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Heat Stress Vulnerable Regions over Saudi Arabia in the Present Climate

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Abstract: Heat stress is one of the most critical natural hazards in Saudi Arabia, driven by its predominantly arid climate. This study evaluates heat stress conditions across Saudi Arabia using observational data from 26 surface stations for the period 1985–2024. The main objectives are to identify the most vulnerable regions and classify them using a thermal comfort scale based on the Heat Index (HI), including the categories Caution, Extreme Caution, Danger, and Extreme Danger. The results reveal strong spatial variability across Saudi Arabia. Southwestern Jazan recorded the highest annual number of discomfort days (334), followed by western Makkah (285) and Jeddah (254), while hilly Abha and Khamis Mushait showed minimal exposure (0–1 days). In Jazan, discomfort days were distributed across Caution (83), Extreme Caution (151), and Danger (100), whereas Makkah and Jeddah were dominated by Extreme Caution conditions. Although most discomfort days occurred in summer, they often extended into spring and autumn, especially in central and coastal regions. Coastal cities experienced near year-round discomfort. Seasonally, Caution conditions persisted year-round, peaking in May and September, while Extreme Caution occurred from March to November, peaking in July. Danger conditions were largely limited to May–October, and Extreme Danger events were rare. A significant upward trend in discomfort days was observed nationwide, highest in Al-Baha (14.1 days/decade) and lowest in Asir (2.1 days/decade). Regionally, Jazan is classified as extremely vulnerable, while Asir and Al-Baha are least vulnerable. These findings highlight rising heat stress risks and the urgent need for impacted sectors.

Keywords: Heat stress, Trends, Regional vulnerability, Saudi Arabia.

1. Introduction

Heat stress refers to the accumulation of body heat caused either internally through physical exertion or externally from environmental conditions (Copernicus 2024). It occurs when the body absorbs more heat than it can effectively dissipate. The ability of the human body to maintain a stable internal temperature is influenced by various physiological and behavioral factors and imbalance occurs in lack of necessary factors (Osilla et al. 2023). This imbalance is typically driven by a combination of factors, including high temperatures, elevated humidity, strenuous physical activity, and insufficient fluid intake. Under normal conditions, a healthy person maintains a core body temperature around 37 ± 0.5 °C, a range critical for proper metabolic function (Hymczak et al. 2021). Even a slight rise of 1–2 °C above the optimal 36.8 °C can cause discomfort (Vancamp 2025). The body's thermal balance or heat budget is determined by the interaction between heat generated internally and exchanged with the environment (Jendritzky 2009). This balance is regulated by the thermoregulatory system, including the hypothalamus, sweat glands, circulatory system, and skin. Factors such as hydration, activity level, clothing, and rest also play a role.

Common symptoms of heat stress include increased core temperature, rapid heartbeat, heavy sweating, nausea, dizziness, and severe heat exhaustion or heat stroke, which can be life-threatening (Raukar 2025). Several risk factors increase an individual's vulnerability to heat stress. Environmental conditions such as high temperatures and humidity significantly reduce the effectiveness of sweat evaporation, the body's primary cooling method (Epstein and Moran 2006). When sweat cannot evaporate efficiently, the body retains heat, heightening the risk of illness. Physical exertion also raises internal heat production, further increasing susceptibility. Personal characteristics like age, underlying health conditions, and certain medications (e.g. diuretics and antihypertensives) can impair the body's heat response (Heat 2025; Kenny et al. 2010; Robert et al. 2020; McCallum 2024). In the era of climate change, the region is warming faster than the global warming rate in the recent decades that can increase the occurrence of heat stress across the country (Syed et al. 2024).

Saudi Arabia's climate ranges from semi-arid to arid (Amin and Ashraf 2023), and under such conditions, even moderate increases in humidity can significantly raise heat stress levels (Rachid et al., 2023; Cheung et al. 2000). Although some studies have addressed heat stress in the Kingdom, particularly during the Hajj in Makkah (e.g. Ghaznawi et al. 1987) or among industrial workers (Al-Bouwarthan et al. 2019; Alshammmary et al. 2020), however comprehensive, long-term assessments using ground-based observations are limited. For example, Alshammmary et al. (2020) evaluated heat exposure using the Wet Bulb Globe Temperature (WBGT) and Heat Strain Score Index (HSSI) among steelworkers in Jubail, finding that many WBGT readings exceeded safety thresholds, placing workers in high-risk zones. Dasari et al. (2021) analyzed outdoor thermal discomfort using ERA reanalysis and WRF model data, but these simulations differ from actual observed data and cannot substitute for ground-truth observations.

To address this gap, the present study calculates the heat stress index across Saudi Arabia using surface observation quality-controlled data from 26 stations, collected following World Meteorological Organization (WMO) standards, for the period 1985 - 2024. The aim is to assess regional heat stress vulnerability in Saudi Arabia and classify each area using a standardized heat stress comfort scale. The utilization of climate models simulations for the heat stress calculation is out of the scope of this study which needs separate documentation for the present and future climates.

2. Data and Methodology

2.1 Data

Daily surface mean temperature and humidity from 26 manned stations across Saudi Arabia collected by the National Meteorological Center (NCM) for the period 1985-2024 following the World Meteorological Organization (WMO) guidelines are used in this study.

2.2 Analysis Methods

Globally, more than 40 indices are used to estimate heat stress and are generally classified into direct, empirical, and rational categories (Burton et al. 2009). Direct indices are relatively simple and rely on basic meteorological variables, whereas empirical and rational indices are more complex, incorporating detailed physiological and environmental modeling. Among these, 16 outdoor heat stress indices (OHSIs) are widely applied, including WBGT, UTCI, HSI, Out_SET, ESI, PMV, CET, DI, ECI, Humidex, SSI, OI, ASV, Australian Apparent Temperature, and the Heat Index (HI). The formulations and computational approaches of these indices are documented in Rachid et al. (2023).

These indices are model-based and depend on assumptions related to factors such as age, activity level, clothing, and exposure, and therefore cannot be directly measured in the field. In this study, five indices HI, Simplified Wet Bulb Globe Temperature (SWBGT), Discomfort Index (DI), Australian Apparent Temperature (AT), and Summer Simmer Index (SSI) were evaluated using data from the Makkah station. The comparison showed strong consistency among HI, DI, SSI, and SWBGT, supporting the selection of HI for application across all stations in Saudi Arabia.

