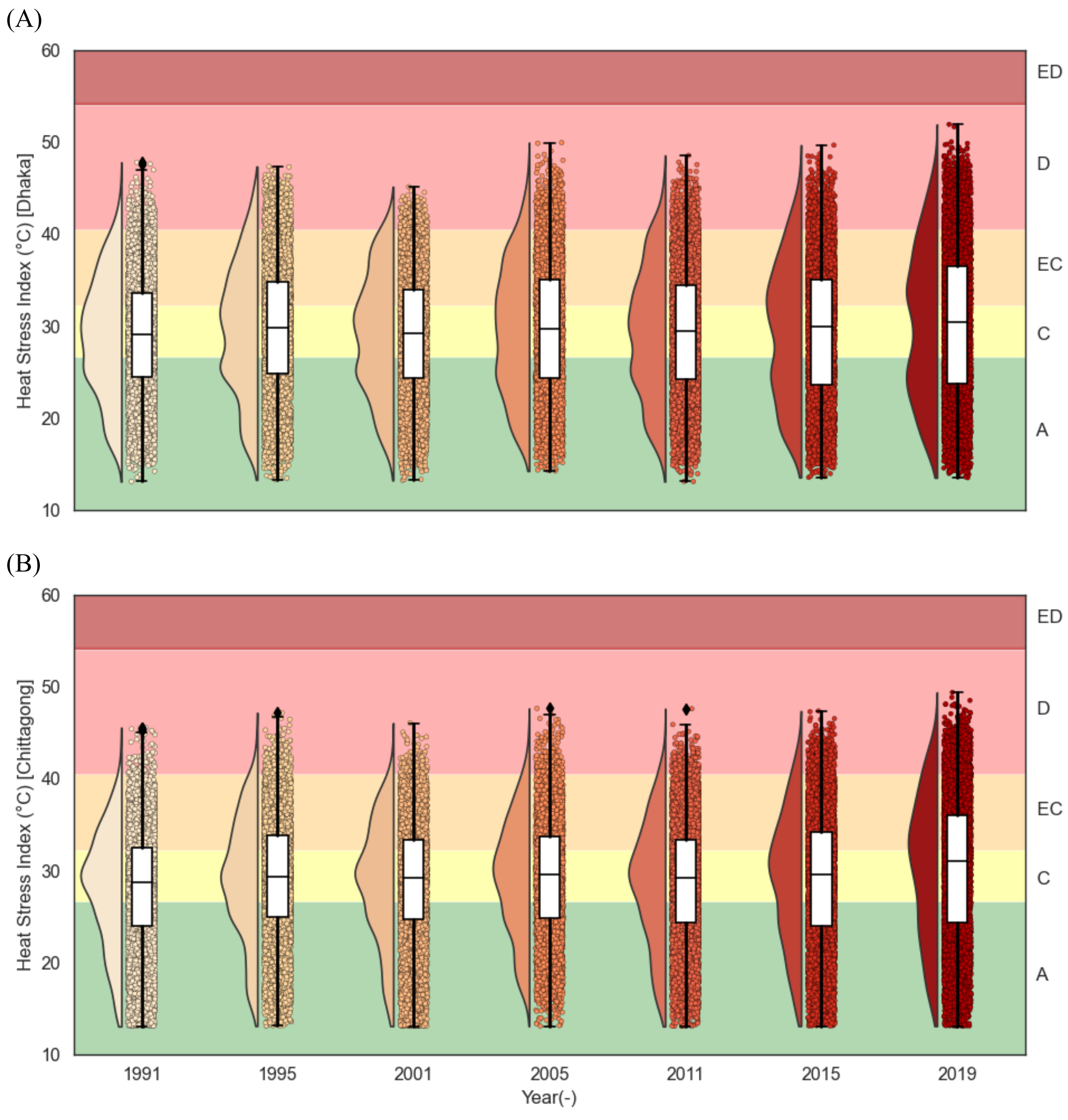
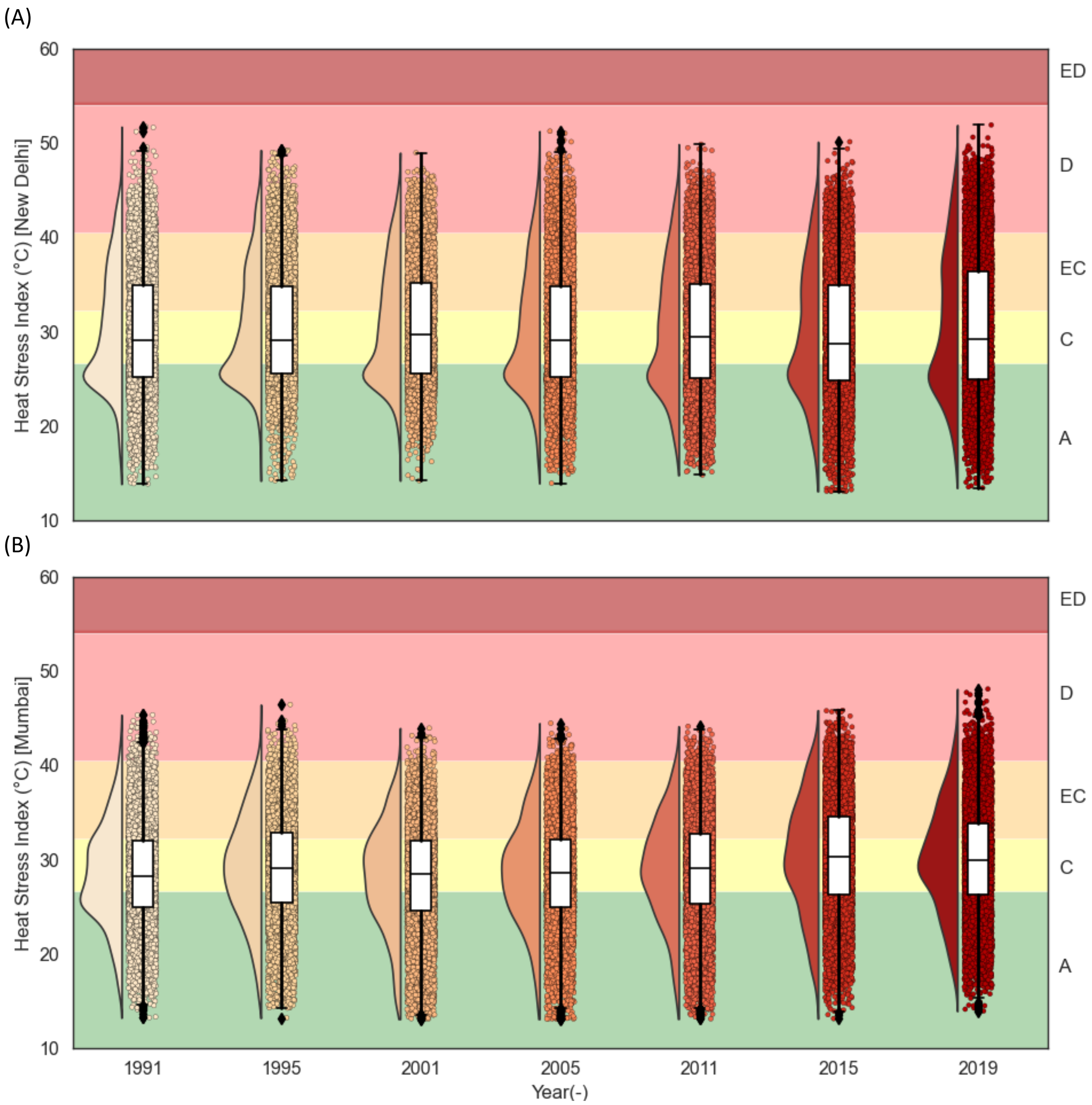


