Graphical Abstract

Assessing Heat-Related Health Risk in Ghana Using Bioclimatic Indices

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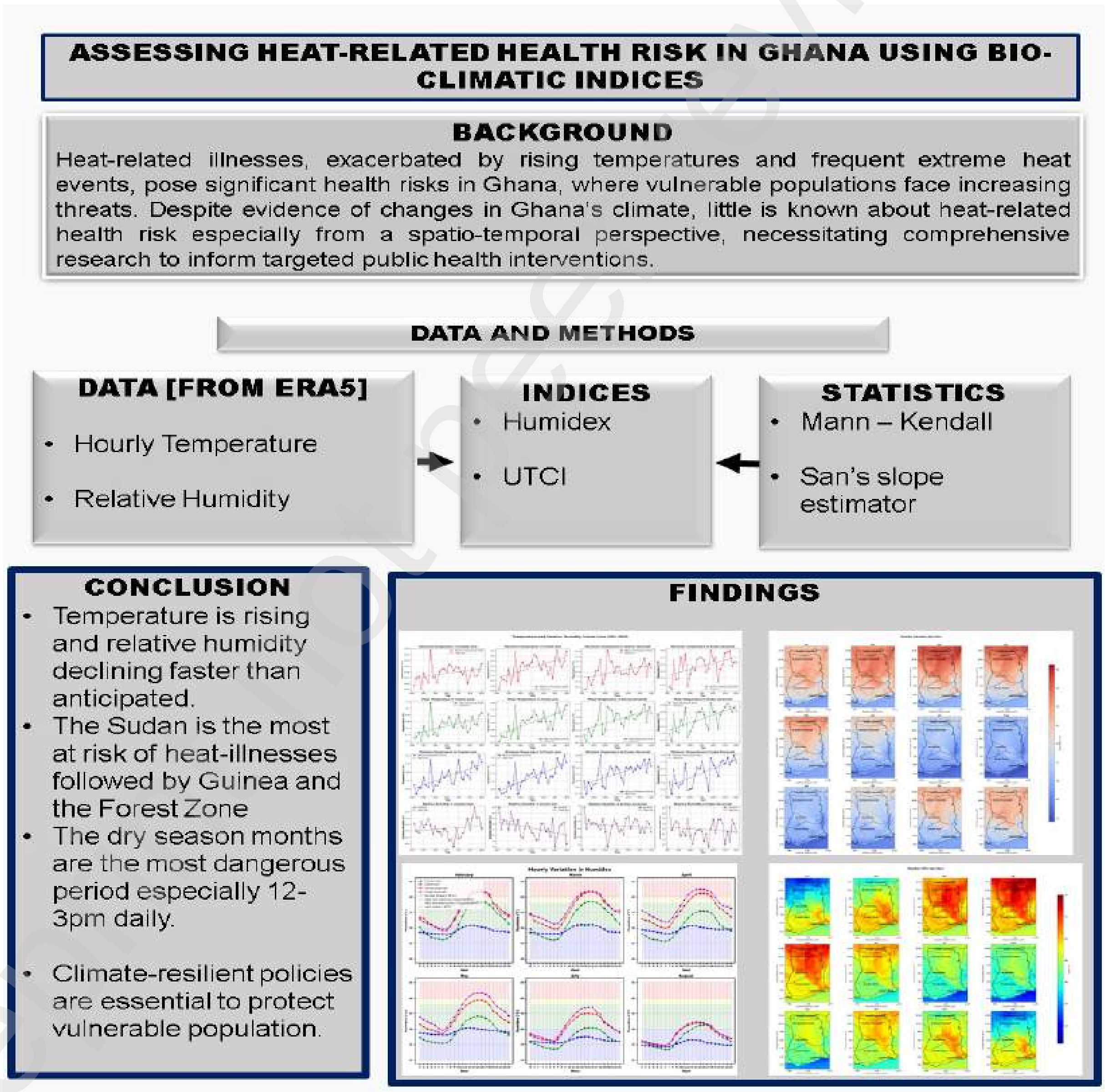

Highlights

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- Climate change is significantly increasing heat exposure across Ghana, particularly in the Sudan Savannah, Guinea Savannah and Forest zones.
- Temperature (especially the minimum temperature) is rising faster whiles humidity is declining significantly than anticipated especially in the Forest zone.
- The Sudan Savannah experiences the worst extreme heat conditions followed by Guinea Savannah and the Forest zone, making them the most vulnerable to heat-related health impacts.
- Seasonally, heat risks are highest from late dry season to early wet season (November-May with peak in March-April), requiring targeted intervention strategies during these months.
- Daily, heat risk are highest between 11 AM and 5 PM with peak at 12-3pm requiring targeted heat action plan within these times.
- Effective heat adaptation strategies, such as public awareness campaigns, early warning systems, and cooling infrastructure, are essential to protect at-risk communities.