The Heat Index is widely used to assess outdoor heat stress and is calculated from air temperature and relative humidity to represent perceived temperature under shaded, resting conditions. Although it does not account for wind, solar radiation, or physical activity, HI provides a practical and reliable measure of heat stress, particularly under humid conditions where evaporative cooling is reduced. The HI is computed using a regression equation developed by Rothfusz (Wikipedia 2025; NOAA NWS 2022; Rachid and Qureshi 2023).

$$HI = -8.78469475556 + 1.61139411 \times T + 2.33854883889 \times RH - 0.14611605 \times T \times RH - 0.012308094 \times T^2 - 0.0164248277778 \times RH^2 + 2.211732 \times 10^{-3} \times T^2 \times RH + 7.2546 \times 10^{-4} \times T \times RH^2 - 3.582 \times 10^{-6} \times T^2 \times RH^2$$

Where, HI is heat index (in degrees Celsius), T is ambient dry-bulb temperature (in °C), and R is relative humidity (in %). If the RH is less than 13% and the temperature is between 27 and 44 °C, then the following adjustment is subtracted from HI:

$$ADJUSTMENT = [(13-RH)/4] \times \text{SQRT}\{[17-ABS(T-35)]/17\}$$

Where ABS and SQRT are the absolute value and square root functions, respectively. On the other hand, if the RH is greater than 85% and the temperature is between 27 and 31 °C, then the following adjustment is added to HI:

$$ADJUSTMENT = [(RH-85)/10] \times [(31-T)/5]$$

The Rothfusz regression is not appropriate when conditions of temperature and humidity warrant a heat index value below about 27 °C. In those cases, a simpler formula is applied to calculate values consistent with Steadman's results:

$$HI = 0.5 \times \{T + 16 + [(T-20) \times 1.2] + (RH \times 0.094)\}$$

In practice, the calculation of the Heat Index (HI) typically begins with a simplified formula. The result is then averaged with the actual air temperature. If the preliminary HI value is 27 °C or higher, the full Rothfusz regression equation along with any necessary adjustments is applied for a more accurate estimate. It is important to note that the Rothfusz regression is not valid under extreme temperature and humidity conditions that fall outside the empirical range originally defined by Steadman. The HI-based thermal comfort scale is categorized as follows: (i) Safe or Comfort: $HI < 27$ °C, (ii) Caution: $27 \leq HI < 32$ °C, (iii) Extreme Caution: $32 \leq HI < 41$ °C, (iv) Danger: $41 \leq HI < 54$ °C, and (v) Extreme Danger: $HI \geq 54$ °C.

Physiological effects of the Heat Index are the following: (i) Caution: Prolonged exposure or physical activity may cause fatigue and continued exertion could lead to heat cramps, (ii) Extreme Caution: Heat cramps and heat exhaustion are possible, and continued activity increases the risk of heat stroke, (iii) Danger: Heat cramps and heat exhaustion are likely and heat stroke is probable with continued exertion, and (iv) Extreme Danger: Heat stroke is highly likely with ongoing exposure and activity.

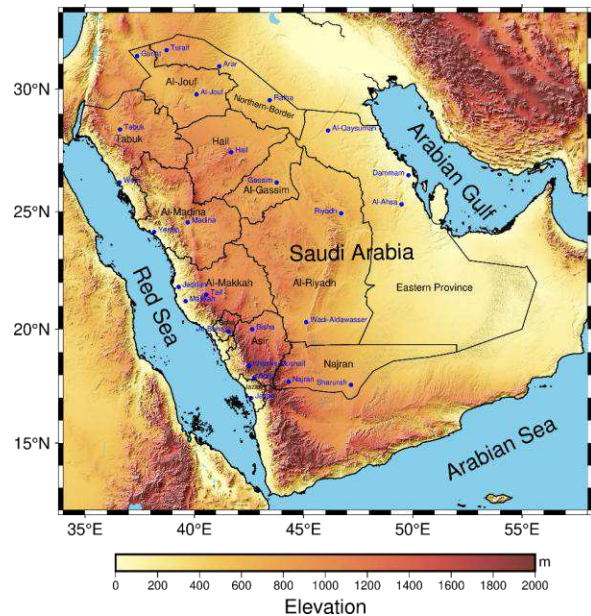


Figure 1. Regional map with elevation (in meters) also showing 13 regions in Saudi Arabia and location of 26 manned stations (blue dots) across the Kingdom.

3. Results and Discussion

3.1 Warm and Dry Conditions

Annual temperatures are generally high across most stations in the western, southern, and eastern regions of Saudi Arabia, where humidity levels are also elevated (Figure 2). Annually, Makkah records the highest average temperature, while Jazan experiences the highest humidity. These mean temperature and relative humidity values are used to calculate the Heat Index across the country.

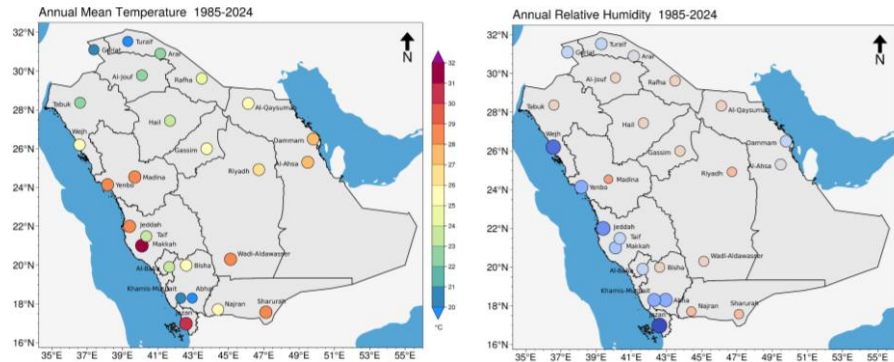
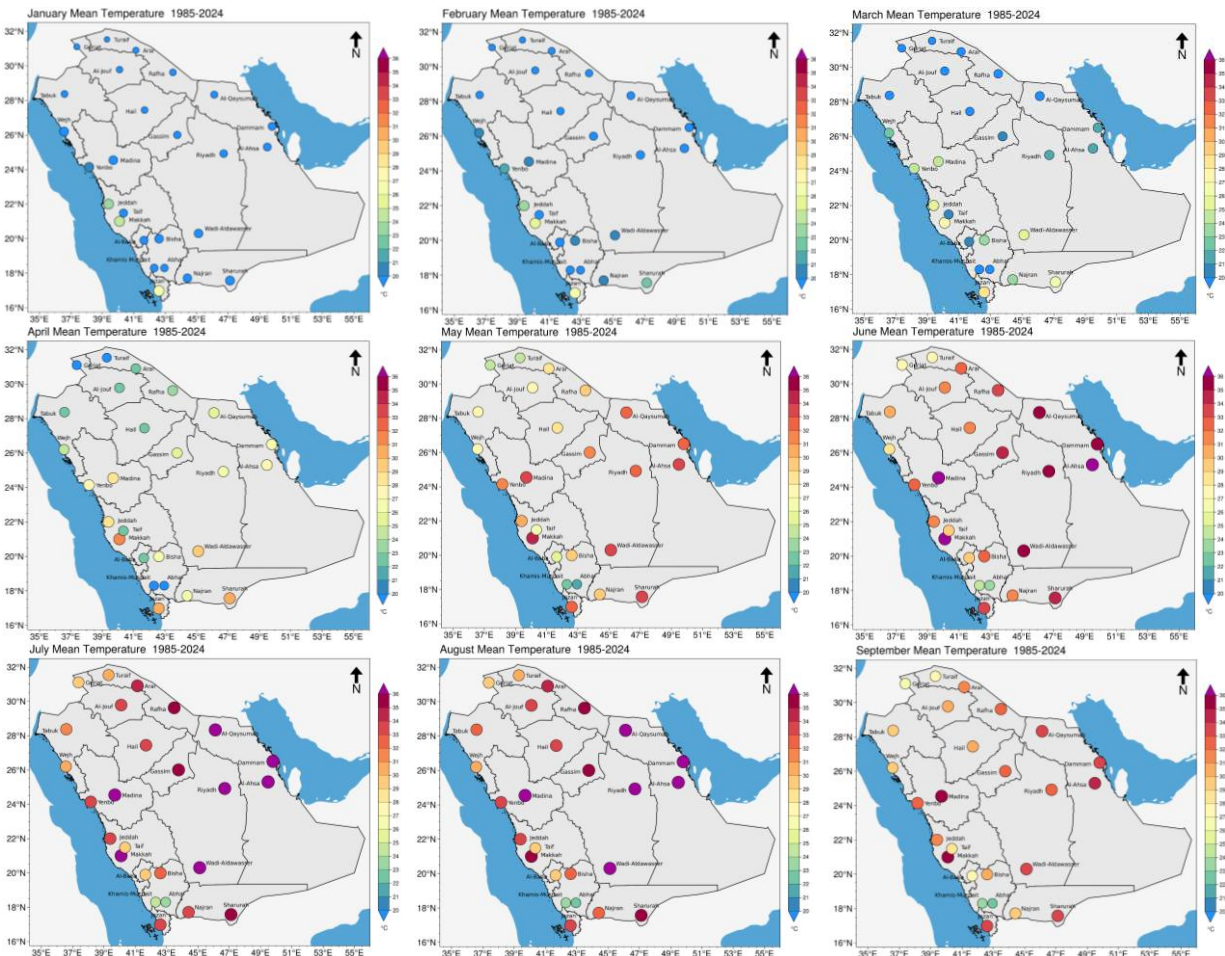


