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Assessing heat-related health risk in Ghana using bioclimatic indices

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ABSTRACT

Climate change is driving rising temperatures worldwide, intensifying the risk of heat-related illnesses such as heat stress, heat stroke, and exhaustion. In Ghana, however, the health risks associated with extreme heat are often underestimated, as most existing assessments rely on subjective perceptions rather than scientifically validated indices. This study addresses this gap by assessing heat-related health risks across Ghana using the Universal Thermal Climate Index and Humidex. Hourly temperature and relative humidity data were extracted from the ERA5 reanalysis dataset to compute bioclimatic indices across all agroclimatic zones. The results show widespread warming across the country, with minimum temperatures increasing more rapidly than maximum temperatures. The Sudan and Guinea Savannah zones experience the highest levels of thermal stress, while declining humidity in the Forest zone further exacerbates discomfort. Seasonally, the greatest risks occur between November and May, peaking in March and April, and diurnally, exposures are most severe between 11:00 and 17:00 h. These findings demonstrate that extreme heat is an escalating public health threat in Ghana, particularly in the Sudan and Guinea Savannah zones. The study highlights the urgent need for adaptation measures such as public awareness campaigns, heat early-warning systems, and climate-resilient cooling infrastructure. By providing robust, index-based evidence, this work contributes valuable insights for policymakers, urban planners, and public health authorities to design effective strategies that protect vulnerable populations from the growing health impacts of climate change.

Introduction

Heat-related illnesses occur when elevated temperatures and high humidity disrupt the body's ability to regulate its core temperature, leading to a wide range of health problems, ranging from mild conditions such as heat cramps and rashes to severe cases such as heat exhaustion and heat stroke [1–4]. Climate change is increasingly evident due to more frequent and intense heat events such as heat waves and deterioration of air quality [5,6]. For example, the Intergovernmental Panel on Climate Change

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(IPCC) observed a 1.59 °C increase in global mean surface temperature during 2011–2020 compared to 1850–1900 [7]. This rise in temperature has triggered more frequent extreme heat events, such as heatwaves, which exacerbate chronic conditions such as cardiovascular disease, respiratory problems, and diabetes, contributing to higher mortality rates [8–11]. In regions like Ghana, where hot and humid climates prevail, the projected increase in temperatures [12] poses a serious risk to public health, particularly among vulnerable groups such as older adults, individuals with chronic diseases and young children [13–16]. Understanding the risk of heat exposure in Ghana is a critical step in implementing effective public health interventions.

Extreme heat events have increasingly occurred throughout the world, often with severe consequences. For example, a heatwave in England in 2006 resulted in 2323 excess deaths [17], while similar events in 2020 led to an additional 2556 fatalities [18]. In China, heat wave exposure between 2010 and 2020 was associated with an annual average of 13,262 preterm births attributable to climate change [19]. In the United States, a 16-year study reported 40,019 hospitalizations related to heat, with the highest rates observed in regions characterized by temperate arid summers [20]. Africa is experiencing similar trends, with rising temperatures and increased frequency of heat waves. In 2015, a Northeast African heat wave resulted in more than 90 deaths in Egypt [21], while record high temperatures of 48.4 °C and 47.6 °C were documented in South Africa and Egypt, respectively [22]. The northern regions of Africa have experienced an average of 40–50 days of heatwaves annually from 1989 to 2009 [23]. More recently, in April 2024, Mali faced a severe heat wave with temperatures soaring to 40 °C, leading to dehydration, heatstroke, and 102 deaths in the first four days [24].

During the past three decades, substantial evidence indicates that the climate in Ghana has undergone significant changes [25, 26]. For example, Yamba et al. [27] identified major changes in climatic patterns, prompting a reclassification of the country's climatic zones to reflect the ongoing climate change. Other studies have also documented a steady warming trend from 1981 to 2020, with the most pronounced changes occurring in the last two decades [28,29]. Despite the growing body of evidence on the changing climate in Ghana, there remains a critical gap in understanding the associated risks of heat-related illnesses across the country, especially on a spatio-temporal perspective. Although Wiru et al. [30] explored the relationship between apparent temperature and mortality, these analyses were geographically confined to Kintampo (an area in the middle part of Ghana) and the use of apparent temperature as a bioclimatic index is scientifically limited. Studies by Frimpong [31] and Kwasi et al. [32], highlighted the impact of heat stress on the health and productivity of farmers in northern Ghana. The issue with these two studies is that they were perception based and not an objective risk assessment and geographically limited to certain parts of northern Ghana. Given the warming trends in Ghana's climate and limited heat health risk information across the country, it is necessary to provide an objective and comprehensive assessment of when, where and what risk occur to support early warming and heat-risk management systems in Ghana.

This study aims to fill critical knowledge gaps by conducting a comprehensive nationwide assessment of heat-related illness risks in Ghana within the context of a changing climate. First, we examined long-term trends in temperature and relative humidity over a 30-year period (1991–2020). Next, we evaluated the spatial and temporal risks of heat-related health conditions such as heat stress, heat stroke, and heat exhaustion using the Humidex (HD) and Universal Thermal Climate Index (UTCI) as bioclimatic indicators. Due to limited availability of data on heat-related hospital admissions and mortality across the country, the study does not establish direct links between climatic conditions and observed health outcomes. Instead, risk assessments are based on established HD and UTCI thresholds, which define the limits of human thermal comfort beyond which individuals are at risk of heat-related illnesses. Our findings highlight vulnerable hotspots and provide critical insights to inform public health strategies designed to protect at-risk populations. Our analysis of regional variations in heat exposure and their associated health effects underscores the need for targeted, region-specific interventions to mitigate the adverse impacts of heat stress throughout the country.

Data and methods

Study area

The study covered all of Ghana, which is located in West Africa between longitude 3.5°W and 1.5°E, and latitude 4.5°N and 12°N (see Fig. 1). Ghana is bordered to the west by Côte d'Ivoire, Togo to the east, Burkina Faso to the north and to the south by the Gulf of Guinea. The country has a warm, humid and monsoonal climate classified into five zones namely; Coastal, Forest, Transition, Guinea and the Savannah of Sudan [27]. The annual average temperature decreases southward with ranges from about 26.0 °C in the south to approximately 30.0 °C in the extreme north [27]. However, annual average rainfall increases southward and ranges from 800 mm in the north to about 1800 mm in the forest zone [27]. The northern parts of the country (including the Sudan and Guinea Savannah zones) experience a unimodal rain season mainly during the months of May to October. The southern part of Ghana, which comprises the transition, forest and coastal zones, has a cooler temperature compared to the north and a bimodal rainfall distribution. The first rainy season runs from March to July, with a peak in June, while the second season runs from September to mid-November, with a peak in October. Between December and February, the harmattan, which is a north-easterly desert wind, dominates the entire country [33]. The harmattan wind is more prevalent in the north, lowering the humidity of the country during this period and also resulting in hotter days and cooler nights [34].

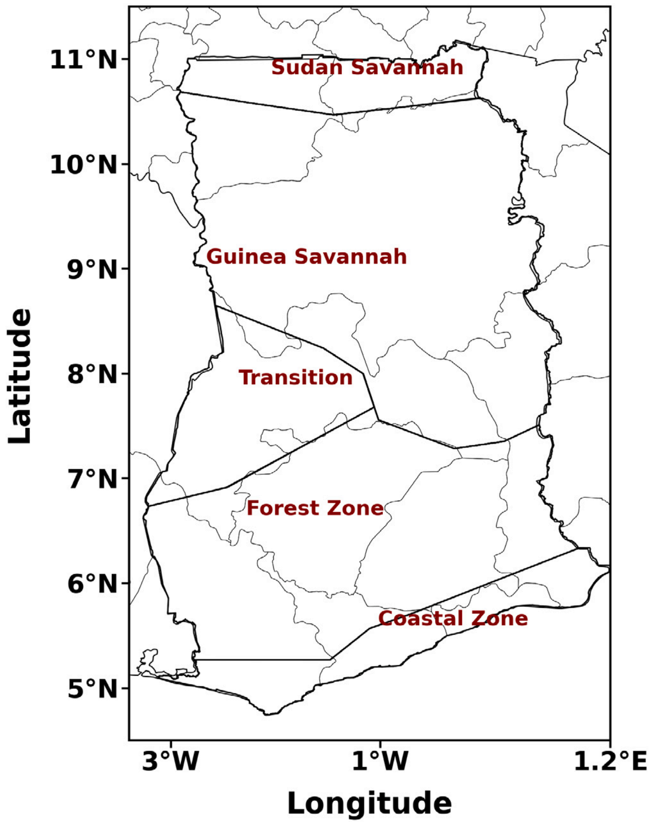

Fig. 1. Map showing the Agro-climatic zones of Ghana.