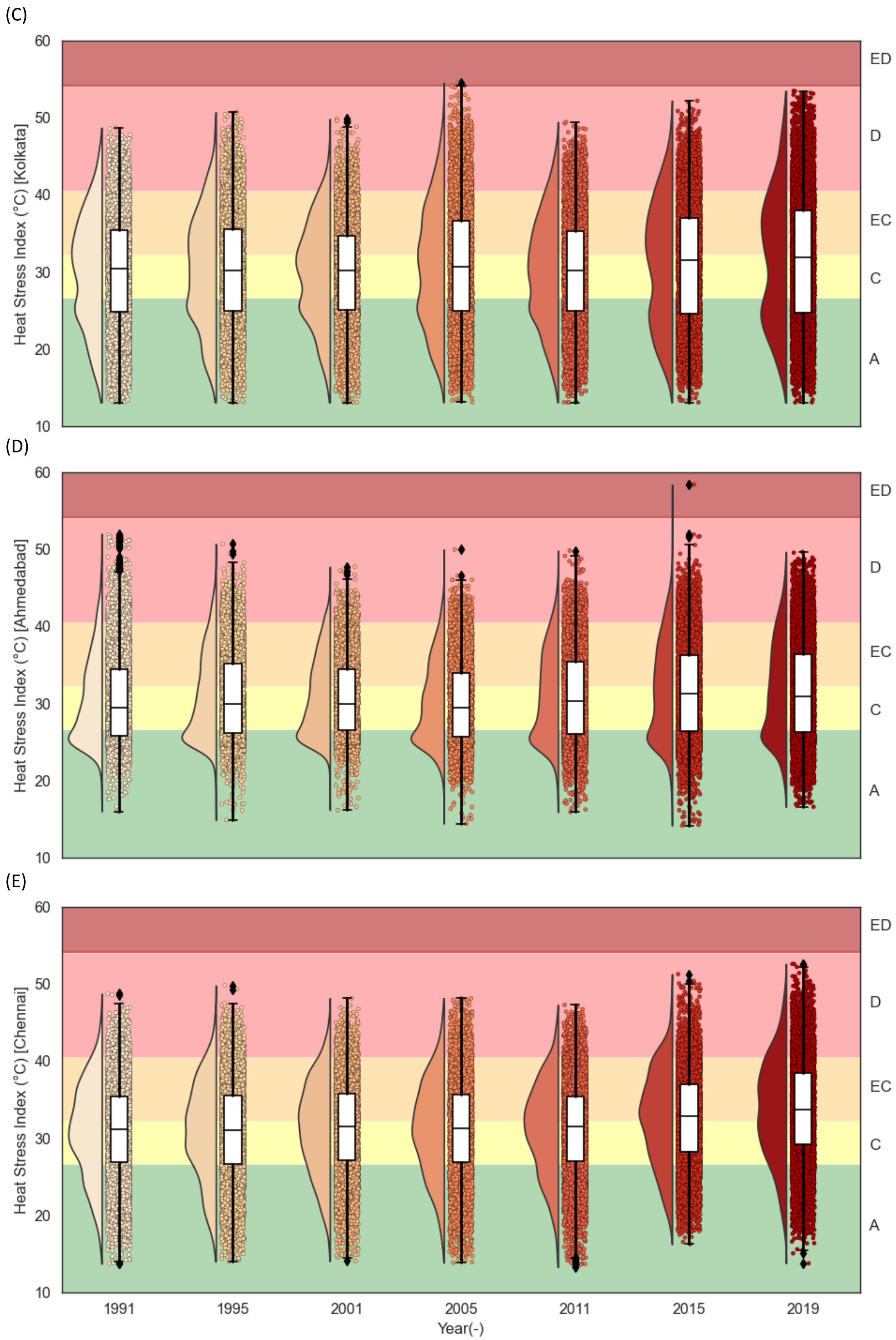
Figure 3: Heat Index (HI) for (A) Dhaka and (B) Chittagong, Bangladesh, in 1991, 1995, 2001, 2005, 2011, 2015, and 2019. Here, ED= Extreme Danger, D= Danger, EC= Extreme Caution, C= Caution, and A= Acceptable.

The average HI increased to 31.62°C in 2019 from 30.18°C in 2011. In the case of Ahmedabad, the danger level of HI exposure was 835h in 2019, 1.8 times that of 2011 (476h). The highest HI was 58.41°C, 49.67°C and 49.83°C in 2015, 2019 and 2011, respectively (Figure 4D). The average HI increased to 31.65°C in 2019 from 31.02°C in 2011. For Chennai, HI, the danger level experienced 1322h, which was 784h in 2015 and 369h in 2011 (Figure 4E). The HI exposure in danger level increased 3.6 times by 2019 than in 2011. The highest HI was 52.61°C in 2019, about 1.3°C and 5.31°C higher than in 2015 and 2011. The average HI increased to 33.71°C in 2019 from 32.63°C in

2015 and 31.16°C in 2011. The HI reached the danger level of 162h in 2019, from 58h in 2015 to only 8 hours in 2011 in Hyderabad (Figure 4F). In 2011-19, the HI exposure to danger increased 20.25 times. The highest HI was 44.30°C in 2019, about 1.2°C and 2.24°C higher than in 2015 and 2011. The average HI increased to 27.77°C in 2019 from 27.30°C in 2011.

In the case of Pune, the danger level of HI exposure was 5h, 0h, and 4h in 2019, 2015, and 2011, respectively (Figure 4G). In contrast to most of the megacities in India, HI in Bengaluru never reached a danger level from 1991-2019 (Figure 4H). Only Pune and Bengaluru in India showed little to no exposure to the danger level of HI. Nevertheless, they also showed an increase in HI levels.