Figure 2. Annual distribution of mean temperature (°C) and relative humidity (%) at different station locations in Saudi Arabia averaged over the period 1985-2024.

The monthly distribution of mean temperature reveals a clear month to month variation and seasonal pattern: higher temperatures observed from May to September and lower values during the remaining months at most station locations (Figure 3). The highest temperatures are observed in the western, eastern, and central regions, while the northern and southwestern mountainous areas experience the lowest.



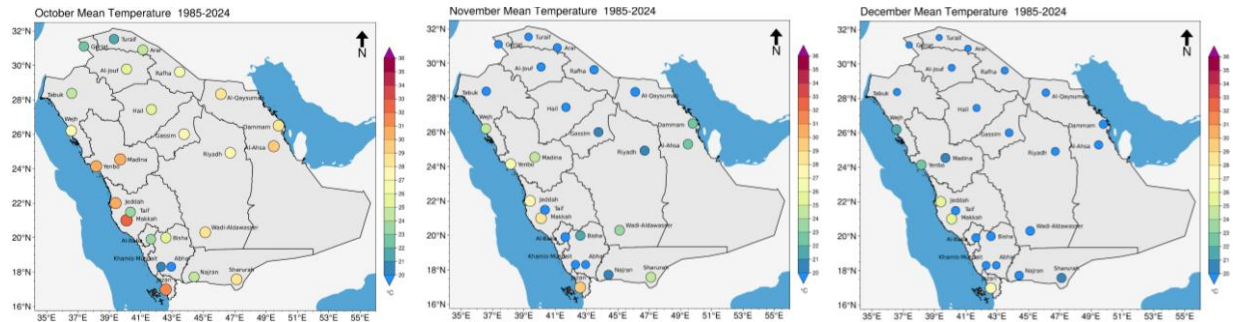
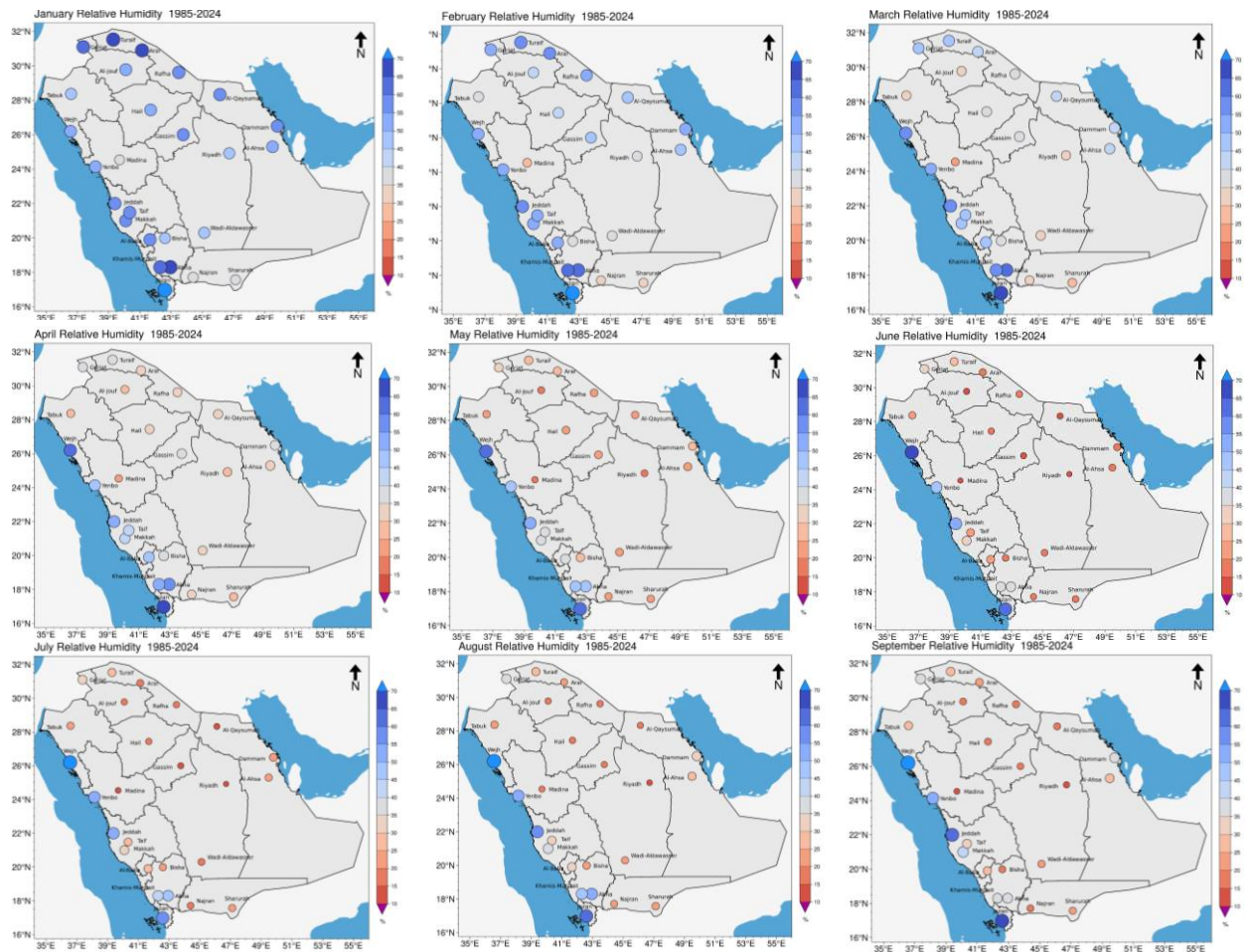


Figure 3. Monthly distribution of mean temperature ($^{\circ}\text{C}$) at different station locations in Saudi Arabia averaged over the period 1985-2024.