Assessing Heat-Related Health Risk in Ghana Using Bioclimatic Indices

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Abstract

Climate change is intensifying extreme temperatures worldwide, leading to serious health risks such as heat stress, heat stroke, and heat exhaustion. In Ghana, despite clear evidence of climate change, high temperatures are often perceived as isolated events, and their associated health risks remain largely overlooked. Existing information primarily rely on subjective perceptions rather than scientifically validated bio-climatic indices. To address this gap and improve early warning systems, we analysed heat-related health risks across Ghana using the Universal Thermal Climate Index (UTCI) and Humidex (HD) as bio-climatic indices. We extracted hourly temperature and relative humidity from ERA5 hourly data on single levels and computed the indices across the country. Our findings revealed that climate change is substantially increasing heat exposure across Ghana, with the Sudan Savannah, Guinea Savannah, and Forest zones being the most affected. Minimum temperatures are rising at a faster rate than maximum temperatures, and humidity is significantly declining especially in the Forest zone, exacerbating thermal discomfort and increasing the risk of heat stress. The Sudan Savannah experiences the most extreme heat conditions, followed closely by the Guinea Savannah, making these regions particularly vulnerable to heat-related health impacts. Seasonally, heat-health risks are highest between November and May, with peak intensity in March and April, emphasizing the need for targeted intervention strategies during this period. Diurnally, heat exposures are most severe between 11 AM and 5 PM, with the highest intensity occurring between 12 PM and 3 PM, underscoring the importance of implementing heat action plans within these hours to mitigate risks. Given the rising threat of extreme heat, urgent adaptation strategies are necessary to protect communities from adverse health effects. Effective measures such as public awareness campaigns, early warning systems, and the development of cooling infrastructure are essential in enhancing resilience, particularly in the Sudan and Guinea Savannah zones where heat-related health risks are most pronounced. Our results highlight the critical need for proactive policies and interventions to safeguard public health against the escalating impacts of climate change.

Keywords: Assessment, Heat-Related, Health, Risks, Ghana, Bioclimatic, Indices

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1. 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, 2, 3, 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 (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, 9, 10, 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, 14, 15, 16]. Understanding the risk of heat exposure in Ghana is a critical step in identifying the populations most at risk and addressing the health impacts of climate change by 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 2,323 excess deaths [17], while similar events in 2020 led to an additional 2,556 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. Two other studies, namely Frimpong [31] and Kwasi et al. [32], highlighted the impact of heat stress on the health and productivity of farmers in northern Ghana, yet these findings lack comprehensive geographic coverage and objective risk assessments, since they are perception-based. To provide a nationwide heat-health risk data to support early warning and risk management systems in Ghana, it is necessary to analyse when, where and what risks occur.

In this study, our aim is to address the existing knowledge gaps by conducting a comprehensive nationwide assessment of heat-related illnesses in Ghana in the context of a changing climate. We analyse current trends in temperature and relative humidity and, using Humidex and the Universal Thermal Climate Index (UTCI) as bioclimatic indicators, we assess the risks of heat-related conditions such as heat stress, heat stroke, and exhaustion, both on the spatial and temporal scales. The Humidex is easier to calculate given that it requires only two input parameters (temperature and humidity)[33], which are commonly measured by meteorological stations. The UTCI model was chosen because it considers the reference outdoor environment that would elicit the same physiological response in the human body as the actual environment, including factors like mean radiant temperature, wind speed, and humidity[34]. 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.

2. Data and Methods

2.1. Study Area

The study covered all of Ghana. The country is located in West Africa between longitude 3.5°W and 1.5°E, and latitude approximately 4.5°N and 12°N (see Figure 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]. As shown in Figure 1, 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. However, annual average rainfall increases southward and ranges from 800 mm in the north to about 1800 mm in the forest zone. 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 [35]. 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 [36].

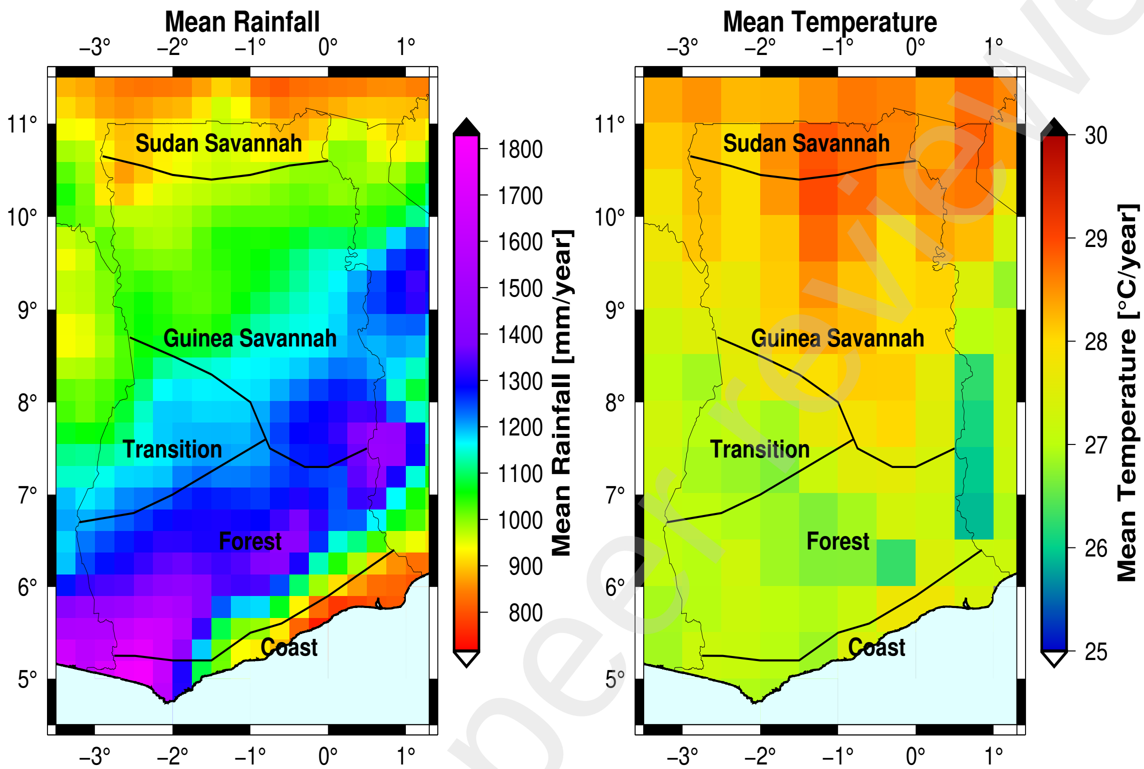

Figure 1: Map of Ghana showing rainfall and temperature patterns across the climatic zones of Ghana.