Data

In this study, the hourly minimum and maximum 2-meter air temperature data as well as the relative humidity data were used, spanning the period 1991–2020. These datasets were recovered from the fifth generation of the European Center for Medium-Range Weather Forecast Reanalysis (ERA5) for Ghana. ERA5 is a spatially gridded reanalysis product with a resolution of 0.25° × 0.25°and is available worldwide on an hourly time scale at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview and https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels?tab=download from 1979 to the present. ERA5 was preferred to other datasets due to its high spatio-temporal resolution and availability. In addition, the data product was built from an advanced data assimilation with long-term consistency and robust quality control. We also performed a validation study (as shown in the Supplementary Material (SM); Figures SM4 and SM5) and found ERA5 to mimic well with the ground observations. Besides, previous validation studies [35,36] have widely recommended it for meteorological research in Africa. The extracted hourly data were resampled daily and monthly using Climate Data Operator (CDO) software. The average daily and monthly temperature was calculated from the corresponding minimum and maximum temperatures.

Analysis

Heat-related health risk

The risks of heat illness were evaluated using two bioclimatic indices, namely HD and the UTCI. Humidex is a simple thermal comfort index based on air temperature and humidity [37]. It was used because it is widely considered to be one of the most robust and effective comfort index. Its values are directly comparable with the dry air temperature and associated with corresponding degrees of thermal comfort [38]. Moreover, the Humidex is easier to calculate given that it requires only two input parameters (temperature and humidity), which are commonly measured by meteorological stations. We computed the Humidex following the widely used empirical equation developed by Masterton and Richardson [38] as:

$$\mathrm{HD} = \mathrm{T} + \frac{5}{9}(\mathrm{e} - 10) \tag{1}$$

where T is the air temperature (°C), e is the partial vapor pressure (hPa). The partial vapour pressure (e) was computed using the relative humidity, Ur (%), and the saturation vapour pressure, esat (hPa), as expressed in Eq. (2) below:

$$e = \frac{U_r \cdot e_{sat}}{100}, \tag{2}$$

esat which depends on air temperature alone was calculated using the Tetens formula [39]:

$$e_{sat} = 6.112 \times 10^{\frac{7.5T}{T+237.7}} \tag{3}$$

Humidex has no specific measurement unit and is mostly associated with the same unit of temperature (°C), although it is not a physical variable. The discomfort levels were then detected using comfort levels corresponding to the Humidex values as shown in Table SM1.

We used UTCI data from the model architecture developed by Havenith et al. [40] and Fiala et al. [41] with detailed documentation in Broede et al. [42]. This model is expressed mathematically as;

$$\mathrm{UTCI}(Ta, Tr, va, \rho_a) = Ta + Offset(Ta, Tr, va, \rho_a) \tag{4}$$

Where; Ta = Air Temperature, T_r = Mean radiant or radiation temperature, υ_a = wind speed, and ρ_a = relative humidity or vapor pressure. The UTCI model takes into consideration the reference outdoor environment that would elicit in the human body the same physiological response (namely sweat production, shivering, skin wettedness, skin blood flow and rectal, mean skin and face temperatures) as the actual environment [42]. Other environmental factors considered in the model include mean radiant temperature (Tr), wind speed (va), and humidity, expressed as water vapor pressure (pa) or relative humidity (RH). UTCI was used because it integrates multiple environmental factors (temperature, humidity, wind, and radiation) and simulates human physiological responses using an advanced thermoregulatory model [43]. In addition, it is highly sensitive to minor climatic changes and more accurately reflects thermal stress and comfort compared to other indices. The precomputed UTCI data are available in ERA5 and were extracted for Ghana over the period 1991–2020, which corresponds to the latest 30-year climatological standard normal period as defined by the World Meteorological Organization(WMO) [44]. To determine the risk level, the calculated UTCI values were measured against the following standards as detailed in Table SM2.

Trends in climate variables

Trends in 2 meter air temperature (minimum (Tmin), mean (Tmean), and maximum (Tmax)), relative humidity (RH), HD, and UTCI were analysed using the Mann–Kendall (MK) test. MK is a nonparametric statistical method for analysing trends in climatological time series of climate variables [45]. MK was used because it does not require the data to follow a normal distribution and is not sensitive to outliers and abrupt breaks caused by inhomogeneous time series [46]. MK test operates under the null hypothesis (H_o) that there is no trend in the data, that is, the data points are independent and randomly ordered, and tests this against the alternative hypothesis (H_a) that there is a trend [47]. The MK statistics was calculated as shown below:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \tag{5}$$

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} 1 & \text{if } x_j - x_i > 0 \\ 0 & \text{if } x_j - x_i = 0 \\ -1 & \text{if } x_j - x_i < 0 \end{cases} \tag{6}$$

where, x_i and x_j are the annual values in i and j years respectively, and n is the number of observations. The strength of the trends detected in the climate variables were measured using the Kendall's tau which has values ranging between ±1. Positive tau values suggest that the ranks of correlated variables increase together, while a negative correlation indicates that as the rank of one variable increases, the other decreases [48]. The rate of change in the trends of the climate variables were determined using Sen slope estimator. This estimator is calculated as [49]:

$$f(t) = Q(t) + B \tag{7}$$

where Q is the slope, B is the constant. Also, the slope Q is derived as shown;

$$Q_i = \frac{X_i - X_j}{i - j}, i = 1, 2, 3, 4, ..Nj > k \tag{8}$$

Results

Trends in temperature and relative humidity (RH)

Figs. 2 and 3 presents the annual trends in maximum, mean, and minimum temperatures and relative humidity for each climatic zone in Ghana. The details of the trend statistics are presented in Table SM3. In all zones, the temperature showed significant warming patterns coupled with a significant decrease in relative humidity. The minimum temperature showed the fastest warming followed by the mean temperature and lastly by the maximum temperature in all the zones. In the coastal zone, the maximum temperature (T_x), which ranged between approximately 28 °C and 31 °C, showed a strong positive trend, increasing at a rate of