Humidity levels are generally higher from November to March and lower during the remaining months at most station locations (Figure 4). The western, southwestern, and northern regions tend to be more humid compared to the central and southern areas.



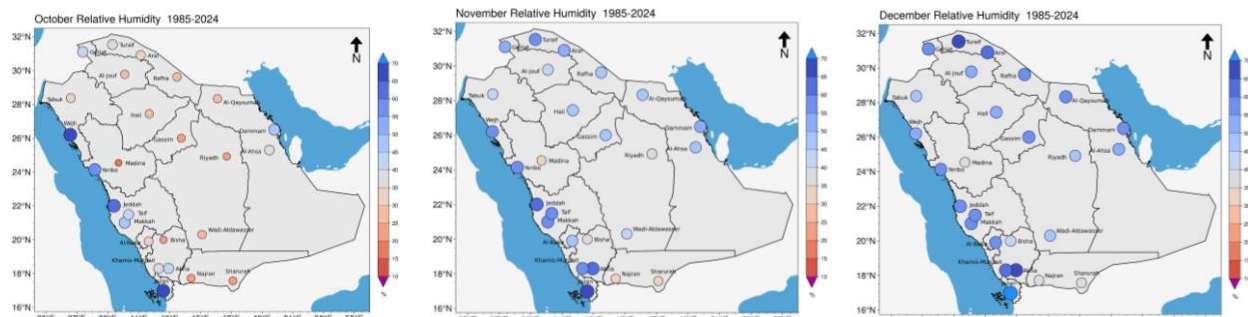


Figure 4. Monthly distribution of relative humidity (%) at different station locations in Saudi Arabia averaged over the period 1985-2024.

3.2 Spatial Distribution of Discomfort Days

The annual distribution of discomfort days defined as days when the Heat Index (HI) is $\geq 27^{\circ}\text{C}$, encompassing the categories of Caution, Extreme Caution, Danger, and Extreme Danger, highlights the southwestern Jazan region as the most vulnerable to heat stress, followed by Makkah, Madinah, the Southern, Eastern, and Riyadh regions (Figure 5). In contrast, the northwestern regions experience significantly fewer discomfort days. Notably, stations in Abha and Khamis Mushait show virtually no annual occurrence of heat stress-related discomfort days, while Al-Baha, Taif, Turaif, and Guriat report relatively low numbers. In Jazan, discomfort days can exceed 330 per year, whereas Abha and Khamis Mushait recorded only 6 and 32 days, respectively, over the entire 40-year period making annual occurrences effectively negligible at these stations.

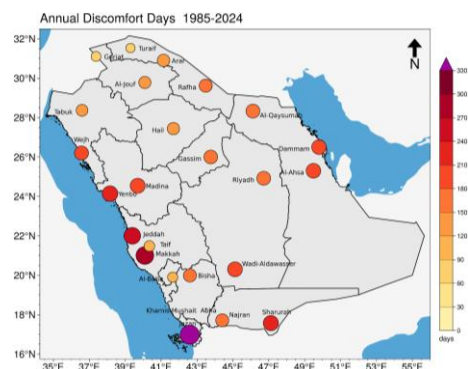


Figure 5. Spatial distribution of annual frequency of discomfort (caution, extreme caution, danger, and extreme danger) days at different station locations in Saudi Arabia averaged over the period 1985-2024.

The distribution of monthly discomfort days, which include Caution, Extreme caution, Danger, and Extreme danger, for a heat index (HI) $\geq 27^{\circ}\text{C}$, shows that these days are most common from April to October (Figure 6). In January, February, and December, discomfort days are observed at only a few stations and in limited numbers. However, in November, discomfort days are more frequent, particularly in Jazan, Makkah, Jeddah, and Yenbo, while little in Madinah, Wejh, Dammam, and Al-Ahsa. From May to September, discomfort days are widespread across the Kingdom. Notably, the number of discomfort days often reaches or exceeds 30 days in a month, especially during June, July, and August. In May, four stations (Makkah, Wadi Al-dawasser, Jazan, and Sharurah) experience over 30

7). Jazan consistently records the highest number of discomfort days, averaging 334 days per year, followed by Makkah (285 days) and Jeddah (254 days). In contrast, Abha reports no annual discomfort days, and Khamis Mushait records just 1 day annually on average. The peak number of discomfort days was observed in Jazan, with 362 days in both 2016 and 2024. Abha recorded a maximum of 6 discomfort days in 2017 and 1 in 1998, while Khamis Mushait experienced discomfort days in only 13 out of the 40 years, peaking at 9 days in 2017.

Most stations exceed the national average (KSA) for discomfort days, except for Abha, Khamis Mushait, Turaif, Gurayat, Al-Baha, Taif, Tabuk, Al-Jouf, Hail, Arar, Najran, Bisha, and Rafha, which fall below it. Overall, the Kingdom shows an increasing trend in discomfort days, rising at an average rate of 7.6 days per decade. The sharpest increases are observed in Al-Baha (14.1 days/decade), Najran (12.8 days/decade), and Jazan (11.5 days/decade). The smallest increases occurred in Abha (0.1 days/decade) and Khamis Mushait (0.5 days/decade).