2.2. Data

In this study, the hourly minimum and maximum 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 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. Previous validation studies [37, 38] 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.

2.3. Analysis

2.3.1. Heat-related health risk

The risks of heat illness were evaluated using two bioclimatic indices, namely Humidex and the Universal Thermal Comfort Index (UTCI). Humidex is a simple thermal comfort index based on air temperature and humidity [39]. It was used because it is widely considered to be one of the most robust and effective comfort index. Its results are directly comparable with the dry temperature in degrees Celsius, and its values are associated with corresponding degrees of thermal comfort. 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 [33] as:

$$\mathbf{H} = T + \frac{5}{9}(e - 10), \tag{1}$$

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 equation 2 below:

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

esat which depends on air temperature alone was calculated using the Tetens formula [40]:

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

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. [41] and Fiala et al. [42] with detailed documentation in Broede et al. [43].

This model is expressed mathematically as ;

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

Where; Ta = Air Temperature, T_r = Mean radiant or radiation temperature, v_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 [43]. 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). 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.

2.3.2. Trends in climate variables

Trends in 2 meter air temperature (minimum (Tmin), mean (Tmean), and maximum (Tmax)), relative humidity (RH), Humidex (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 ($\mathrm{H_o}$) 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 ($\mathrm{H_a}$) that there is a trend [47]. The MK statistics was calculated as shown below:

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

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

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;

$$Q_{\mathrm{i}} = \frac{X_{\mathrm{i}} - X_{\mathrm{j}}}{i - j}, i = 1, 2, 3, 4, ..Nj > k \tag{8}$$

3. Results

3.1. Trends in temperature and RH

Figure 2 presents the annual trends in maximum, mean, and minimum temperatures along with relative humidity for each climatic zone in Ghana. The details of the trend statistics are presented in Table 1. 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 0.0127°C per year (see Table 1). 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 1).

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.

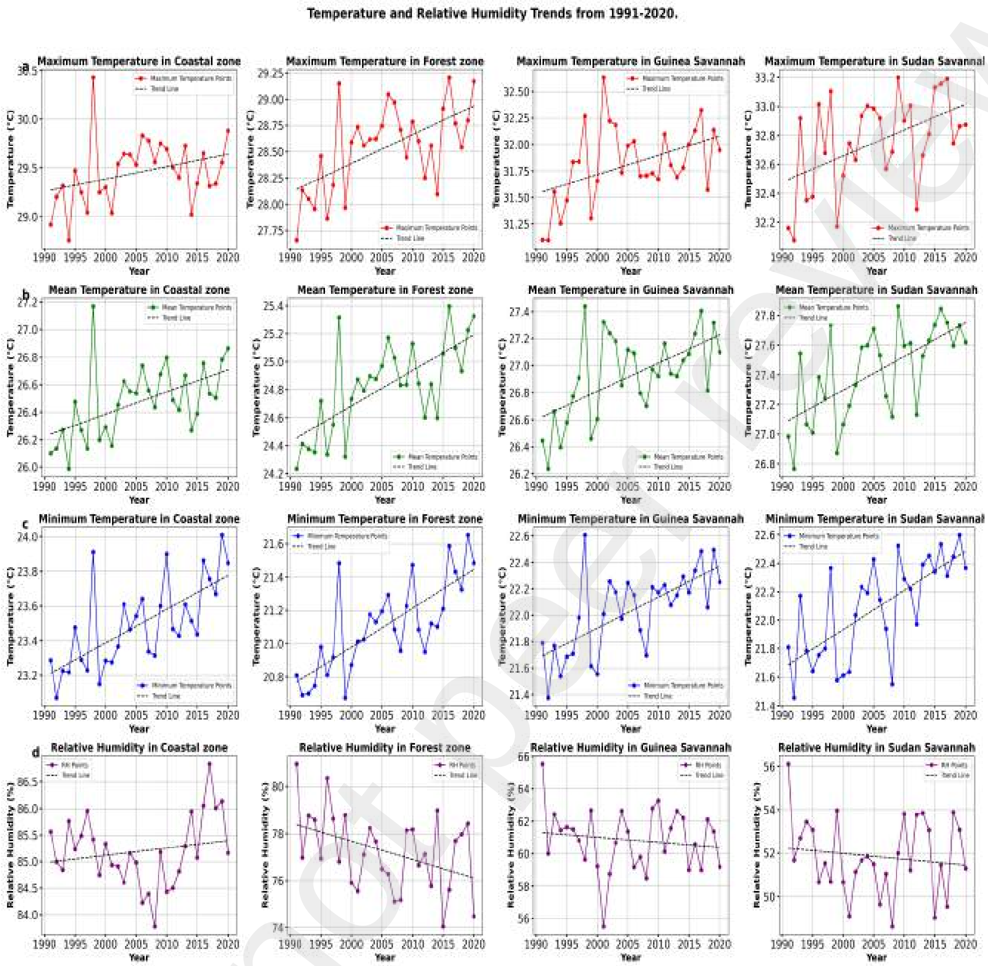

Figure 2: **Annual trends in temperature and Relative Humidity over the climatic Zones of Ghana**. Top row: maximum temperature, middle row: mean temperature, third row: minimum temperature, and fourth row: relative humidity.

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 1.

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.

Table 1: Annual trends in T_{min}, T_{mean}, T_{max} and RH for climatic zone in Ghana. Variables with significant trends are boldfaced.