(C)
Heat Stress Index (°C) [Kolkata]
60
50
40
30
20
10
ED
D
EC
C
A
(D)
Heat Stress Index (°C) [Ahmedabad]
60
50
40
30
20
10
ED
D
EC
C
A
(E)
Heat Stress Index (°C) [Chennai]
60
50
40
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2015
2019
Year(-)

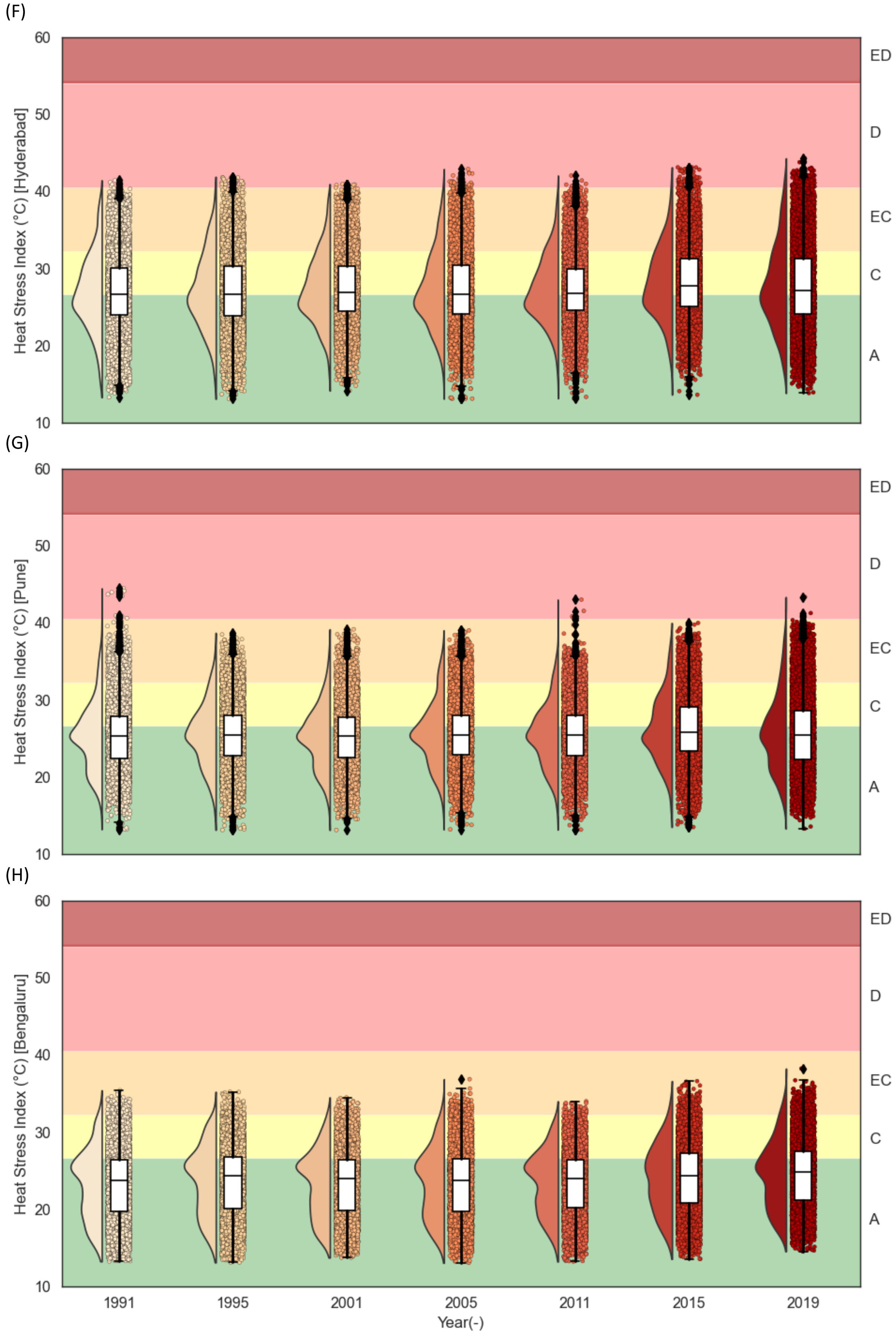


Figure 4: HI for (A) New Delhi, (B) Mumbai, (C) Kolkata, (D) Ahmadabad, (E) Chennai, (F) Hyderabad,

(G) Pune, and (H) Bengaluru (also called Bangalore), India in 1991, 1995, 2001, 2005, 2011, 2015, and 2019. Here, ED= Extreme Danger, D= Danger, EC= Extreme Caution, C= Caution, and A= Acceptable.

3.2 Environmental Stress Index (ESI)

In the case of ESI, we considered the 30°C — wet bulb globe temperature (WBGT) threshold to be considered 28°C [47], and ESI can substitute WBGT [42, 48]— as the threshold above which the hours were deemed vulnerable to people to conduct outdoor physical activities.

In Bangladesh, Dhaka and Chittagong showed elevated hours above the ESI vulnerability thresholds. The highest ESI was 34.95°C and 34.57°C in 2019 in Dhaka and Chittagong, respectively (Figure 5). The ESI for Dhaka was higher than the threshold for 1592h in 2019 and 1119h in 2011. For Chittagong, the ESI was higher than 30°C for 1559h in 2019, which was 882h in 2011; therefore, a 1.77-time increase in 8 years.