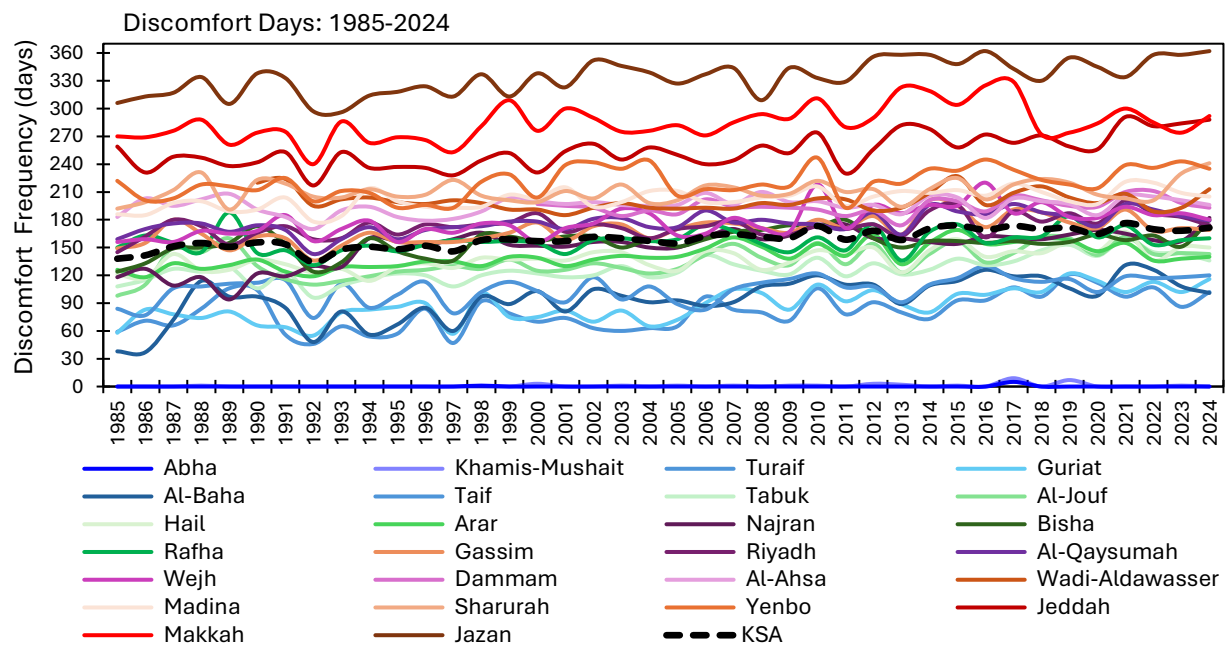
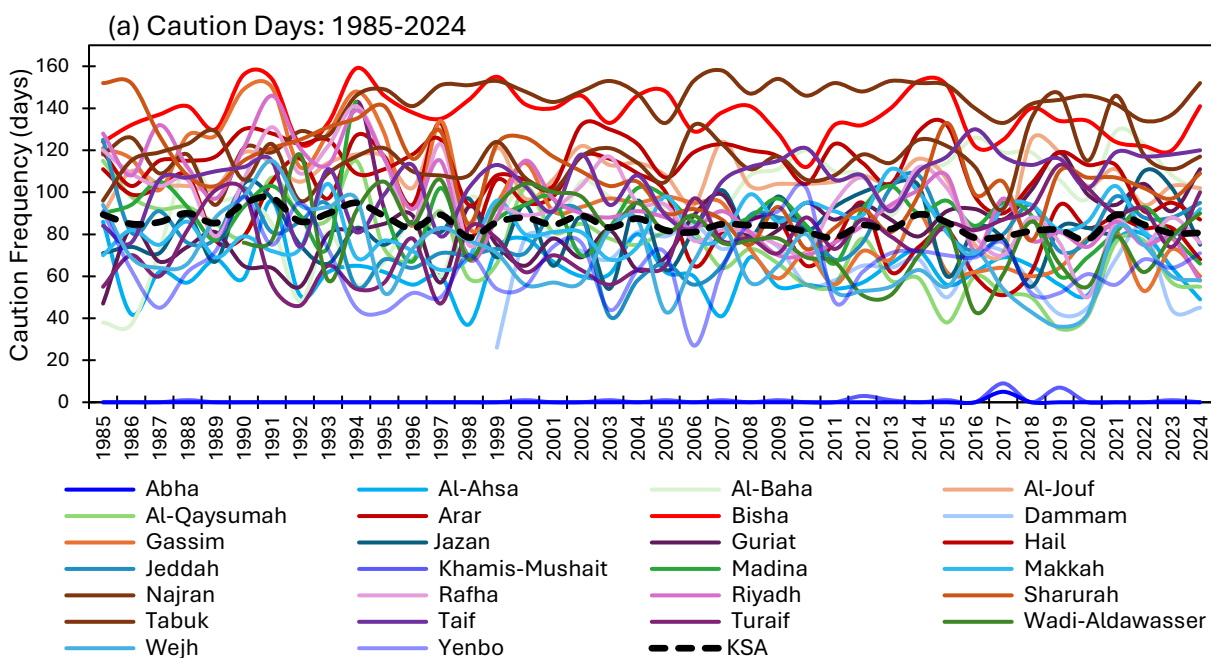


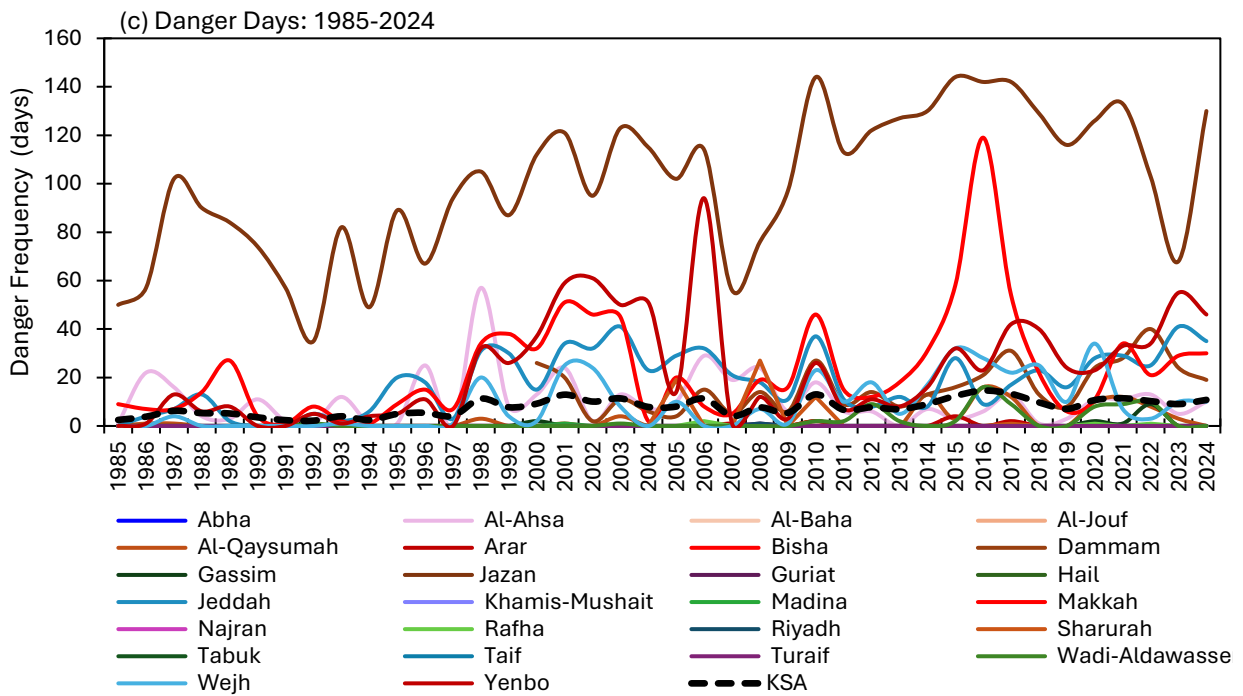
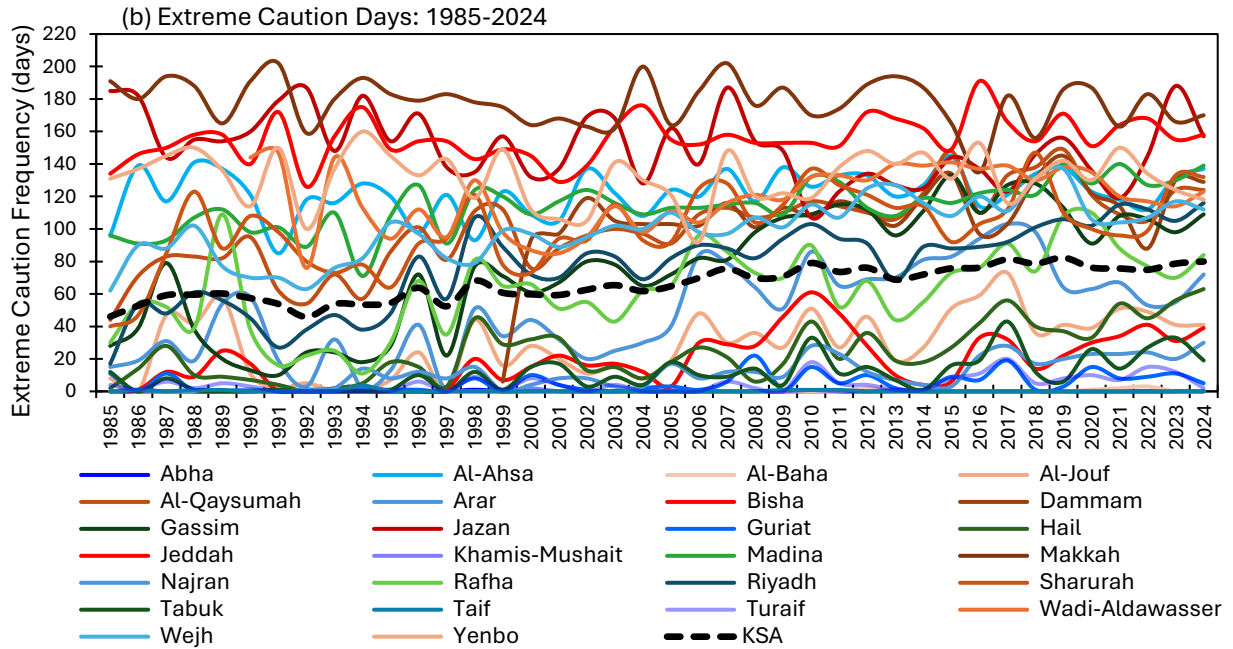
Figure 7. Time sequences of annual frequency of discomfort (caution, extreme caution, danger, and extreme danger) days at different station location across Saudi Arabia averaged over the period 1985-2024.