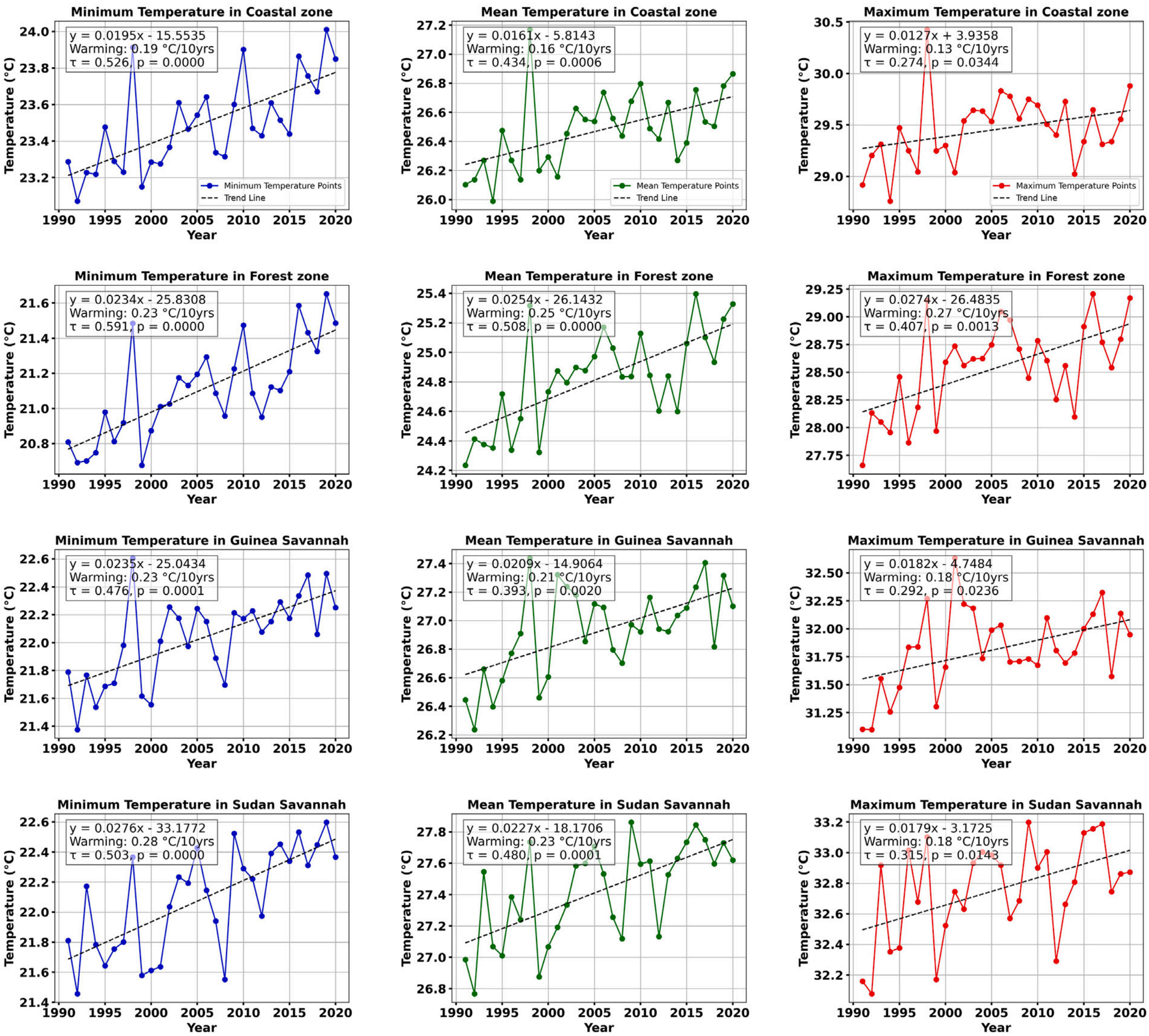

Fig. 2. Annual trends in temperature over the climatic zones of Ghana. First column: minimum temperature, middle column mean temperature, third column: maximum temperature.

0.0127 °C per year (see Table SM3). Similarly, the mean temperature (T_m), which varies from 26 °C to 27.5 °C, demonstrates a significant upward trend at a warming rate of 0.0161 °C. The minimum temperature (T_n), with values ranging from 22 °C to 24 °C, followed the same trajectory, displaying a significant positive trend at a rate of 0.0195 °C per year. Relative humidity (RH) in the coastal zone revealed an upward trend that was statistically insignificant (see Table SM3).

The Forest Zone which had the lowest temperature ranges displayed the fastest warming compared to other zones. T_{max}, which ranged from 27.6 °C to 29.2 °C, warmed at a rate of 0.0274 °C per year, T_{mean}, spanned between 24.6 °C and 25.4 °C warmed at a high rate of 0.0254 °C per year, while T_{min}, with values between 22 °C and 24 °C, showed a warming rate of 0.0235 °C. Unlike temperature, the relative humidity in the forest zone ranged between 74% and 81% and exhibited a statistically significant downward trend at a rate of −0.0784% annually, as seen in Table SM3.

In the Guinea Savannah Zone, T_x ranged from 31 °C to 33 °C warming at a rate of 0.0182 °C per year, T_m with values between 26.2 °C and 28 °C increasing at a rate of 0.0209 °C, while T_n, spanned from 21 °C to 23 °C and changed at a rate of 0.0235 °C per year. RH in the Guinea Savannah showed low ranges (55.5% and 65.5%) compared to that of the forest zone and with a non-significant downward trend at a rate of −0.0315% annually.

The Sudan Savannah Zone showed the highest temperature and the lowest RH compared to other zones. T_x ranged from 32 °C to 33.2 °C with an upward trend at a rate of 0.0179 °C annually. T_m, spanned from 26 °C to 28 °C and warms at a rate of 0.0227 °C per year, while T_n, varied between 21 °C and 23 °C with a warming rate of 0.0276 °C per year. Relative humidity was in the low range of 48% and 56% with a statistically insignificant downward trend.

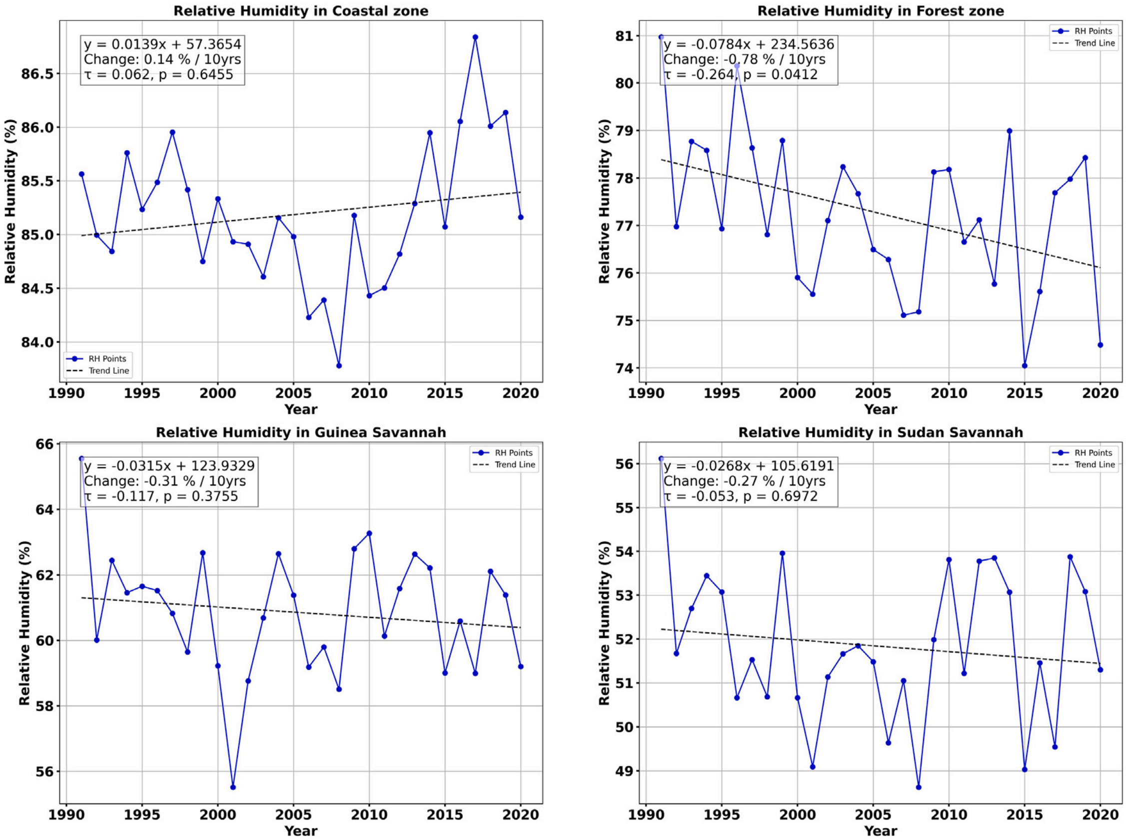

Fig. 3. Annual trends in relative humidity over the climatic zones of Ghana.