Climatic Zone	Variable	Tau Kendall (τ)	P-Value	Rate	Amount of Increase (30 yrs)
Coastal Zone	$\mathbf{T_{max}}$	0.274	**0.0344**	0.0127	0.381
	$\mathbf{T_{mean}}$	0.434	**0.0006**	0.0161	0.483
	$\mathbf{T_{min}}$	0.526	**0.0000**	0.0195	0.585
	RH	0.062	0.6455	0.0139	0.417
Forest Zone	$\mathbf{T_{max}}$	0.407	**0.0013**	0.0274	0.822
	$\mathbf{T_{mean}}$	0.508	**0.0000**	0.0254	0.762
	$\mathbf{T_{min}}$	0.519	**0.0000**	0.0234	0.702
	RH	-0.264	**0.0412**	-0.0784	-2.352
Guinea Savannah	$\mathbf{T_{max}}$	0.292	**0.0236**	0.0182	0.546
	$\mathbf{T_{mean}}$	0.393	**0.0020**	0.0209	0.627
	$\mathbf{T_{min}}$	0.476	**0.0001**	0.0235	0.705
	RH	-0.117	0.3755	-0.0315	-0.945
Sudan Savannah	$\mathbf{T_{max}}$	0.315	**0.0143**	0.0179	0.537
	$\mathbf{T_{mean}}$	0.480	**0.0001**	0.0227	0.681
	$\mathbf{T_{min}}$	0.503	**0.0000**	0.0276	0.828
	RH	-0.053	0.6972	-0.0268	-0.804

3.2. Spatio-temporal variation in HD and UTCI

Figure 3 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

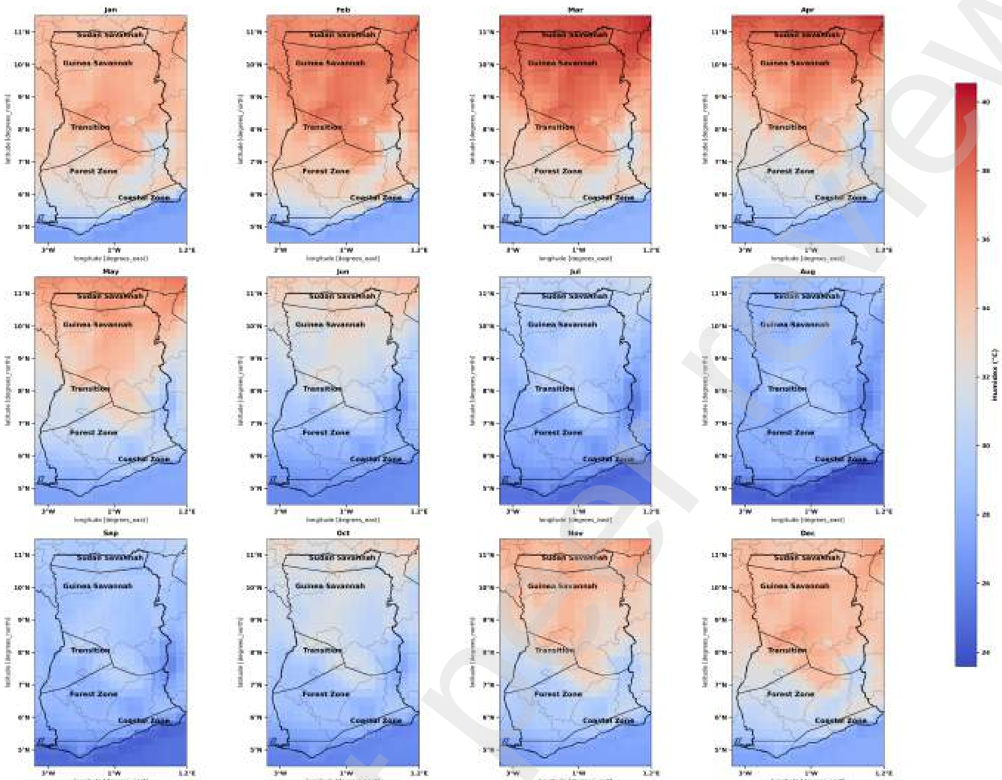

Figure 3: Spatial variation in monthly average Humidex over Ghana (1991-2020)

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.

3.3. Annual Trends in HD and UTCI

Figure 4 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 SM3. In all zones, consistent and significant upward trends in HD values were observed. In the Sudan Savannah zone, HD values ranged from 42.5°C to 45.0°C with a statistically significant upward trend at a rate of 0.0254°C per year. The Guinea Savannah zone exhibited a similar trend, increasing at an annual rate of 0.0272°C with ranges from 43.5°C to 46.0°C. The forest zone, despite showing low HD values of 42.0°C, saw increases to 44.5°C, represented the steepest trend among all zones with an annual rate of 0.0377°C. Lastly, the coastal zone showed the lowest overall HD values, ranging from 37.7°C to 39.5°C. It also showed a significant upward trend, increasing at a rate of 0.0235°C per year. A parallel analysis performed with the UTCI Index is provided in Figure SM2 and a detailed trend statistics in Table SM3.