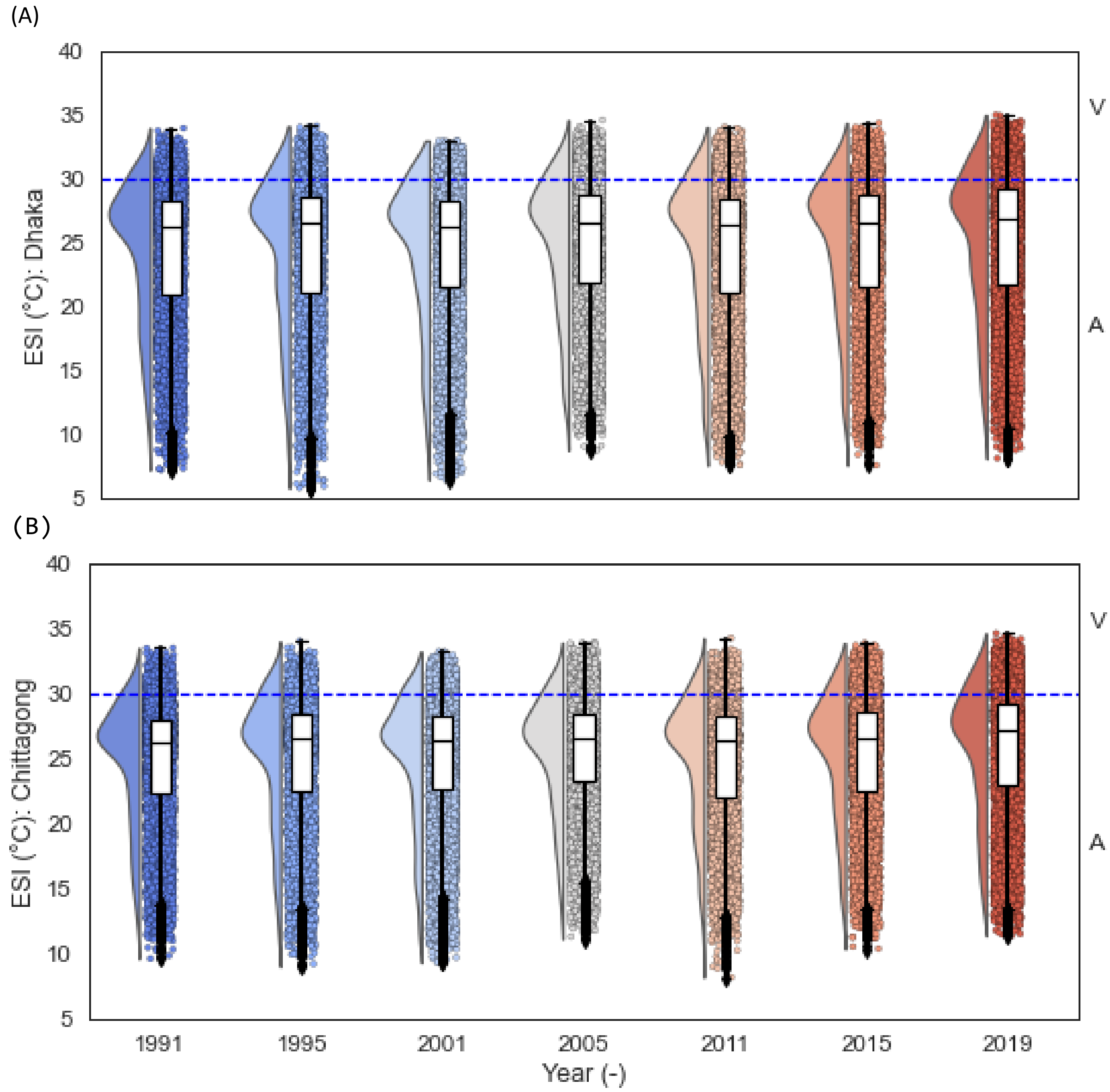
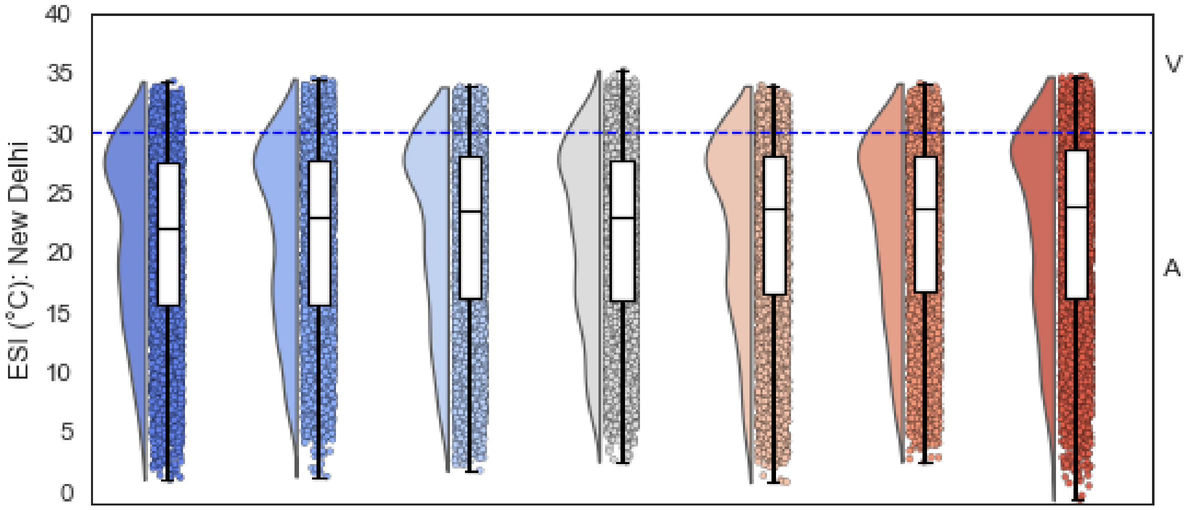


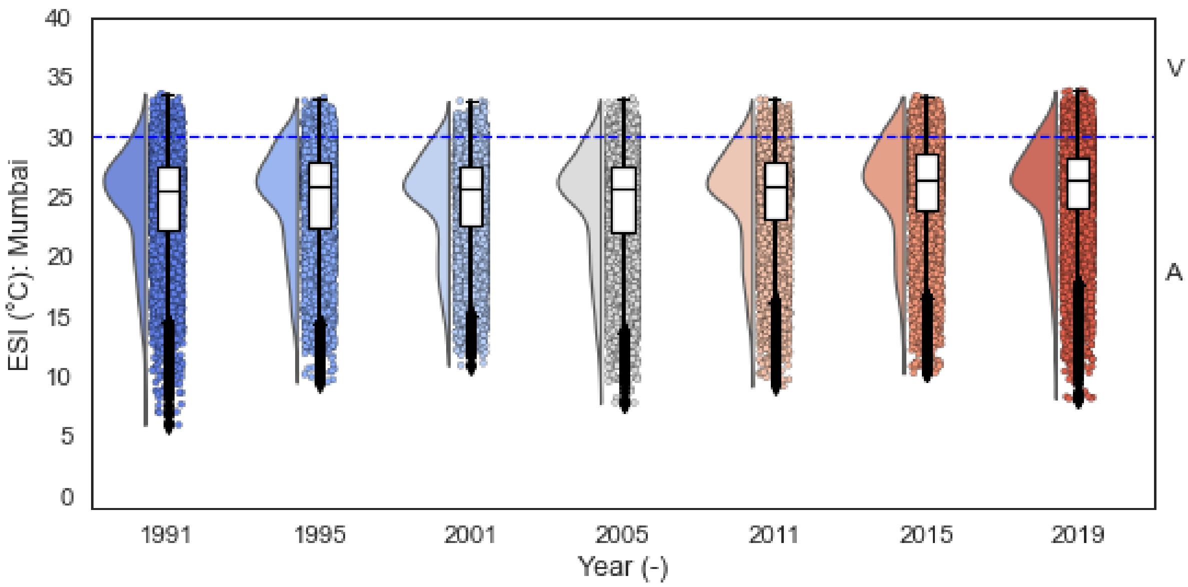
Figure 5: ESI for (A) Dhaka and (B) Chittagong, Bangladesh, in 1991, 1995, 2001, 2005, 2011, 2015, and 2019. Here, V= vulnerable and A= Acceptable.