Spatio-temporal variation in HD and UTCI

Fig. 4 illustrates the spatial variations in monthly Humidex (HD) across the country. In general, HD values are highest in the months of November to May, with extreme values in February to April. For all months with high HD, the Sudan Savannah showed the highest, followed by the Guinea Savannah, then the Forest, while the Coastal areas showed the lowest among all the zones. In January, for example, the HD values were as low as 30.5 °C in the southern part of the country and as high as 36.5 °C in the northern part. The month of February showed a similar distribution but with slightly increased increased HD values 31.5 °C in the south to 38.5 °C in the north. The rise in HD signals the intensification of heat in the northern regions as the dry season continues. In March, HD values reached their peak, ranging from 30.5 °C in the south to a maximum of about 40.5 °C in the north, particularly in the Sudan Savannah. In April, a decline in the upper range of HD values is observed, ranging from 30 °C to 39 °C in the south and north, respectively. This downward trend continues into June, with values further dropping to between 27 °C and 32 °C. In particular, the lowest HD values occurred from July to September with values ranging between 25 °C and 28 °C.

The UTCI (see Figure SM1) revealed distinct similar seasonal patterns to that of HD except some slight variations in the dry season especially the months of December and January. During the dry season, which spans December to February, higher UTCI values are predominantly recorded in the southern regions, while the northern regions experience relatively lower values. Specifically, in December and January, the UTCI values range from approximately 23 °C in the northern parts to 30 °C in the coastal and forested areas of the southern. In February, this geographical gradient remains evident, with UTCI values slightly increasing, ranging from 27 °C in the north to 32 °C in the south. From March to June, there is a seasonal reversal in the UTCI distribution. In this period, the northern regions experience higher UTCI values compared to the southern regions. March to May, in particular, marks the peak of UTCI values throughout the country, with extreme temperatures reaching 34 °C in the northern Sudan and Guinea Savannah zones, while the Transition, Forest and Coastal zones record relatively lower values, averaging around 30 °C. A noticeable decline in UTCI values is observed in July and August, coinciding with the peak of the monsoon season. During this period, the UTCI values remain consistently low, ranging from 24 °C in the southern regions to 29 °C in the northern regions. Between September and November, the UTCI values gradually increase once again. In September, temperatures begin to increase modestly, with values ranging from 27 °C in the south to 29 °C in the north. The warming trend peaks in October, where the UTCI values reach approximately 28 °C in the southern regions and 30 °C in the north. In November, the onset of another seasonal shift is observed, marked by a gradual reversal of the north-south warming pattern.

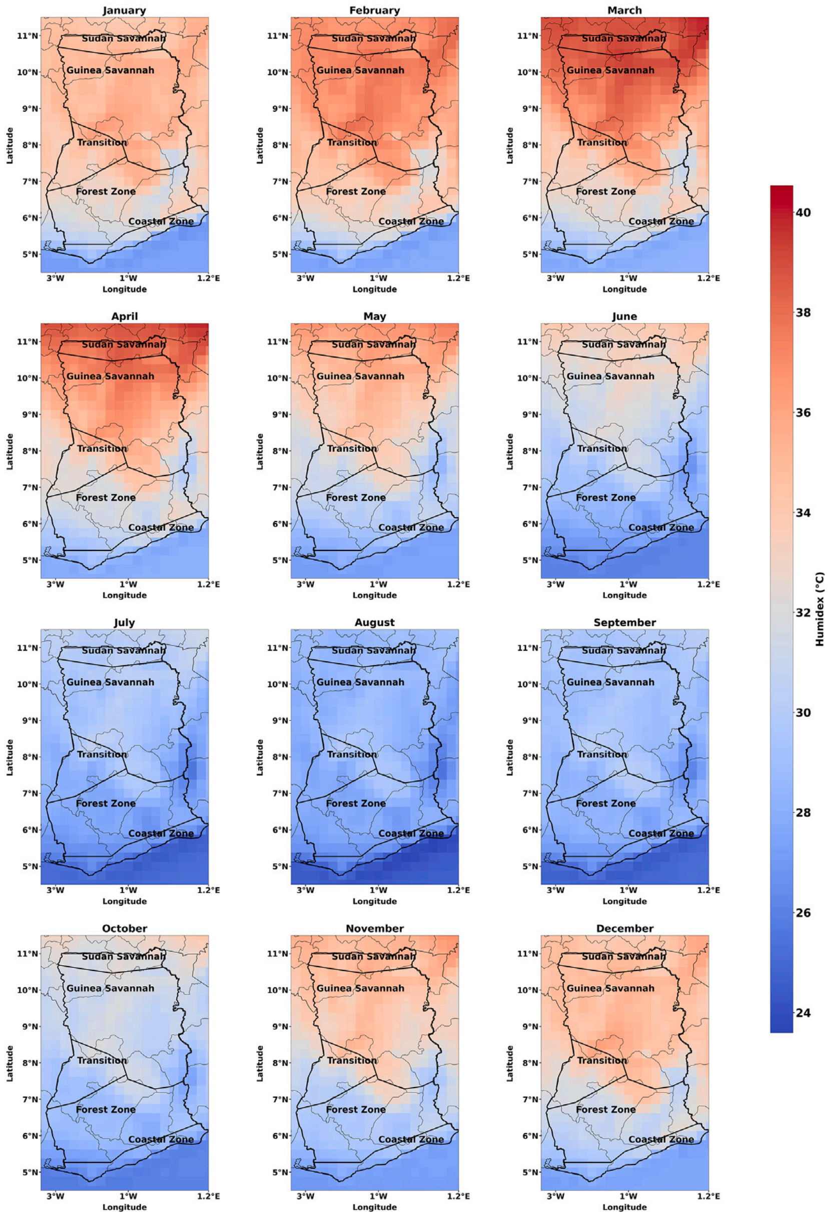

Fig. 4. Spatial variation in monthly average Humidex over Ghana (1991–2020).

Annual trends in HD and UTCI

Fig. 5 shows the annual trends in Humidex (HD) in four different climatic zones in Ghana during the period 1991–2020 with detailed trend statistics shown in Table SM4. In all zones, consistent and significant upward trends in HD values were observed. In the Sudan Savannah zone, HD values ranged from 31 °C to 33.5 °C with a statistically significant upward trend at a rate of 0.0333 °C per year. The Guinea Savannah zone exhibited a similar trend, increasing at an annual rate of 0.0163 °C with ranges from 30.5 °C to 33 °C. The forest zone, despite showing low HD values of 26.5 °C, saw increases to 29.5 °C, represented the steepest trend among all zones with an annual rate of 0.0229 °C. Lastly, the coastal zone showed the lowest overall HD values, ranging from 26 °C to 28.4 °C. It also showed a significant upward trend, increasing at a rate of 0.0109 °C per year. A parallel analysis performed with the UTCI Index is provided in Figure SM2 and a detailed trend statistics in Table SM4.

Similarly to the trends observed in HD, all zones showed consistent and significant upward trends in UTCI values. The Sudan Savannah showed the most significant increase, rising from 31.5 °C to 35.0 °C at a rate of 0.0194 °C per year (see Table SM4). Similarly, the Guinea Savannah exhibited a notable increase, with UTCI values increasing from 31.0 °C to 34.0 °C at a rate of