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 0.0193°C

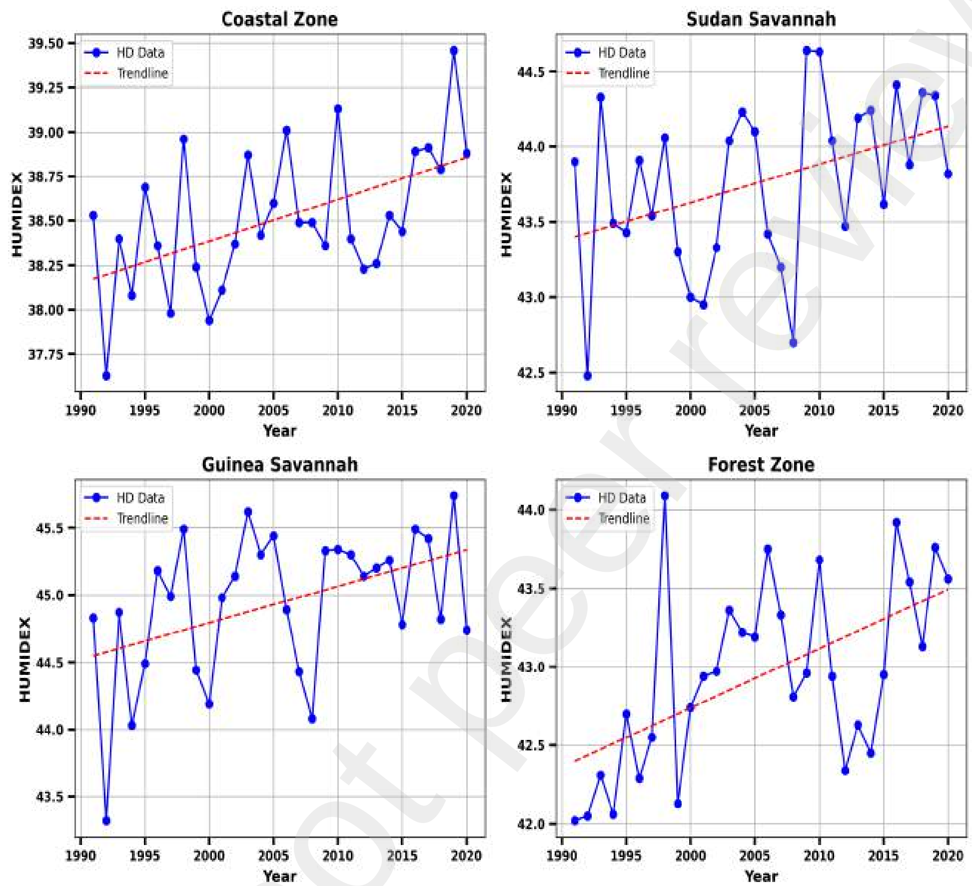

Figure 4: Annual trends in Humidex (HD) in four climatic Zones.

per year (see Table SM3). Similarly, the Guinea Savannah exhibited a notable increase, with UTCI values increasing from 31.0°C to 34.0°C at a rate of 0.0230°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 0.0259°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 0.0117°C per year.

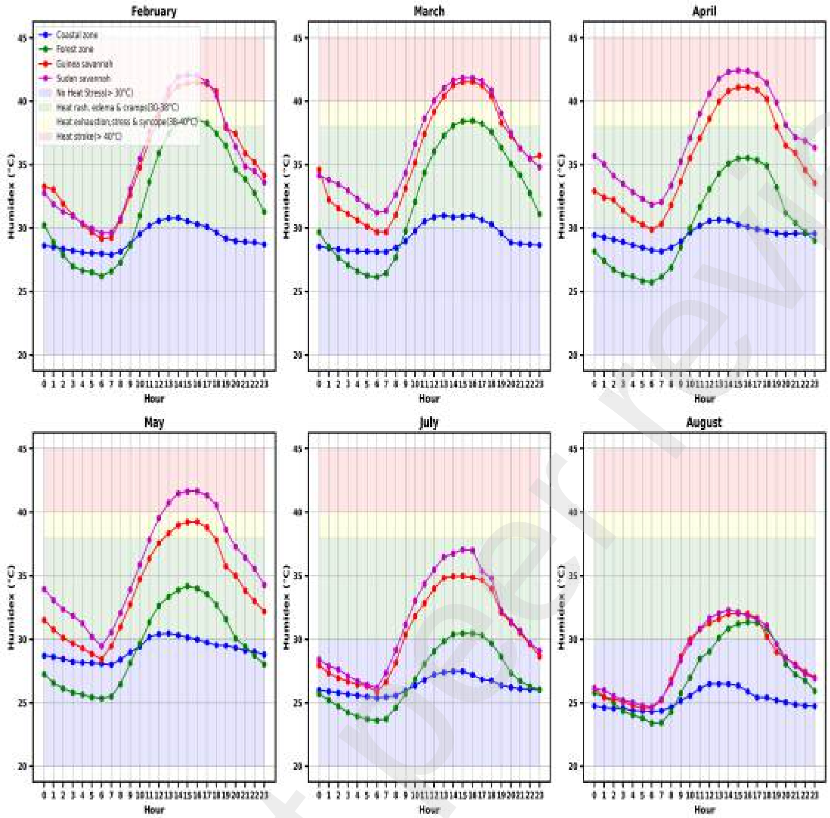

Figure 5: Hourly of Humidex for selected Months.

3.4. 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. Figure 5 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, HD intensity is highest in February, March, and April in all zones, with a noticeable decline in 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 am 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 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.