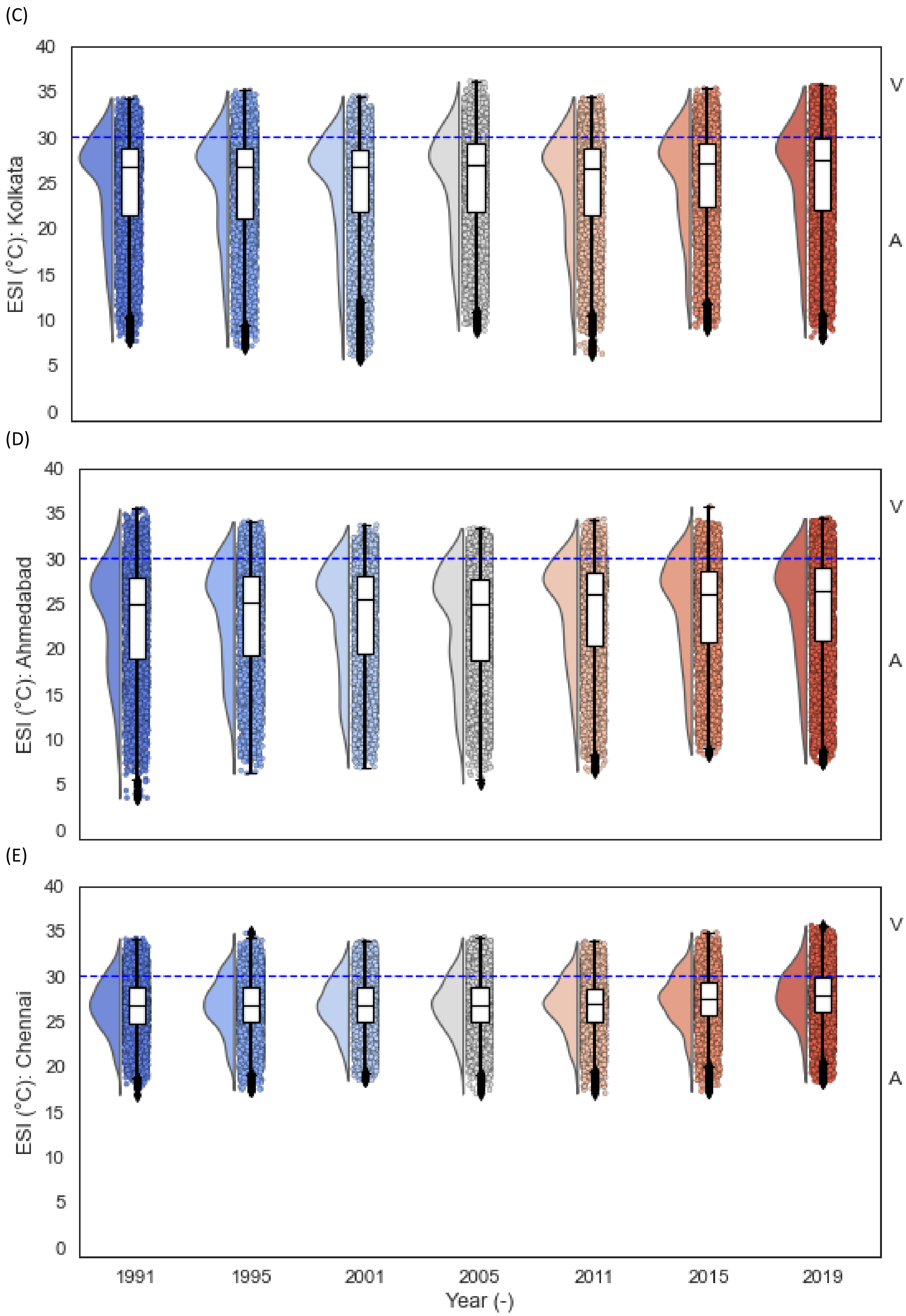
In India, apart from Bengaluru, all the megacities showed elevated exposure to vulnerable level ESI in 2019 compared to 2011. The highest ESI were 34.70°C, 33.83°C, 35.64°C, 34.43°C, 35.62°C, 33.07°C, and 31.47°C in New Delhi, Mumbai, Kolkata, Ahmedabad, Chennai, Hyderabad, and Pune, respectively, in 2019. In New Delhi, the ESI was higher than the threshold for 1299h in 2019, which was 1068h in 2011; therefore, 1.22 times increase. Higher than threshold ESI exposure hours elevated to 937h (from 564h in 2011), 2015h (from 1258h in 2011), 1378h (from 1016h in 2011), 2057h (from 1090h in 2011), 324h (from 117h in 2011) and 87h (from 1h in 2011) for Mumbai, Kolkata, Ahmedabad, Chennai, Hyderabad, and Pune, respectively, in 2019 (Figure 6).

(A)



(B)





(C)
ESI (°C): Kolkata
V
A
(D)
ESI (°C): Ahmedabad
V
A
(E)
ESI (°C): Chennai
V
A
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5
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25
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1991
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2015
2019
Year (-)

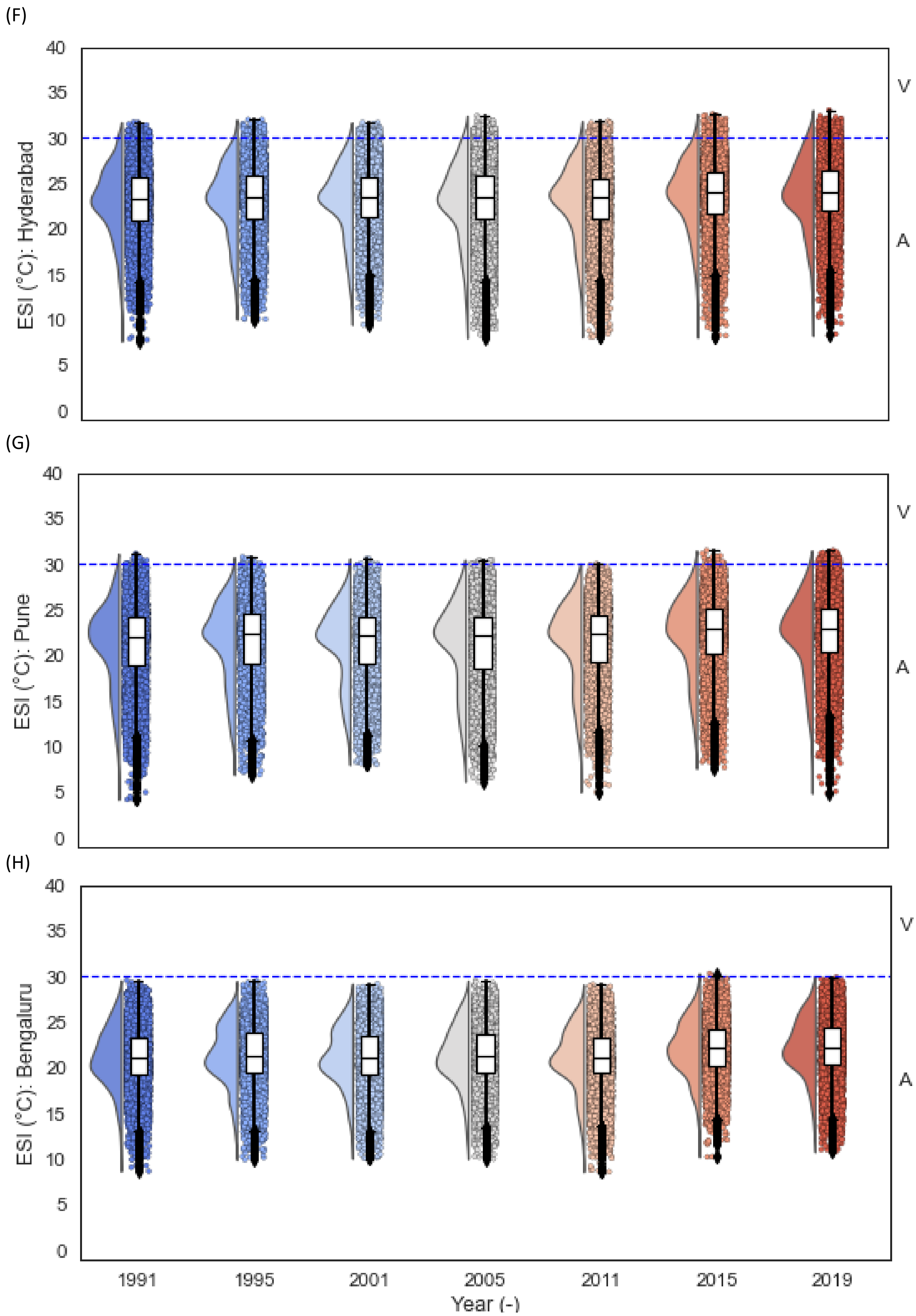

Figure 6: ESI for (A) New Delhi, (B) Mumbai, (C) Kolkata, (D) Ahmadabad, (E) Chennai, (F) Hyderabad, (G) Pune, and (H) Bengaluru (also called Bangalore), India in 1991, 1995, 2001, 2005, 2011, 2015, and 2019. Here, V= vulnerable and A= Acceptable.