The occurrence of Caution days (Heat Index of 27–32 °C) across Saudi Arabia shows pronounced interannual variability, with an average of 85 days per year nationwide. Najran records the highest annual frequency, followed by Bisha, while Abha and Khamis Mushait experience the fewest Caution days. Several stations including Madinah, Gassim, Arar, Riyadh, Rafha, Al-Baha, Taif, Sharurah, Al-Jouf, Hail, Tabuk, Bisha, and Najran exceed the national average. Overall, Caution days exhibit a declining national trend of –2.3 days per decade, although spatial variations are evident. The strongest decrease occurs in Gassim (–19.9 days per decade), whereas Al-Baha shows the largest increase (+13.9 days per decade).

Extreme Caution days average 66 days per year and generally follow a similar interannual pattern. Higher-than-average frequencies are observed in Riyadh, Gassim, Wejh, Sharurah, Al-Qaysumah, Dammam, Madinah, Wadi Al-Dawasser, Al-Ahsa, Yanbu, Jazan, Jeddah, and Makkah. Makkah records the highest annual average (178 days), followed by Jeddah (156 days) and Jazan (148 days). Nationally, Extreme Caution days are increasing at a rate of 7.9 days per decade, with the largest rise in Gassim, while Jazan, Makkah, Taif, and Yanbu show declining trends and Abha and Khamis Mushait remain stable.

Danger days occur at about ten stations, with Jazan showing the highest and most consistent frequency, followed by Makkah and Yanbu. These days are increasing nationally by 2.0 days per decade. Extreme Danger days are rare, appearing only after 1997 at a few stations, mainly in coastal and eastern regions, with isolated events observed across the study period.





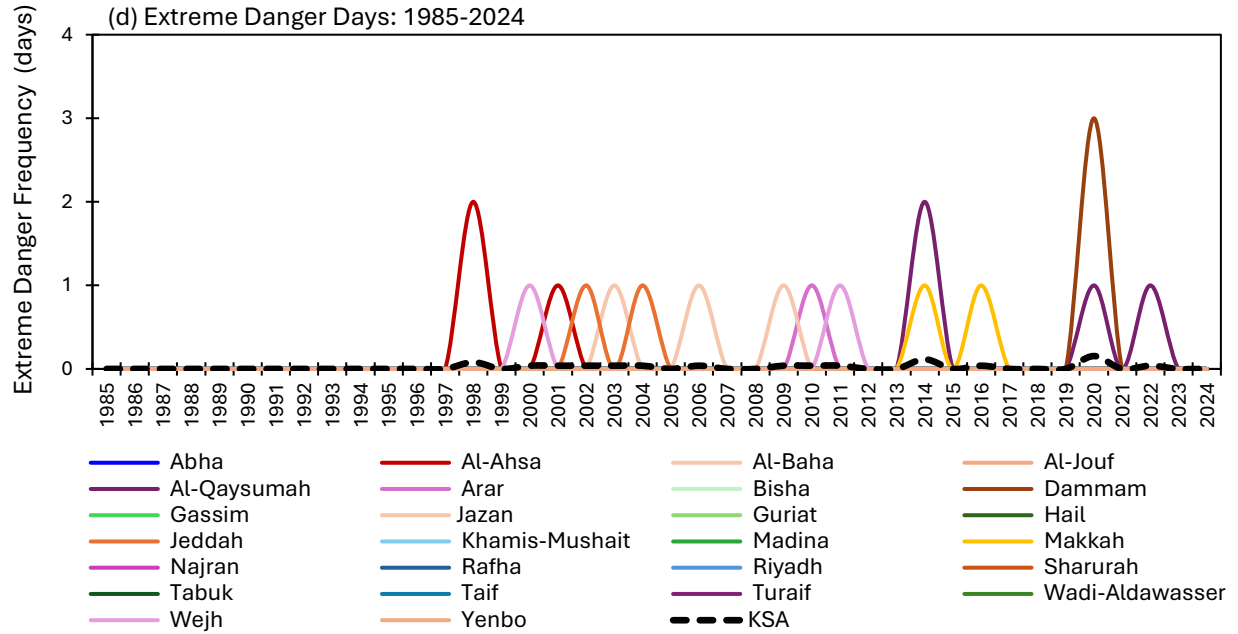


Figure 8. Time sequences of annual frequency of (a) Caution, (b) Extreme Caution, (c) Danger, and (d) Extreme Danger days at different station location across Saudi Arabia averaged over the period 1985-2024. Note that scales in vertical axis are not same for all plots.