4. Discussion

Our trend analysis as illustrated in Figure 2 as well as the Mann-Kendall statistics presented in Table 1 indicated that all temperature variables (maximum, mean and minimum) exhibited statistically significant increasing trends during the study period in all zones. These upward trends provide clear evidence that all climatic zones in Ghana have experienced progressive warming. This finding aligns well with previous conclusions from other studies [27, 50, 51] that Ghana is experiencing climate warming at varying degrees in all zones. The observed increase in temperature has critical health implications because they are conducive for extreme heat events that exacerbate heat-related diseases, such as heat stress and cardiovascular complications [52, 11]. The minimum temperatures is observed warming rapidly than the maximum and mean temperatures, indicating a pronounced rise in nighttime temperatures [25]. This rapid increase could be attributed to external influences, including anthropogenic activities such as urbanization and changes in land use, which exacerbate the heat island effect [25]. During the past three decades, the change in land cover has increased due to deforestation and urbanization [53, 54, 55]. This has led to reduced vegetation and natural cooling mechanisms, leading to increased heat retention, especially at night. The loss of green spaces, coupled with heat-absorbing surfaces like concrete and asphalt, prevents nighttime cooling, further elevating minimum temperatures. The rise in nighttime temperatures has serious health implications. Higher minimum temperatures is known to reduce the body's ability to recover from daytime heat, increasing the risk of heat-related illnesses such as heat exhaustion and heatstroke. Additionally, prolonged exposure to elevated nighttime temperatures can disrupt sleep patterns, contributing to cardiovascular stress and other chronic health issues. Relative humidity trends varied across the agroclimatic zones, with a general decline observed in the Guinea, Sudan, and Forest zones, while the coastal zone exhibited a contrasting increasing trend (see Table 1). As stated above, these zones showed increasing temperature trends. The rise in temperature combined with the decrease in relative humidity in these zones has significant implications for heat-related diseases and overall human health [56]. As temperatures rise, the body's ability to cool itself through sweating becomes crucial. When relative humidity is low, sweat evaporates more efficiently, helping to cool [57]. However, if temperatures continue to rise beyond a critical point, excessive sweating can lead to dehydration, increasing the risk of heat exhaustion and heat stroke [14]. High temperatures put additional strain on the cardiovascular system, increasing the risk of heat-related mortality, especially in vulnerable populations such as the elderly, children, and outdoor workers in these zones [58]. In coastal areas, an increasing trend of temperature is observed combined with an increase in relative humidity. This poses an even greater risks for heat-related illnesses due to the reduced ability of the body to cool itself effectively [59]. When both temperature and humidity are high, the body struggles to regulate its temperature through sweating because sweat does not evaporate as efficiently under humid conditions [58]. This can trap heat within the body, leading to rapid overheating and an increased risk of heat exhaustion and heat stroke [14].

The study revealed significant temporal and spatial variability in Humidex (HD) and UTCI in Ghana, driven by climatic factors, with crucial implications for heat risk. November to May indicated an increase in thermal stress with HD values that ranged above 34.0°C with peak values of approximately 40.0°C in March / April in the Savannah zone of Sudan and Guinea. This means that people in this zone are highly at risk of heat-related fainting, heat exhaustion, and heat stroke with a high potential of heat stroke in March / April. This pattern aligns with the trends of Sahelian heat waves, where increased solar radiation and reduced humidity exacerbate heat stress [60]. In contrast, from June to October, HD values drop to milder levels (25–32°C) due to the moderating effects of the West African monsoon [35], which does not indicate serious discomfort or heat risk. Similarly, the UTCI patterns showed a geographic gradient, with lower values at 23°C in the north during January due to Harmattan winds, which may not cause heat stress, while the south remained warmer at 30°C, where mild discomfort and symptoms such as heat rash can occur. A reversal occurs in March, with peak UTCI values in the north, signifying the highest thermal burden before the rainy season, corresponding to moderate to severe discomfort, increasing the likelihood of heat exhaustion or heat stroke. The cooling trend from June to August, when the UTCI values drop to as low as 26°C in the south, underscores the role of the monsoon in alleviating heat stress. The subsequent increase from October onward marks the transition into the dry season driven by rising solar insolation and weakening monsoonal effects [61], leading to a return of heat-related risks. In particular, the Sudan Savannah zone consistently records the highest HD and UTCI values, reflecting extreme thermal conditions and an elevated risk of severe heat-related illnesses, while the coastal zone, moderated by the Atlantic Ocean, experiences relatively lower thermal stress.

The increasing trends in HD and UTCI in Ghana's agroclimatic zones over the past three decades suggest a concerning increase in heat-related illnesses. In the Sudan and Guinea Savannah zones, HD values have increased from moderate to severe discomfort, suggesting increased occurrences of heat exhaustion and syncope, with the potential for a surge in life-threatening cases of heat stroke if the trend persists. In these zones, high levels of solar radiation, reduced vegetation cover, and prolonged dry seasons are becoming common [62] and exacerbating heat stress, making outdoor labour increasingly hazardous. Similarly, in the Forest zone, where HD has historically been lower, the rising trends in HD and UTCI suggest a transition from moderate to severe discomfort and increase the risk of heat cramps, heat exhaustion, heat stroke complications after the observed rising temperatures and reduce humidity, which has an impact on the efficiency of sweating for cooling [63]. Human activities such as deforestation, urbanization, and industrialization are further intensifying heat stress by reducing vegetation's cooling effect and increasing solar radiation absorption in built environments. In the coastal zone, while the increase in HD and UTCI is more gradual, urban areas face increasing heat stress due to the effect of the urban heat island, which particularly affects vulnerable populations such as the elderly, children, and outdoor workers [31]. A major concern in this region is the underestimation of the risks of heat stress, leading to inadequate adaptation strategies and increased susceptibility to extreme heat events.