3.3 Vulnerability

Considering the vulnerability to extreme heat from **Table 2** and Equations 4, 5 and 6, the high number of hours exposed to danger level HI in most of the megacities in India and Bangladesh contributed to the reduction of massive work hours to cope with the heat stress-related health issues. Among India's megacities, Chennai and Kolkata showed the highest amount of work hours reductions annually. The results showed that 2402h and 2182h of total work hours per person were reduced 2019 for heavy work in Chennai and Kolkata, respectively (Figure 7). In 2015, 1803.5h and 1879.4h total work hours (per person) were reduced for heavy work in Chennai and Kolkata, respectively. Therefore, the work hours reduction (due to heat stress) elevated by 33.2% and 16.1%, and by 100.1% and 66% in 2019 compared to 2015 and 2011 for the heavy work in Chennai and Kolkata, respectively. Considering the moderate work, 1595.9h and 1554h of total work hours per person were reduced in Chennai and Kolkata, respectively, in 2019, which was 49.5% and 23% higher compared to 2015 and 162.6% and 95.6% higher than in 2011. Under a light work scenario, 721.1h and 860.6h of total work hours per person were reduced in Chennai and Kolkata, respectively, in 2019, which was 127.9% and 44.1% higher compared to 2015, and 362.4% and 175.1% higher than 2011.

Although the work hours reduced due to heat stress were not as high as in Chennai and Kolkata, they were substantial in New Delhi, Ahmedabad, and Mumbai. The results showed that 1678.7h, 1645.4h and 865.6h of total work hours (per person) for heavy work were reduced in 2019 in New Delhi, Ahmedabad, and Mumbai, respectively (Figure 7). In 2015, 1255h, 1594.5h and 1018.2h total work hours were reduced in New Delhi, Ahmedabad, and Mumbai, respectively, for the heavy work. Therefore, the work hours reduction for heavy work due to heat stress raised 33.8%, 3.2% for New Delhi and Ahmedabad, but reduced by 15% in Mumbai in 2019 compared to 2015. The 15% reduction for Mumbai in 2019 was due to the highest work hours reduced in 2015 in the study period 1990-2019. Compared to 2011, the work hours reduction due to heat stress elevated by 29.8%, 29.7% and 63.8% in 2019 for heavy work. For moderate work, 1156.8h, 1056.9h and 419.3h of total work hours per person were reduced in New Delhi, Ahmedabad, and Mumbai, respectively, in 2019, which was 50% and 6% higher and 18.5% lower compared to 2015, and 42.7%, 52.9% and 110.4% higher than 2011. Considering the light work, 601.6h, 429.7h and 109.1h of total work hours per person were reduced in New Delhi, Ahmedabad, and Mumbai, respectively, in 2019, which were 102.7% and 12.8% higher and 0.2% lower compared to 2015, and 86.1%, 118.3% and 407.8% higher than 2011. The heat stress was much lower than in other Indian megacities in Bengaluru, Pune, and Hyderabad; therefore, the work-hour reductions were low to none for heavy work. In the case of India, annual hours were reduced for moderate work and light work in all selected megacities apart from Bengaluru.

In the case of Bangladesh, Dhaka and Chittagong showed 1736h and 1560h of total work hours (per person) were reduced for heavy work in 2019 (Figure 7). In 2015, 1274.8h and 1000.5h total work hours (per person) were reduced for heavy work in Dhaka and Chittagong, respectively. Therefore, the work hours reduction for heavy work due to heat stress elevated by 36.2% and 55.9% in 2019 compared to 2015, compared to 2011, the work hours reduced due to heat stress by 55.5% and 104.2% in Dhaka and Chittagong, respectively, in 2019 for the heavy work. Considering the moderate work, 1207h and 985.8h of total work hours (per person) were reduced in Dhaka and Chittagong, respectively, in 2019, which was 57.8% and 74% higher compared to 2015, and 84.4% and 174.3% higher than in 2011. Under a light work scenario, 594.3h and 379.7h of total work hours per person were reduced in Dhaka and Chittagong, respectively, in 2019, which was 109.2% and 131.6% higher compared to 2015, and 214.4% and 500.5% higher than 2011.

Figure 7: Annual hours reduced per person for light, moderate and heavy work in South Asian megacities.

4 Discussion

Our results showed that most megacities were already experiencing 'Extreme caution' and 'Danger' levels of Heat Stress. We estimated a 1.2-2.3°C and 2-5.31°C increase by 2019 in the HI since 2015 and 2011, respectively, in the megacities of Bangladesh (Dhaka and Chittagong) and India (New Delhi, Mumbai, Kolkata, Ahmedabad, and Chennai). The vulnerable population in the studied megacities might have to reduce annually 0.25-860.6h (light work), 43-1595.9h (moderate work) and 291-2402h (heavy work) of work hours due to extreme heat in 1990-2019. Such heat stress and vulnerability might extensively impact productivity, income, and health, with far-reaching effects on India and Bangladesh's Gross Domestic Product (GDP) and Sustainable Development Goals (SDGs).

4.1 Impact of heat stress

Heat stress would have a significant impact on productivity, income, health, GDP, and SDG progress in megacities in India and Bangladesh:

- **Productivity:** Workers exposed to high temperatures and humidity were at risk of heat-related illnesses, such as heat cramps, exhaustion, stroke, and even death. Workers might need to take time off from work when they become ill, resulting in lost productivity and reduced work hours [43]. Evidence from different studies showed heat stress was responsible for productivity loss in India [49, 50, 51] and Bangladesh [52]. For example, productivity was reduced by about 2% for female brickfield workers for every degree increase in temperature [53]. Another study showed 18-35% productivity loss in India due to heat stress [54]. Under the present climate (2001-2020 mean), India led the most significant heat exposure impacts on heavy work (>101 billion hours lost/year), despite its modest average per-capita work losses (162 lost hours/person/year) considering 12-h workday. In the case of Bangladesh, the 12-hour population-weighted loss of work hours was 14 billion hours lost per year [55]. Considering the +1ºC global temperature increase, India would lose 156 billion hours yearly, whereas Bangladesh would lose 21 billion hours annually from heat exposure. Furthermore, a +2ºC global temperature increase would be devastating as India and Bangladesh lose 230 and 31 billion hours annually from heat exposure [55]. Workers losing productivity or missing work due to heat-related illnesses/rest could lead to a reduction in income, which could mainly be challenging for workers in low-wage industries (particularly informal workers in megacities) who were highly unlikely to have access to sick leave or other forms of compensation in India and Bangladesh. Thus, heat stress could have various negative consequences, adversely impacting individual and community economies and decreasing family income [56].
- **Health:** Heat stress can have serious health risks, particularly for vulnerable populations such as older people, children, and those with pre-existing health conditions. Heat-related illnesses could lead to hospitalisation and, in severe cases, death. People with lower income had limited access and were meant to afford (basic) necessities, such as clean water, proper sanitation, dependable transportation, and healthcare, to deal with the health effects of extreme heat in India [57]. Heat waves were associated with an increased risk of hospitalisation for respiratory and cardiovascular diseases [58] and kidney diseases [59] in South Asia, particularly in India and Bangladesh.
- **GDP:** Heat stress could reduce productivity and increase healthcare costs, which would have a negative impact on GDP. According to a recent projection, if the global temperature increased by 3°C, India's GDP could decrease by 10% in 2100 due to a reduction in agricultural output, increased expenses on healthcare, and rising sea levels. In case of a 2°C temperature rise, GDP might decline by 2.6%, while it could fall by 13.4% if the temperature increased beyond 4°C. The drop in GDP was predicted to be a reduction in labour productivity caused by changes in precipitation and temperature. Furthermore, a 3°C temperature rise could cause a 90% decline in India's GDP [60]. Additionally, industries that rely on outdoor labour, such as agriculture and construction, were particularly vulnerable to the impacts of heat stress.

- **SDG progress:** The SDGs address various global challenges, including poverty, inequality, and climate change. Heat stress could undermine progress toward these goals by exacerbating existing challenges [32]. For example, heat stress could lead to decreased labour productivity in megacities, which could increase food insecurity, inequality, and poverty and undermine progress toward SDG 1 (No Poverty), SDG 2 (Zero Hunger), SDG 10 (Reduced Inequality) and SDG 8 (Decent Work and Economic growth). Heat stress could also exacerbate health inequalities and undermine progress toward SDG 3 (Good Health and Well-being). Furthermore, not addressing the factors contributing to heat stress, such as urban heat islands and lack of green spaces and implementing measures to protect vulnerable populations could challenge SDG 11 (Sustainable cities and communities).

4.2 Reasons for heat stress

Megacities in India and Bangladesh were among the world's most vulnerable regions to heat stress. The impact of heat stress was intensified by factors such as urbanisation, climate change, and low levels of preparedness. Among the analysed megacities, New Delhi, Mumbai, Kolkata, Chennai and Ahmedabad in India, and Dhaka and Chittagong in Bangladesh were particularly susceptible due to the Urban Heat Island (UHI) effect, unplanned urban development and inadequate access to essential resources such as clean water, healthcare, and transportation [61]. The main reasons for heat stress were:

- **Climate change:** Due to climate change, India and Bangladesh have been experiencing elevated frequency and intensity of heat waves. Highly densely populated cities and megacities in South Asia face extreme danger due to heat waves [62]. Rising temperatures, changes in precipitation patterns, and changes in wind patterns contribute to the increased likelihood of heat waves in these countries [63].

- **Urban Heat Island (UHI) Effect and Urban Heat:** The UHI effect occurs when urban areas experience higher temperatures than surrounding rural areas due to the absorption and retention of heat by buildings (roof and skin), roads and pavement [64]. Heatwaves were associated with UHI and urban heat, resulting in very high levels of heat stress [65, 66]. As urbanisation contributed to the UHI effect in cities and megacities in India and Bangladesh [31, 67], with rapid urban area expansions, the UHI effect and urban heat became more pronounced, exacerbating the impacts of heat waves [68] in New Delhi, Mumbai, Kolkata, Chennai and Ahmedabad in India, and Dhaka and Chittagong in Bangladesh.

- **Unplanned urban development:** Rapid and unplanned urban development in India and Bangladesh's cities and megacities led to the proliferation of heat-trapping materials such as concrete and asphalt [61, 69]. The construction of high-rise buildings and the removal of green spaces also contributed to the UHI effect. It made urban areas, mainly analysed megacities such as New Delhi, Mumbai, Kolkata, Chennai and Ahmedabad in India, and Dhaka and Chittagong in Bangladesh, which showed higher levels of heat stress exposure, more susceptible to heat waves [70, 71, 72].

- **Lack of green spaces and trees:** The rapid urbanisation and industrialisation in India and Bangladesh resulted in the loss of green spaces and trees [70, 73]. Trees and vegetation played a crucial role in regulating temperature and providing shade. Still, the reduction in their number and density led to an increase in temperature, especially in urban areas [71]. For example, from the studied megacities, Dhaka lost 56% greenspace between 1989 and 2020 [74], and Mumbai lost 22.6 % between 2001 and 2011 [75], which might have contributed to the high heat stress level.

- **Poor infrastructure and living conditions:** Many people in New Delhi, Mumbai, Kolkata, Chennai and Ahmedabad in India, and Dhaka and Chittagong in Bangladesh live in inadequate housing and work with poor ventilation and insulation, which could exacerbate the effects of heat stress [76, 77]. Additionally, the lack of basic amenities such as clean water, electricity, and air conditioning might make it difficult for people to cool down during extreme heat events, particularly in megacities in India and Bangladesh [76, 61].

- **Occupational exposure to heat:** Workers in outdoor industries such as agriculture, construction, and transportation, requiring heavy manual work, were at a higher risk of heat stress due to prolonged exposure to the sun and high temperatures in urban areas [78], particularly New Delhi, Mumbai, Kolkata, Chennai and Ahmedabad in India, and Dhaka and Chittagong in Bangladesh. These workers often worked long hours and had limited access to shade, water, and rest breaks, which could increase their vulnerability to heat stress significantly [61, 76].

4.3 Recommendations

4.3.1 Heat Action Plan (HAP)

Heat Action Plans (HAPs) were implemented in several cities in India — the exact number of HAPs in India was unknown; some estimates claim +100 HAPs nationwide [79]—to address the impacts of extreme heat: Ahmedabad (the first HAP in India and South Asia in 2013), Nagpur (2016) and Kolkata (2019) in India. Mumbai drafted the Mumbai Climate Action Plan (MCAP) in 2022. Overall, HAPs could be essential in mitigating extreme heat impacts, particularly in New Delhi, Mumbai, Kolkata, Chennai and Ahmedabad in India, and Dhaka and Chittagong in Bangladesh. However, HAPs in India did not address issues such as local context, identification of vulnerable groups, funding, legal foundation, transparency, and capacity building [80]. Therefore, ongoing monitoring, updating and evaluation were necessary for the existing HAPs to ensure these plans were practical and adapted to the changing climate conditions. The critical components for HAPs (for the megacities that have not implemented them yet) in addition to the recommendations by [80] could be:

- **Early warning systems** might provide alerts when temperatures are expected to reach dangerous levels. These systems might also guide staying cool and hydrated during extreme heat events.
- **Cool shelters** —such as air-conditioned community centres or public buildings— sheltered vulnerable populations could go to escape the heat. Similar shelters were used in the Korean peninsula's 2018 heat wave [81].
- **Water supply** might be included to ensure adequate access to safe drinking water during extreme heat events, particularly in areas where water scarcity could be a concern, such as Dhaka, Mumbai [82], and Chennai [83].
- **Public outreach** campaigns might be needed to raise awareness about the risks of heat stress and educate people on staying safe during extreme heat, including distributing educational materials, hosting community events, or using social media to share information.
- **Interagency coordination** between multiple government agencies, such as health departments, emergency services, and urban planning departments, might be necessary to ensure a comprehensive approach to mitigating the impacts of extreme heat.
- **Shifting the work hours** during the evening or night might be considered as resting, or not working in warm daytime often negatively impacts the low-income population. Such a shift might also ensure lower health risks among the public, thus reducing the pressure on the health sector. Recently, Karnataka (India) took steps to reschedule working hours to deal with heat waves [84].