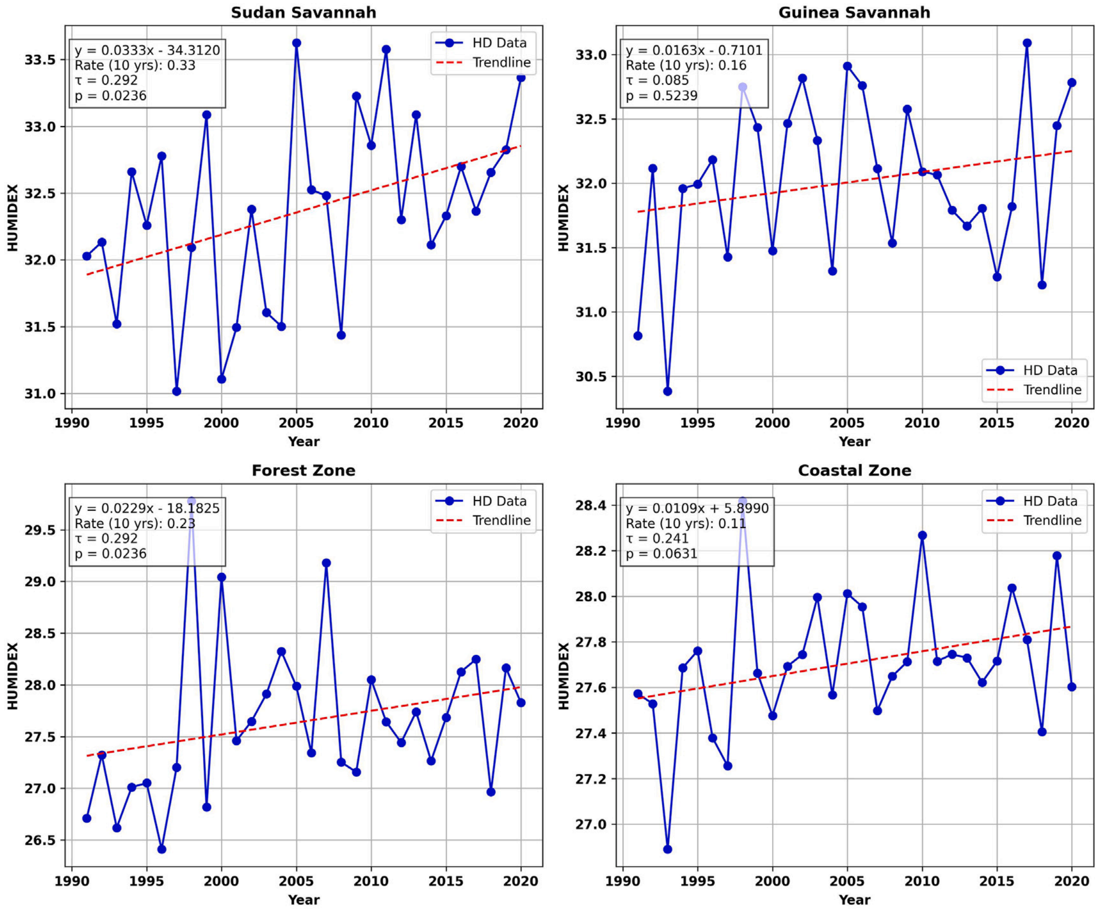

Fig. 5. Annual trends in Humidex gr(HD) in four climatic zones.

0.0229 °C per year. Like HD trends, the Forest zone showed the steepest UTCI trends. UTCI values increased from 28.0 °C to 31.0 °C in a significant positive upward trend with a rate of 0.0260 °C annually. The coastal zone recorded UTCI values that increased from 27.5 °C to 29.5 °C, again showing a significant positive upward trend at a rate of 0.0118 °C per year.

Hourly variations of humidex and UTCI selected months

In the analysis of HD and UTCI values spatially, a clear seasonal pattern emerged. The months of February, March, April, and May consistently recorded the highest HD and UTCI values, indicating peak heat stress during this period. In contrast, July and August showed significantly lower values reflecting a reduction in thermal stress. These distinct differences in thermal conditions between the two periods provide a compelling rationale for focusing on these months to examine hourly variations. Fig. 6 shows the hourly variations of Humidex (HD) in different climatic zones in Ghana for selected months. The observed trend exhibits a sinusoidal pattern, consistent between all climatic zones and months. Specifically, HD values are lowest around 6am, peaking at approximately 3pm and subsequently declining throughout the night, returning to low values by 6am the following day. In general, In all zones, HD intensity is highest from February to April and then declines by August. In terms of climatic zones, the Sudan Savannah zone consistently recorded the highest HD values, followed by the Guinea Savannah zone, the Forest zone, and finally the coastal areas, which exhibit the lowest values. During February, March, April and May, HD values in the Sudan and Guinea Savannah zones remain above 30 °C throughout the day. At 6am, these zones exhibit minimum values of 30 °C, which increase to peak values of approximately 43 °C between 12pm and 6pm. The forest zone shows lower HD values compared to the Sudan and Guinea Savannah zones. In this zone, HD values range from 25 °C to 30 °C between 12am and 9am, rising to a peak of about 38 °C between 12 pm and 7 pm. Unlike other zones, the coastal zone does not show significant variations in HD values. Throughout the day, HD values in the coastal zone range between 27 °C and 31 °C, with slight peaks observed from 11am to approximately 4pm. Similar results were also observed using the UTCI depicted in Figure SM3.

Throughout all months, the UTCI values are highest in the Sudan and Guinea Savannah zones, followed by the Forest zone, while the coastal zone showed the lowest UTCI values. Throughout the day, UTCI values are generally low from 12am to 6am and from

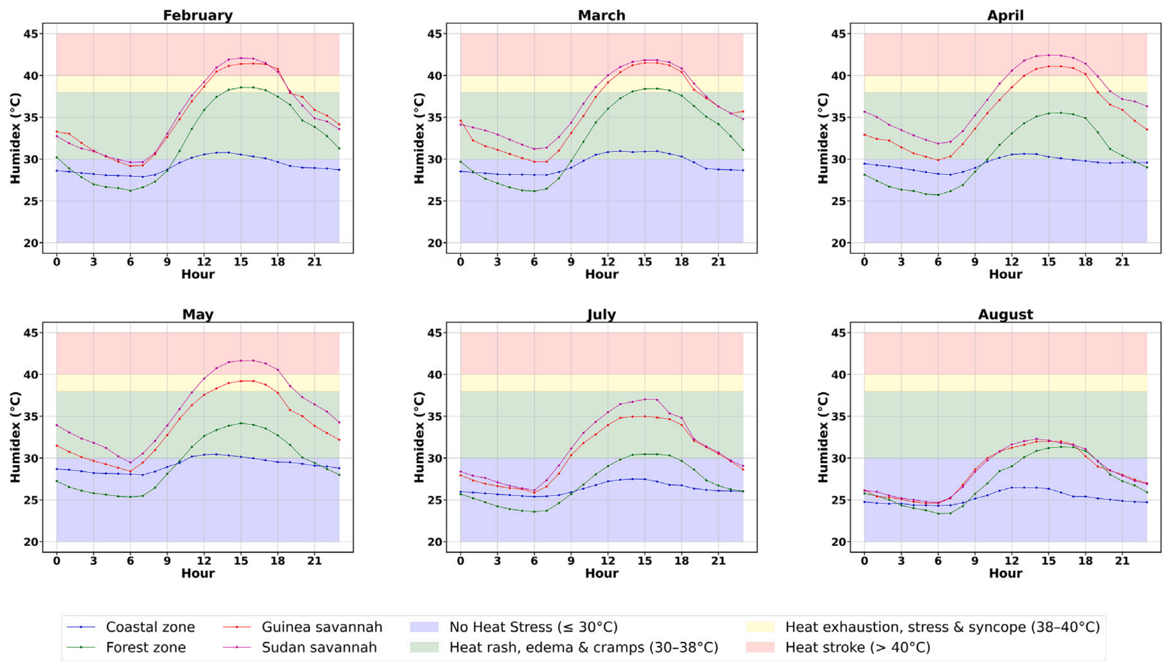

Fig. 6. Hourly of Humidex for selected months.

6pm to 11pm. Higher UTCI values are observed between 6am and 6pm, peaking between 11am and 5pm. During peak hours in the Sudan and Guinea Savannah zones, UTCI values range from 35 °C to 45 °C in February, March, April, and May, decreasing to between 30 °C and 35 °C in July and August. Similarly, the forest zone records UTCI values ranging from 35 °C to 40 °C degrees in February, March and April, declining between 30 °C and 35 °C in May, July, and August. The coastal zone consistently exhibits lower UTCI values, ranging from 25 °C to 30 °C degrees throughout all months.