3.4 Station Level Discomfort Days

The number of discomfort days varies across stations, with an inverse relationship to the number of comfort days, as illustrated in Figure 9. For Abha and Khamis Mushait, there are no discomfort days, meaning they experience almost 365 comfort days each year. Jazan, with the highest number of discomfort days (334 days annually), has the fewest comfort days, just 31. Makkah follows with 285 discomfort days and 81 comfort days. The discomfort days are classified into four categories as Caution, Extreme caution, Danger, and Extreme danger with the following distribution: nine stations (Jazan, Makkah, Jeddah, Yanbu, Al-Ahsa, Dammam, Wejh, Al-Qaysumah, and Wadi Aldawasser) experience Caution, Extreme caution, and Danger days; 13 stations (Sharurah, Madinah, Riyadh, Gassim, Rafha, Bisha, Najran, Arar, Hail, Al-Jouf, Tabuk, Gurait, and Turaif) experience Caution and Extreme caution days; two stations (Al-Baha and Taif) experience only Caution days; and Abha and Khamis Mushait have no discomfort days. In Jazan, the 334 discomfort days are distributed as follows: 83 days of caution, 151 days of extreme caution, and 100 days of danger.

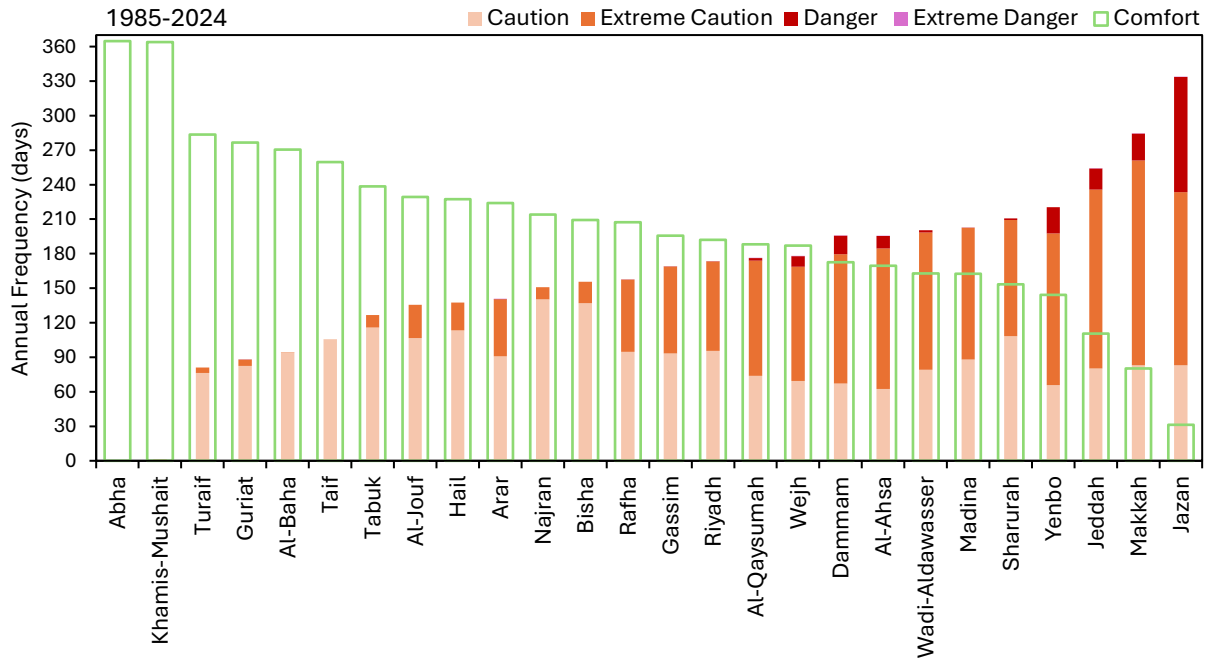


Figure 9. Annual frequency of comfort and discomfort (caution, extreme caution, danger, and extreme danger) days at different station location in Saudi Arabia averaged over the period 1985-2024.

There is a clear increasing trend of annual discomfort days in each 10-year period from 1985 to 2024 for every station except Abha and Khamis Mushait (Figure 10). Among all stations, Jazan has the highest number of discomfort and lowest number of comfort days. In Jazan, the number of discomfort days was approximately 315, 330, 340, and 350 days for the time slots 1985-1994, 1995-2004, 2005-2014, and 2015-2024, respectively. This represents an increase of about 5 days in the 2005-2014 period and 15 days in the 2015-2024 period above the base period (1991-2020) average of 334 days annually. For most of the stations, the latest two 10-year slots (2005-2014 and 2015-2024) show a higher number of discomfort days than base period average where the earlier two 10-year slots (1985-1994 and 1995-2004) show a lower number of discomfort days than base period average. Overall, for most of stations the discomfort days exceed the climatology (1991-2020) average in the recent two decades while lower in the earlier two decades.

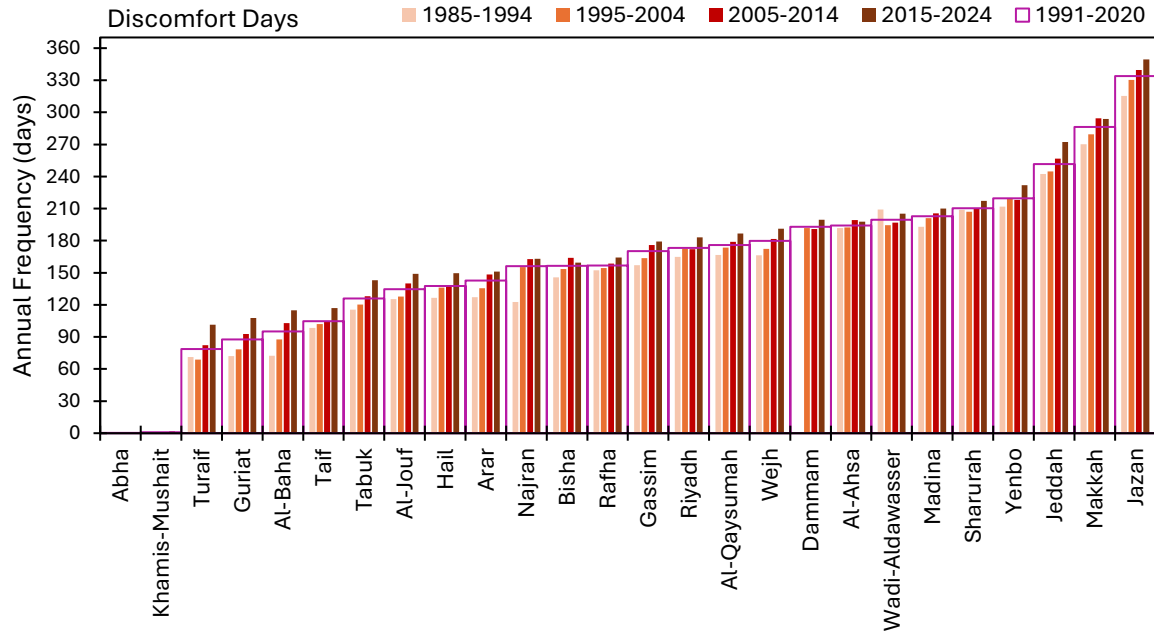


Figure 10. Frequency of discomfort (caution, extreme caution, danger, and extreme danger) days at different station location in Saudi Arabia averaged over 10-year period time slots from 1985-2024 with climatology (1991-2020).