The hourly variations in HD and UTCI in Ghana's agroclimatic zones during the hot months (February to May) and the cooler months (July and August) have significant implications for human thermal comfort and health. In the Sudan and Guinea Savannah zones, HD values often exceeded 30°C whiles UTCI values often reach 45°C, suggesting severe heat discomfort during these hours (Figure 5 & Figure SM3). As shown in Table SM1 and Table SM2, these extreme HD and UTCI values pose serious health risks related to heat, including heat stroke, heat exhaustion, and syncope, particularly in the afternoons. The high levels of HD and UTCI in these regions suggest that prolonged exposure could lead to severe dehydration, increased cardiovascular stress, and reduced outdoor productivity, especially for labour-intensive activities such as farming. The forest zone, although slightly cooler, still shows high HD and UTCI values between 38°C and 40°C in these hotter months. These have the potential for moderate to severe heat discomfort. However, the coastal zone remains the least affected, with HD values ranging from 27°C to 31°C and UTCI values staying below 32°C, mostly indicating mild discomfort. The minimal fluctuations in the coastal zone suggest the moderating influence of oceanic breezes, which likely mitigate the risks of extreme heat. However, even in these areas, people who engage in prolonged physical activity may experience symptoms such as heat rash and cramps. The seasonal variation further highlights the impact of climate, as HD and UTCI values decline in July and August, reducing the risk of severe heat-related illnesses. However, the persistence of moderate discomfort in inland areas even during the cooler months underscores the need for heat adaptation measures such as proper hydration, heat mitigation infrastructure, and adjusted work schedules to reduce exposure during peak hours.

5. Conclusions

The study assessed heat-related health risks in Ghana using bioclimatic indices, specifically HD and UTCI. These indices were chosen for their effectiveness in capturing thermal variability and its impact on human health. The analysis used hourly UTCI, temperature and relative humidity data from the ECMWF reanalysis dataset (1991-2020) with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$.

This study provided compelling evidence of significant and widespread increase in temperature in all agroclimatic zones in Ghana, as demonstrated by the Mann-Kendall trend analysis. The rise in temperatures, particularly the minimum temperatures, indicates worsening heat conditions at night. This trend is likely influenced by anthropogenic activities such as urbanization and changes in land use, which contribute to the effect of heat island in urban settings. In addition, the observed warming patterns align with regional and global climate change trends, confirming that Ghana is undergoing progressive climate warming at varying intensities in its agroclimatic zones.

Beyond temperature trends, the analysis revealed critical climatic changes in relative humidity with profound implications. In particular, the Guinea, Sudan and forest zones exhibited a general decline in humidity, while the coastal zone demonstrates an increasing trend. The decline in humidity, particularly in the forest zone, raises concerns about its effects on agriculture, water availability, and human comfort. Drier air intensifies heat stress and can significantly reduce crop yields, threatening food security and livelihoods. In contrast, although increasing humidity in the coastal zone may help moderate some warming effects, it could also exacerbate thermal discomfort by increasing the sensation of heat stress. These contrasting humidity patterns highlight the need for region-specific adaptation strategies that consider the unique environmental and socio-economic challenges of each zone.

Furthermore, the study's assessment of Humidex (HD) and the Universal Thermal Climate Index (UTCI) offers crucial insights into the intensification of thermal stress in Ghana. The findings revealed that heat stress is most pronounced in the Sudan and Guinea Savannah zones, placing residents at increased risk for heat-related diseases such as heat stroke and cardiovascular complications. Seasonal fluctuations in HD and UTCI underscore the moderating influence of monsoonal cooling during certain months. However, the overall upward trajectory of these thermal indices suggests an increasing public health concern, particularly in regions experiencing prolonged and extreme heat conditions. Also, during the hours of 9am to 3pm, people in the Guinea and Sudan Savannah are at risk of heat-related illnesses such as heat stress, exhaustion, and heat stroke. Given these findings, there is an urgent need for the implementation of heat mitigation strategies, including sustainable urban planning, increased vegetation cover, and comprehensive public awareness initiatives to protect vulnerable populations from increasing heat stress. The broader significance of this study lies in its practical applications for policymakers, urban planners, and public health officials. By providing empirical evidence of Ghana's increasing thermal burden, this research serves as a valuable resource for shaping climate adaptation strategies. Understanding key trends in temperature, humidity, and heat indices allows the development of targeted interventions aimed at reducing heat-related health risks and improving environmental sustainability. The findings underscore the importance of proactive measures such as heat action plans, improved weather forecasting systems, and climate-resilient infrastructure to protect communities from the worsening effects of climate change. Ultimately, this study deepens the scientific understanding of climate variability in Ghana and reinforces the need for comprehensive adaptation and mitigation efforts to protect both human populations and ecological systems from the increasing impacts of climate change.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

Author Contributions

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, and Writing - Review & Editing.

Leonard K. Amekudzi: Conceptualization, Methodology, Validation, and Writing - Review & Editing.

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Data Availability Statement

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 & Environmental Medicine 26 (2015) 69–75.

[2] W. F. Atha, Heat-related illness., Emergency medicine clinics of North America 31 (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 & environmental medicine 24 (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., Journal of Special Operations Medicine: a Peer Reviewed Journal for SOF Medical Professionals (2024) W7TV–MBRZ.

[5] M. De Sario, K. Katsouyanni, P. Michelozzi, Climate change, extreme weather events, air pollution and respiratory health in europe, European Respiratory Journal 42 (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, An IPCC Special Report on the impacts of global warming 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, International journal of environmental research and public health 15 (2018) 952.

[9] P. L. Kinney, Temporal trends in heat-related mortality: implications for future projections, Atmosphere 9 (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 (2006) 585–596.

[12] N. A. B. Klutse, K. Owusu, Y. A. Boafo, Projected temperature increases over northern ghana, SN Applied Sciences 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, International journal of environmental research and public health 16 (2019) 432.

[14] R. Gauer, B. K. Meyers, Heat-related illnesses, American family physician 99 (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 (2022) 2542.

[16] A. Ireland, D. Johnston, R. Knott, Heat and worker health, Journal of health economics 91 (2023) 102800.

[17] S. Kovats, R. Brisley, Health, communities and the built environment, The Third UK Climate Change Risk Assessment Technical Report 10 (2021).