Discussion

Trends in temperature and relative humidity

The analysis revealed statistically significant increasing trends in maximum, mean, and minimum temperatures across all agroclimatic zones in Ghana, with minimum temperatures (nighttime warming) rising faster than maximum and mean temperatures. Relative humidity showed a declining trend in the Guinea, Sudan, and Forest zones but an increasing trend in the coastal zone. The consistent warming across Ghana indicates progressive intensification of thermal stress, with nighttime warming being particularly critical since it reduces the body's ability to recover from daytime heat. Declining relative humidity in most zones, combined with rising temperatures, suggests greater reliance on evaporative cooling, which can lead to dehydration and amplify heat stress [14]. Conversely, the simultaneous rise in both temperature and humidity in the coastal zone creates compounded risks, as reduced sweat evaporation impairs thermoregulation, increasing vulnerability to heat-related illnesses [50]. These findings align with earlier research that identified significant warming trends across Ghana [27,51,52]. The rapid nighttime warming supports prior observations of enhanced urban heat island effects due to land-use change and reduced vegetation cover [25,53]. For instance, the change in land cover has increased over the past three decades due to deforestation and urbanization [53]. This has led to reduced vegetation and natural cooling mechanisms, leading to increased heat retention, especially at night. The humidity patterns echo broader regional climate studies, but recent work shows the humidity–health relationship is complex, with some studies reporting conflicting physiological and epidemiological evidence on whether humidity exacerbates or moderates heat risks [54–57]. The increasing thermal burden has direct implications for public health, especially for vulnerable groups such as the elderly, children, and outdoor workers [58]. Policy interventions should integrate climate adaptation measures such as urban greening, improved building design, and public heat-health awareness campaigns. Moreover, understanding the nuanced role of humidity in health outcomes is critical for refining heat-health warning systems and improving predictive models under future climate scenarios.

Heat-related health risks

Both HD and UTCI exhibited strong seasonal and spatial variability. From November to May, HD values exceeded 34 °C, peaking at 40 °C in March/April in the Savannah zones, indicating high risk of heat exhaustion and heat stroke. Conversely, from June to

October, HD values dropped to milder levels (25–32 °C) due to the moderating influence of the monsoon. UTCI followed similar seasonal shifts, with extreme values in March in northern zones and cooling during June–August. The results suggest that heat stress is not uniformly distributed but follows clear spatio-temporal patterns, with the Sudan Savannah consistently experiencing the most extreme conditions. This seasonal variability indicates that exposure risks peak just before the rainy season, when reduced humidity and high solar radiation create the most hazardous conditions. These findings mirror studies on Sahelian heat waves and the moderating role of the West African monsoon [33,59]. The seasonal transitions observed also align with earlier work on monsoon dynamics in West Africa [60], which highlighted their role in reducing thermal stress during wet periods. Identifying peak-risk months is critical for developing seasonal heat-health warning systems. Public health agencies should prioritize preparedness in March–April, when risks of fainting, heat exhaustion, and heat stroke are highest. Regional differences underscore the need for locally tailored interventions, particularly in the Sudan Savannah, where vulnerability is greatest.

The long-term analysis showed upward trends in both HD and UTCI across all agroclimatic zones. The Sudan and Guinea Savannah zones shifted from moderate to severe discomfort categories, while even the Forest and Coastal zones, historically less exposed, are now showing rising thermal stress. This progression indicates that climate warming is translating into worsening human thermal burden. Outdoor workers, particularly in agriculture and construction, are becoming increasingly vulnerable to heat exhaustion, syncope, and potentially fatal heat stroke, with occupational health risks rising sharply in the hotter inland zones. Our findings confirm earlier reports of intensifying occupational heat stress in Sub-Saharan Africa [61], as well as work linking deforestation and urbanization to reduced natural cooling and enhanced thermal discomfort [31,62]. While coastal areas have shown slower increases, the urban heat island effect is amplifying local risks in cities, consistent with global urban climate literature. The observed trends highlight the urgent need for occupational health guidelines and climate-smart policies in Ghana. Failure to recognize the escalating risks could undermine labor productivity, food security, and health resilience. Urban planning and rural development strategies must incorporate adaptive cooling strategies, shading infrastructure, and behavioral interventions.

The hourly analysis showed that HD and UTCI reached extreme levels in the afternoon hours during hot months (February–May), particularly in the Sudan and Guinea Savannah zones, where UTCI values often exceeded 45 °C. The Forest zone recorded moderately high values, while the Coastal zone experienced the lowest discomfort, moderated by oceanic breezes. Seasonal cooling during July–August reduced but did not eliminate heat risks. The diurnal cycle indicates that peak afternoon hours are the most hazardous for human health, particularly for outdoor laborers exposed to prolonged solar radiation. Even in relatively cooler regions, vulnerable groups engaging in physical activity face risks of dehydration, heat rash, and cramps. These findings are consistent with prior assessments of daily thermal stress in West Africa, where afternoon peaks in heat load are the dominant driver of health risks [62]. The moderating role of coastal breezes aligns with studies highlighting the buffering effect of proximity to large water bodies on urban thermal comfort. Hourly risk profiles emphasize the importance of adaptive work-rest cycles, shaded rest areas, and hydration strategies, particularly for agricultural and construction workers. Public health authorities should incorporate time-specific advisories into early warning systems, encouraging avoidance of peak-heat hours.

Impacts of socio-economic status, occupation, and access to cooling on heat-health risks

The increasing risk of heat-related illnesses in Ghana has critical implications for vulnerable populations, with impacts unevenly distributed across different groups. Socio-economic status, occupation, and access to cooling resources play a central role in shaping both individual and community vulnerability to extreme heat [63]. Outdoor workers, particularly those in farming, construction, and fishing, are at heightened risk due to prolonged exposure during peak heat hours [64]. Low-income households face an added burden as they often lack access to effective cooling measures such as fans or air conditioning, leaving them disproportionately exposed to extreme heat [65]. Limited availability and affordability of quality healthcare further exacerbate risks, as delays in diagnosis and treatment can increase the likelihood of severe outcomes, including mortality [66]. In urban centers such as Accra, Kumasi, and Tamale, residents of informal or poorly planned settlements are particularly vulnerable. Overcrowding, poor ventilation, and the scarcity of cooling green spaces contribute to heightened exposure and reduced opportunities for relief [67]. Consequently, socio-economic disparities significantly amplify the health risks associated with rising temperatures and humidity, intensifying the burden on disadvantaged groups. These findings highlight the urgent need for equitable adaptation strategies. Policy priorities should include expanding access to affordable cooling technologies, improving healthcare infrastructure, and incorporating green infrastructure into urban planning. In addition, targeted public health interventions are essential for raising awareness and protecting high-risk communities. Such measures are critical to reducing the disproportionate impacts of heat stress and strengthening resilience among Ghana's most vulnerable populations.

Conclusions

This study assessed heat-related health risks in Ghana by applying HD and UTCI as bioclimatic indices, using temperature and relative humidity data derived from the ECMWF reanalysis dataset. The analysis revealed statistically significant warming trends across all agroclimatic zones, with minimum (nighttime) temperatures rising more rapidly than maximum and mean temperatures. These findings confirm progressive climate warming in Ghana, consistent with regional and global climate trends. The bioclimatic indices further highlighted increasing thermal stress, with the Sudan and Guinea Savannah zones experiencing the most extreme conditions. Seasonal fluctuations underscored the moderating role of the monsoon, but the overall trajectory of HD and UTCI points to a growing risk of heat-related illnesses, particularly between 11:00 am and 5:00 pm when exposure is greatest.

This study makes an important contribution by providing the first comprehensive assessment of heat-related health risks in Ghana using bioclimatic indices such as HD and UTCI across multiple spatial and temporal scales. By integrating trend analyses of temperature, relative humidity, and derived thermal indices, the study advances understanding of how climate variability translates into human health risks across agroclimatic zones. A key strength lies in the use of both HD and UTCI, which together capture thermal stress more holistically than temperature alone, thereby offering novel insights into regional disparities and seasonal vulnerabilities. Moreover, the study's emphasis on hourly patterns provides a nuanced perspective on exposure risks, with practical relevance for occupational health and public health interventions.