4.3.2 Urban Heat Island (UHI) and Urban Heat (UH) Reduction

As the UHI effect and UH in different parts of the megacities were recognised as one of the leading causes of heat stress in New Delhi, Mumbai, Kolkata, Chennai and Ahmedabad in India, and Dhaka and Chittagong in Bangladesh, reducing the UHI effect and UH could be prioritised through the following measures at different scales and require collaboration between multiple stakeholders, including urban planners, architects, engineers, policymakers, and community members:

- Increasing green cover by planting trees and vegetation in urban areas could reduce the temperature with shade and enhance the evapotranspiration of water from plants, thus cooling the surrounding environment [85]. Air temperature could be reduced up to 12°C by planting trees and vegetation in tropical urban areas [86]. Furthermore, increasing open spaces, such as parks and gardens, could lower the temperature by allowing air to circulate and dissipate heat and reducing the amounts of heat-absorbing surfaces such as concrete and asphalt.

- Using cool materials for roofs and pavements, such as reflective paint or tiles, can reduce the heat absorbed and radiated by buildings [77] and streets. Also, improving building design to reduce heat absorption by incorporating features such as green roofs, cool roofs, and shading devices [87]. Furthermore, reducing energy consumption could reduce the heat generated by buildings and appliances (mainly using air conditioning units), thereby reducing the ambient temperature in urban areas.
- Increasing the number of water bodies, such as lakes, fountains, and water parks, can reduce the UHI effect [70] and UH.

4.3.3 Planned Urban Development

Planned urban development and climate change adaptation could be critical in reducing heat stress in megacities, particularly New Delhi, Mumbai, Kolkata, Chennai and Ahmedabad in India, Dhaka, and Chittagong in Bangladesh, which showed a higher number of hours exposure to heat stress in our studies compared to Pune, Hyderabad, and Bengaluru. Incorporating the following measures into urban planning and development could reduce the negative impacts of heat stress on health, the economy, and the environment in the megacities:

- Planned integration of green infrastructure —downspout disconnection, rainwater harvesting, rain gardens, planter boxes, bioswales, permeable pavements, green streets and alleys, green parking, green roofs, urban tree canopy, land conservation parks [88]— into urban planning could mitigate heat stress in urban areas [89], cool the environment [90], reduce air pollution, and enhance urban biodiversity [91].
- Effective water management strategies, including rainwater harvesting, green roofs, and permeable pavements, could reduce the heat absorbed and radiated by buildings, pavements and streets [92] and the risk of flash flooding during extreme weather events.
- Encouraging sustainable transportation such as public transportation, walking, and cycling might decrease the heat and air pollution and greenhouse gas emissions generated by motor vehicles and promote physical activity [93].
- Building design strategies (such as using energy-efficient materials, green roofs, and bioclimatic design) could reduce heat absorption and improve thermal comfort for occupants [94].
- Community engagement would raise awareness about the impacts of heat stress and the importance of adaptation measures [29]. Community-led initiatives such as urban gardens and tree planting could also reduce the UHI effect [95].

4.3.4 Megacities and Climate Migration

Climate migrations were exacerbating the heat stress in megacities in India and Bangladesh as more people moved to urban areas in search of better opportunities; cities were becoming overcrowded, and unplanned urban development was leading to the UHI effect and worsening the megacities' services by enlarging the informal settlements [96]. Additionally, many climate migrants in informal settlements lived on low wages and could not afford air conditioning or other cooling technologies, making them more vulnerable to heat stress [97]. Providing affordable housing options could reduce the number of people living in informal settlements and slums, often more prone to heat stress due to poor ventilation and overcrowding. Furthermore, adopting appropriate localised climate adaptation strategies and policy implementation might reduce the climate migration to the megacities in the first place, thereby keeping heat stress management at a manageable scale in megacities.

4.3.5 *Lack of data*

Various studies pointed out the lack of data on India and Bangladesh's formal and informal labour force [98, 99]. Due to the lack of available granular data on the formal and informal labour force and work patterns and their health issues in connection to extreme heat in the selected megacities of India and Bangladesh, estimating the impact of HI and ESI on the different parts of the megacity or workforce was out of the scope of this study. It is recommended that the local government, city corporations and responsible authorities invest in collecting granular data on the formal and informal labour force, their work pattern and health issues connected to extreme heat in the megacities to facilitate detailed, evidence-based research and policy development.

5 Conclusion

As ten megacities (a global total of 33) were situated in South Asia (India and Bangladesh) and extreme heatwaves were becoming an annual phenomenon, in this study, we evaluated historical climate data for heat stress (HI and ESI) in those megacities. We also estimated the vulnerability of the working population in terms of annual hours reduced for light, moderate and heavy work in megacities due to heat stress.

Our results showed that most megacities were experiencing 'Extreme caution' and 'Danger' levels of Heat Stress, which may lead to heat cramps, exhaustion, stroke, and even death. We estimated a 1.2-2.3°C and 2-5.31°C increase by 2019 in the HI since 2015 and 2011, respectively, in the megacities of Bangladesh (Dhaka and Chittagong) and India (New Delhi, Mumbai, Kolkata, Ahmedabad, and Chennai). The vulnerable population in the studied megacities might have to reduce annually 0.25-860.6h (light work), 43-1595.9h (moderate work) and 291-2402h (heavy work) of work hours due to extreme heat in 1990-2019. Furthermore, in India (apart from Bengaluru) and Bangladesh, all the megacities showed elevated exposure to vulnerable level ESI in 2019 compared to 2011. The increased frequency and intensity of heat waves in these regions adversely affect health, income, and labour productivity. It also significantly impacts the economy, including reduced GDP and setbacks in attaining SDGs.

The megacity's urban development, devoid of sustainable contextual climate change adaptation and mitigation strategies, exacerbated the heat stress-linked vulnerabilities. We discussed the reasons behind the heat stress: climate change, urban heat island (UHI) effects, unplanned urban development, lack of green spaces and trees, poor infrastructure and living conditions, and occupational exposure to heat. We recommended the implementation of contextualised Heat Action Plans (HAPs) along with strategies for UHI reduction, planned urban development, and management of climate migration in the studied megacities, which could be essential for adaptation to the evident heat stress from this study. Our study enhances our understanding of the effect of climate change on megacities in developing South Asian countries. It highlights hazardous futures that require action, as, by 2050, more people will be living in megacities and cities than in rural areas in South Asia.

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