[18] Public Health 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, Nature communications 13 (2022) 7565.

[20] A. Liss, E. N. Naumova, Heatwaves and hospitalizations due to hyperthermia in defined climate regions in the conterminous usa, Environmental monitoring and assessment 191 (2019) 1–16.

[21] D. Mitchell, 14. human influences on heat-related health indicators during the 2015 egyptian heat wave, Bulletin of the American Meteorological Society 97 (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, Climate Dynamics 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, Scientific African 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 (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 Climate 2 (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, Environmental Systems Research 11 (2022) 24.

[29] J. Kwakye, et al., Effect of temperature and rainfall variability on selected crop yields in wenchi municipality of ghana, American Journal of Environment and Climate 2 (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, Journal of environmental and public health 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, Sustainable Agriculture Research 3 (2014).

[33] J. M. Masterton, F. Richardson, Humidex: a method of quantifying human discomfort due to excessive heat and humidity., 1981.

[34] K. Blazejczyk, Y. Epstein, G. Jendritzky, H. Staiger, B. Tinz, Comparison of utci to selected thermal indices, International Journal of Biometeorology 56 (2012) 515–535.

[35] 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 (2015) 416–434.

[36] J. Aryee, L. Amekudzi, E. Quansah, N. Klutse, W. Atiah, C. Yorke, Development of high spatial resolution rainfall data for ghana, International Journal of Climatology 38 (2018) 1201–1215.

[37] D. Parsons, D. Stern, D. Ndanguza, M. B. Sylla, Evaluation of satellite-based air temperature estimates at eight diverse sites in africa, Climate 10 (2022) 98.

[38] S. Gleixner, T. Demissie, G. T. Diro, Did era5 improve temperature and precipitation reanalysis over east africa?, Atmosphere 11 (2020) 996.

[39] I. Charalampopoulos, A comparative sensitivity analysis of human thermal comfort indices with generalized additive models, Theoretical and applied climatology 137 (2019) 1605–1622.

[40] F. R. d. ALFANO, B. I. Palella, G. Riccio, Thermal environment assessment reliability using temperature—humidity indices, Industrial health 49 (2011) 95–106.

[41] G. Havenith, D. Fiala, K. Błazejczyk, M. Richards, P. Bröde, I. Holmér, H. Rintamaki, Y. Benshabat, G. Jendritzky, The utci-clothing model, International journal of biometeorology 56 (2012) 461–470.

[42] D. Fiala, G. Havenith, P. Bröde, B. Kampmann, G. Jendritzky, Utci-fiala multi-node model of human heat transfer and temperature regulation, International journal of biometeorology 56 (2012) 429–441.

[43] 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, Industrial health 51 (2013) 16–24.

[44] A. Arguez, R. S. Vose, The definition of the standard wmo climate normal: The key to deriving alternative climate normals, Bulletin of the American Meteorological Society 92 (2011) 699–704.

[45] T. Mavromatis, D. Stathis, Response of the water balance in greece to temperature and precipitation trends, Theoretical and Applied Climatology 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, Agricultural and forest meteorology 151 (2011) 128–136.

[47] K. Koudahe, D. Koffi, J. Kayode, S. Awokola, A. Adebola, Impact of climate variability on crop yields in southern togo, Environ. Pollut. Clim. Chang 2 (2018) 1–9.

[48] J. El Kasri, A. Lahmili, H. Soussi, I. Jaouda, M. Bentaher, Trend analysis of meteorological variables: rainfall and temperature, Civil Engineering Journal 7 (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, Global and planetary change 100 (2013) 172–182.

[50] S. Adu-Prah, S. Appiah-Opoku, D. Aboagye, Spatiotemporal evidence of recent climate variability in ghana, African Geographical Review 38 (2019) 172–190.

[51] 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 (2021) 340–347.

[52] A. A. Khan, Heat related illnesses: Review of an ongoing challenge, Saudi medical journal 40 (2019) 1195.

[53] H. Dadashpoor, P. Azizi, M. Moghadasi, Land use change, urbanization, and change in landscape pattern in a metropolitan area, Science of the Total Environment 655 (2019) 707–719.

[54] T. Lin, X. Xue, L. Shi, L. Gao, Urban spatial expansion and its impacts on island ecosystem services and landscape pattern: A case study of the island city of xiamen, southeast china, Ocean & coastal management 81 (2013) 90–96.

[55] L. S. Bertolo, G. T. Lima, R. F. Santos, Identifying change trajectories and evolutive phases on coastal landscapes. case study: São sebastião island, brazil, Landscape and Urban Planning 106 (2012) 115–123.

[56] O. I. Ropo, M. S. Perez, N. Werner, T. Enoch, Climate variability and heat stress index have increasing potential ill-health and environmental impacts in the east london, south africa, Int. J. Appl. Eng. Res 12 (2017) 6910–6918.

[57] N. B. A. Sonpol, Adapting indoor spaces for outdoor sports in hot climate environments-a literature review, in: 2024 International Conference on Decision Aid Sciences and Applications (DASA), IEEE, 2024, pp. 1–5.

[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, International Journal of Climatology 43 (2023) 405–425.

[59] A. Sobolewski, M. Młynarczyk, M. Konarska, J. Bugajska, The influence of air humidity on human heat stress in a hot environment, International journal of occupational safety and ergonomics 27 (2021) 226–236.

[60] 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 and Climate Extremes 45 (2024) 100704.

[61] D. Lieberman, Seasonality and phenology in a dry tropical forest in ghana, The Journal of Ecology (1982) 791–806.

[62] 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 (2022) 67–102.

[63] 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, The Lancet 398 (2021) 709–724.