Despite these contributions, some limitations should be acknowledged. The study relies primarily on observational climate data and derived indices, which may not fully capture individual-level physiological responses or behavioral adaptations to heat. The absence of epidemiological health outcome data limits direct quantification of morbidity and mortality attributable to extreme heat. In addition, the potential effects of urban microclimates (e.g., heat islands) and socio-economic factors could not be fully disentangled at finer spatial scales due to data constraints. Future research should build on these findings by integrating epidemiological data with bioclimatic indices to establish stronger quantitative linkages between heat exposure and health outcomes. High-resolution urban climate modeling could improve understanding of localized heat risks in rapidly growing cities. Further, interdisciplinary studies combining climate science, public health, and socio-economic analysis are needed to explore how access to cooling, occupational patterns, and adaptive behaviors mediate vulnerability. Such research would strengthen the evidence base for targeted interventions and inform heat-health action plans tailored to Ghana and similar climate-vulnerable regions.

CRediT authorship contribution statement

Mary J. Adjei: Methodology, Software, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Edmund I. Yamba:** Conceptualization, Methodology, Validation, Formal analysis, Supervision, and Writing – original draft. **Cascade Tuholske:** Methodology, Validation, Supervision, Writing – review & editing. **Cosmos S. Wemegah:** Methodology, Validation, Writing – review & editing. **Leonard K. Amekudzi:** Conceptualization, Methodology, Validation, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.sciaf.2025.e02926.

Data availability

The ERA5 data used in this work are available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview and https://cds.climate.copernicus.eu/datasets/reanalysis-era5-pressure-levels?tab=download.

References

[1] R.R. Pryor, B.L. Bennett, F.G. O'Connor, J.M. Young, C.A. Asplund, Medical evaluation for exposure extremes: heat, Wilderness Environ. Med. 26 (2015) 69–75.

[2] W.F. Atha, Heat-related illness., Emerg. Med. Clin. North Am. 31 (4) (2013) 1097–1108.

[3] G.S. Lipman, K.P. Eifling, M.A. Ellis, F.G. Gaudio, E.M. Otten, C.K. Grissom, Wilderness medical society practice guidelines for the prevention and treatment of heat-related illness, Wilderness Environ. Med. 24 (4) (2013) 351–361.

[4] R.M. Kester, P.A. Abraham, J.C. Leggit, J.B. Harp, J.B. Kazman, P.A. Deuster, F.G. O'Connor, Heat tolerance testing and the return to duty decision: A two-year case cohort analysis., J. Spec. Oper. Med.: A Peer Rev. J. SOF Med. Prof. (2024) W7TV–MBRZ.

[5] M. De Sario, K. Katsouyanni, P. Michelozzi, Climate change, extreme weather events, air pollution and respiratory health in europe, Eur. Respir. J. 42 (3) (2013) 826–843.

[6] S.I. Seneviratne, X. Zhang, M. Adnan, W. Badi, C. Dereczynski, A.D. Luca, S. Ghosh, I. Iskandar, J. Kossin, S. Lewis, et al., Weather and climate extreme events in a changing climate, Cambridge University Press, 2021.

[7] V. Masson-Delmotte, P. Zhai, H. Portner, D. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, et al., IPCC, 2018: summary for policymakers, global warming of 1.5° c, IPCC Spec. Rep. Impacts Glob. Warm. of 1 (2018).
[8] T. Kapwata, M.T. Gebreslasie, A. Mathee, C.Y. Wright, Current and potential future seasonal trends of indoor dwelling temperature and likely health risks in rural southern africa, Int. J. Environ. Res. Public Heal. 15 (5) (2018) 952.
[9] P.L. Kinney, Temporal trends in heat-related mortality: implications for future projections, Atmosphere 9 (10) (2018) 409.
[10] J.C. Semenza, Climate change and human health, 2014.
[11] A. Haines, R.S. Kovats, D. Campbell-Lendrum, C. Corvalán, Climate change and human health: impacts, vulnerability and public health, Public Health 120 (7) (2006) 585–596.
[12] N.A.B. Klutse, K. Owusu, Y.A. Boafo, Projected temperature increases over northern ghana, SN Appl. Sci. 2 (2020) 1–14.
[13] T.N. Dang, Y. Honda, D. Van Do, A.L.T. Pham, C. Chu, C. Huang, D. Phung, Effects of extreme temperatures on mortality and hospitalization in ho chi minh city, Vietnam, Int. J. Environ. Res. Public Heal. 16 (3) (2019) 432.
[14] R. Gauer, B.K. Meyers, Heat-related illnesses, Am. Fam. Physician 99 (8) (2019) 482–489.
[15] G. Savioli, C. Zanza, Y. Longhitano, A. Nardone, A. Varesi, I.F. Ceresa, A.C. Manetti, G. Volonnino, A. Maiese, R. La Russa, Heat-related illness in emergency and critical care: recommendations for recognition and management with medico-legal considerations, Biomedicines 10 (10) (2022) 2542.
[16] A. Ireland, D. Johnston, R. Knott, Heat and worker health, J. Heal. Econ. 91 (2023) 102800.
[17] S. Kovats, R. Brisley, Health, communities and the built environment, the third uk climate change risk assessment, Technical Report, 10, Prepared for the Climate Change Committee London, 2021.
[18] P.H. England, Heatwave Mortality Monitoring Report: 2020, Technical Report, Public Health England, London, UK, 2020, URL: https://www.gov.uk/government/publications/phe-heatwave-mortality-monitoring/heatwave-mortality-monitoring-report-2020.
[19] Y. Zhang, S. Hajat, L. Zhao, H. Chen, L. Cheng, M. Ren, K. Gu, J.S. Ji, W. Liang, C. Huang, The burden of heatwave-related preterm births and associated human capital losses in China, Nat. Commun. 13 (1) (2022) 7565.
[20] A. Liss, E.N. Naumova, Heatwaves and hospitalizations due to hyperthermia in defined climate regions in the conterminous USA, Environ. Monit. Assess. 191 (2019) 1–16.
[21] D. Mitchell, 14. Human influences on heat-related health indicators during the 2015 Egyptian heat wave, Bull. Am. Meteorol. Soc. 97 (12) (2016) S70–S74.
[22] W.M. Organization, WMO Statement on the Status of the Global Climate in 2015, World Meteorological Organization (WMO), 2016.
[23] K.H. Cook, E.K. Vizy, Impact of climate change on mid-twenty-first century growing seasons in africa, Clim. Dyn. 39 (2012) 2937–2955.
[24] Africanews, No respite from deadly heat in mali and elsewhere in the sahel, Africanews (2024) URL: https://www.africanews.com/2024/04/19/no-respite-from-deadly-heat-in-mali-and-elsewhere-in-the-sahel/.
[25] C.S. Wemegah, E.I. Yamba, J.N. Aryee, F. Sam, L.K. Amekudzi, Assessment of urban heat island warming in the greater accra region, Sci. Afr. 8 (2020) e00426.
[26] J. Ankrah, A. Monteiro, H. Madureira, Extreme temperature and rainfall events and future climate change projections in the coastal savannah agroecological zone of ghana, Atmosphere 14 (2) (2023) 386.
[27] E.I. Yamba, J.N. Aryee, E. Quansah, P. Davies, C.S. Wemegah, M.A. Osei, M.A. Ahiataku, L.K. Amekudzi, Revisiting the agro-climatic zones of ghana: A re-classification in conformity with climate change and variability, PLoS Clim. 2 (1) (2023) e0000023.
[28] B.F. Frimpong, A. Koranteng, F. Molkenthin, Analysis of temperature variability utilising Mann–Kendall and Sen's slope estimator tests in the Accra and Kumasi Metropolises in Ghana, Environ. Syst. Res. 11 (1) (2022) 24.
[29] J. Kwakye, et al., Effect of temperature and rainfall variability on selected crop yields in wenchi municipality of ghana, Am. J. Environ. Clim. 2 (1) (2023) 24–32.
[30] K. Wiru, F.B. Oppong, O. Agyei, C. Zandoh, O.E. Nettey, R. Adda, A. Gasparrini, K.P. Asante, The influence of apparent temperature on mortality in the kintampo health and demographic surveillance area in the middle belt of ghana: A retrospective time-series analysis, J. Environ. Public Heal. 2020 (2020).
[31] K. Frimpong, An appraisal of experiences of climate change and adaptive response to heat stress by farmers in rural ghana, 2015.
[32] F. Kwasi, J. Oosthuizen, E.V. Etten, The extent of heat on health and sustainable farming in ghana–bawku east, Sustain. Agric. Res. 3 (526-2016-37861) (2014).
[33] L.K. Amekudzi, E.I. Yamba, K. Preko, E.O. Asare, J. Aryee, M. Baidu, S.N. Codjoe, Variabilities in rainfall onset, cessation and length of rainy season for the various agro-ecological zones of ghana, Climate 3 (2) (2015) 416–434.
[34] J. Aryee, L. Amekudzi, E. Quansah, N. Klutse, W. Atiah, C. Yorke, Development of high spatial resolution rainfall data for ghana, Int. J. Climatol. 38 (3) (2018) 1201–1215.
[35] D. Parsons, D. Stern, D. Ndanguza, M.B. Sylla, Evaluation of satellite-based air temperature estimates at eight diverse sites in africa, Climate 10 (7) (2022) 98.
[36] S. Gleixner, T. Demissie, G.T. Diro, Did ERA5 improve temperature and precipitation reanalysis over east africa? Atmosphere 11 (9) (2020) 996.
[37] I. Charalampopoulos, A comparative sensitivity analysis of human thermal comfort indices with generalized additive models, Theor. Appl. Climatol. 137 (1) (2019) 1605–1622.
[38] J.M. Masterton, F. Richardson, Humidex: a method of quantifying human discomfort due to excessive heat and humidity, 1981.
[39] F.R.d. ALFANO, B.I. Palella, G. Riccio, Thermal environment assessment reliability using temperature—humidity indices, Ind. Health 49 (1) (2011) 95–106.
[40] G. Havenith, D. Fiala, K. Błazejczyk, M. Richards, P. Bröde, I. Holmér, H. Rintamaki, Y. Benshabat, G. Jendritzky, The UTCI-clothing model, Int. J. Biometeorol. 56 (2012) 461–470.
[41] D. Fiala, G. Havenith, P. Bröde, B. Kampmann, G. Jendritzky, UTCI-fiala multi-node model of human heat transfer and temperature regulation, Int. J. Biometeorol. 56 (2012) 429–441.
[42] P. Broede, K. Blazejczyk, D. Fiala, G. Havenith, I. Holmer, G. Jendritzky, K. Kuklane, B. Kampmann, The universal thermal climate index UTCI compared to ergonomics standards for assessing the thermal environment, Ind. Health 51 (1) (2013) 16–24.
[43] K. Blazejczyk, Y. Epstein, G. Jendritzky, H. Staiger, B. Tinz, Comparison of UTCI to selected thermal indices, Int. J. Biometeorol. 56 (2012) 515–535.
[44] A. Arguez, R.S. Vose, The definition of the standard WMO climate normal: The key to deriving alternative climate normals, Bull. Am. Meteorol. Soc. 92 (6) (2011) 699–704.
[45] T. Mavromatis, D. Stathis, Response of the water balance in Greece to temperature and precipitation trends, Theor. Appl. Climatol. 104 (2011) 13–24.
[46] H. Tabari, S. Marofi, A. Aeini, P.H. Talaee, K. Mohammadi, Trend analysis of reference evapotranspiration in the western half of Iran, Agricult. Forest. Meterol. 151 (2) (2011) 128–136.
[47] K. Koudahe, D. Koffi, J. Kayode, S. Awokola, A. Adebola, Impact of climate variability on crop yields in southern togo, Env. Pollut. Clim. Chang. 2 (1) (2018) 1–9.
[48] J. El Kasri, A. Lahmili, H. Soussi, I. Jaouda, M. Bentaher, Trend analysis of meteorological variables: rainfall and temperature, Civ. Eng. J. 7 (11) (2021) 1868–1879.
[49] M. Gocic, S. Trajkovic, Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia, Glob. Planet. Change 100 (2013) 172–182.
[50] A. Sobolewski, M. Młynarczyk, M. Konarska, J. Bugajska, The influence of air humidity on human heat stress in a hot environment, Int. J. Occup. Saf. Ergon. 27 (1) (2021) 226–236.
[51] S. Adu-Prah, S. Appiah-Opoku, D. Aboagye, Spatiotemporal evidence of recent climate variability in ghana, Afr. Geogr. Rev. 38 (2) (2019) 172–190.

[52] N.A.B. Klutse, K. Owusu, F. Nkrumah, O.A. Anang, Projected rainfall changes and their implications for rainfed agriculture in northern ghana, Weather 76 (10) (2021) 340–347.
[53] H. Dadashpoor, P. Azizi, M. Moghadasi, Land use change, urbanization, and change in landscape pattern in a metropolitan area, Sci. Total Environ. 655 (2019) 707–719.
[54] J.W. Baldwin, T. Benmarhnia, K.L. Ebi, O. Jay, N.J. Lutsko, J.K. Vanos, Humidity's role in heat-related health outcomes: a heated debate, Environ. Health Perspect. 131 (5) (2023) 055001.
[55] S. Sivaraj, J. Zscheischler, J.R. Buzan, O. Martius, S. Brönnimann, A.M. Vicedo-Cabrera, Heat, humidity and health impacts: How causal diagrams can help tell the complex story, Environ. Res. Lett.: ERL [Web Site] 19 (7) (2024) 074069.
[56] I. Hamdi, M. Fawzy, M. Zelenakova, W. Abbas, Heat island dynamics and heat stress implications on the population of el-mansourah conurbation, Egypt: temporal and proposed solutions using modis imagery and ENVI-met simulation, Geomat. Nat. Hazards Risk 15 (1) (2024) 2291328.
[57] J. Boudreault, C. Campagna, F. Chebana, Machine and deep learning for modelling heat-health relationships, Sci. Total Environ. 892 (2023) 164660.
[58] C. Di Napoli, T. Allen, P.A. Méndez-Lázaro, F. Pappenberger, Heat stress in the caribbean: Climatology, drivers, and trends of human biometeorology indices, Int. J. Climatol. 43 (1) (2023) 405–425.
[59] T.E. Morakinyo, K.A. Ishola, E.O. Eresanya, M.T. Daramola, I.A. Balogun, Spatio-temporal characteristics of heat stress over Nigeria using evaluated ERA5-HEAT reanalysis data, Weather. Clim. Extrem. 45 (2024) 100704.
[60] D. Lieberman, Seasonality and phenology in a dry tropical forest in ghana, J. Ecol. (1982) 791–806.
[61] L.G. Ioannou, J. Foster, N.B. Morris, J.F. Piil, G. Havenith, I.B. Mekjavic, G.P. Kenny, L. Nybo, A.D. Flouris, Occupational heat strain in outdoor workers: a comprehensive review and meta-analysis, Temperature 9 (1) (2022) 67–102.
[62] O. Jay, A. Capon, P. Berry, C. Broderick, R. de Dear, G. Havenith, Y. Honda, R.S. Kovats, W. Ma, A. Malik, et al., Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities, Lancet 398 (10301) (2021) 709–724.
[63] C.J. Gronlund, Racial and socioeconomic disparities in heat-related health effects and their mechanisms: a review, Curr. Epidemiol. Rep. 1 (2014) 165–173.
[64] T. Abokhashabah, B. Jamoussi, A.S. Summan, E. Abdelfattah, A. Ijaz, Effects of heat stress exposure and climate change on health and safety of outdoor workers, Curr. World Environ. 16 (3) (2021) 836.
[65] T. Berger, F.A. Chundeli, R.U. Pandey, M. Jain, A.K. Tarafdar, A. Ramamurthy, Low-income residents' strategies to cope with urban heat, Land Use Policy 119 (2022) 106192.
[66] J.S. Weissman, R. Stern, S.L. Fielding, A.M. Epstein, Delayed access to health care: risk factors, reasons, and consequences, 1991.
[67] A.Y. Lo, C.Y. Jim, P.K. Cheung, G.K. Wong, L.T. Cheung, Space poverty driving heat stress vulnerability and the adaptive strategy of visiting urban parks, Cities 127 (2022) 103740.