3.5 Annual Cycle of Discomfort Days

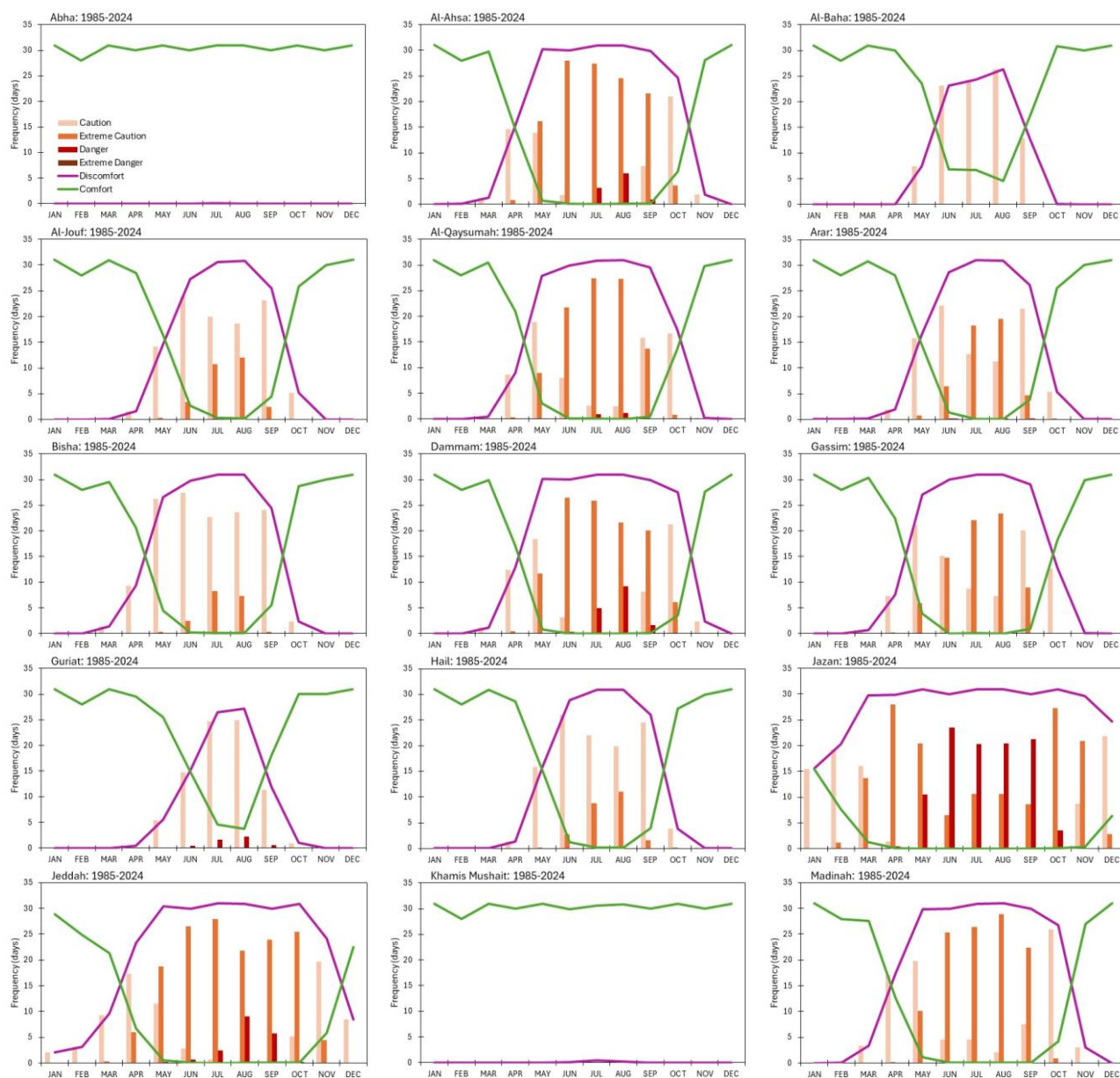
The annual cycle of discomfort and comfort days shows significant variation both month-to-month and station-to-station (Figure 11). Generally, comfort days occur during the winter months and can extend into some spring and autumn months at certain stations, such as Jeddah, Jazan, and Makkah. Conversely, discomfort days are typically observed during the summer months, with some stations like Makkah, Madinah, Al-Ahsa, Al-Qaysumah, Dammam, Jazan, and Gassim experiencing discomfort days that can extend into the autumn and spring months. Notably, Abha and Khamis Mushait have almost no discomfort days. Exceptions to this trend include Makkah, Jeddah, Jazan, and Yenbo, where discomfort days are recorded round the year, reflecting the national average across Saudi Arabia (KSA).

The comfort scale for the thermal stress index, expressed as the heat index (HI), shows that Caution days mainly occur during the summer months for stations such as Al-Baha, Al-Jouf, Arar, Bisha, Hail, Najran, Tabuk, Taif, and Turaif. For other stations, including Al-Ahsa, Al-Qaysumah, Gassim, Jeddah, Madinah, Makkah, Riyadh, Sharurah, Wejh, and Yenbo, Caution days are observed in both the spring and autumn months, with Jazan being an exception, experiencing Caution days in the winter months. For the rest of the stations, Caution days are almost nonexistent (Figure 11). Overall, Caution days occur year-round across the Kingdom, with the highest numbers typically recorded during the spring and autumn months, peaking in May and September.

The occurrence of Extreme caution days varies across different stations compared to caution days. Extreme caution days are primarily observed during the summer months at most stations, except for Jazan, where a higher number of extreme caution days occur in the spring and autumn months. In stations like Jazan, Makkah, Jeddah, and Yenbo,

255 Extreme caution days are seen from spring to autumn. Across the Kingdom, Extreme caution days are most commonly
 256 observed from March to November, with a peak in July.

257 The occurrence of Danger days varies across stations, with some stations like Al-Ahsa, Dammam, Jeddah, Makkah,
 258 Wejeh, and Yenbo experiencing 5 to 10 Danger days in certain months, while Jazan records the highest number, ranging
 259 from 20 to 25 days per month. Overall, the Kingdom experiences fewer than 5 Danger days per month between May
 260 and October. Extreme danger days are rare across the Kingdom, with a total of only 20 days observed throughout the
 261 1985-2024 analysis period. These extreme danger days were recorded as follows: 4 in Al-Qaysumah, 3 each in Al-
 262 Ahsa, Dammam, and Jazan, 2 in Jeddah, Makkah, and Wejeh, and 1 in Arar. Consequently, the annual cycle of Extreme
 263 danger days is almost nonexistent at most stations.



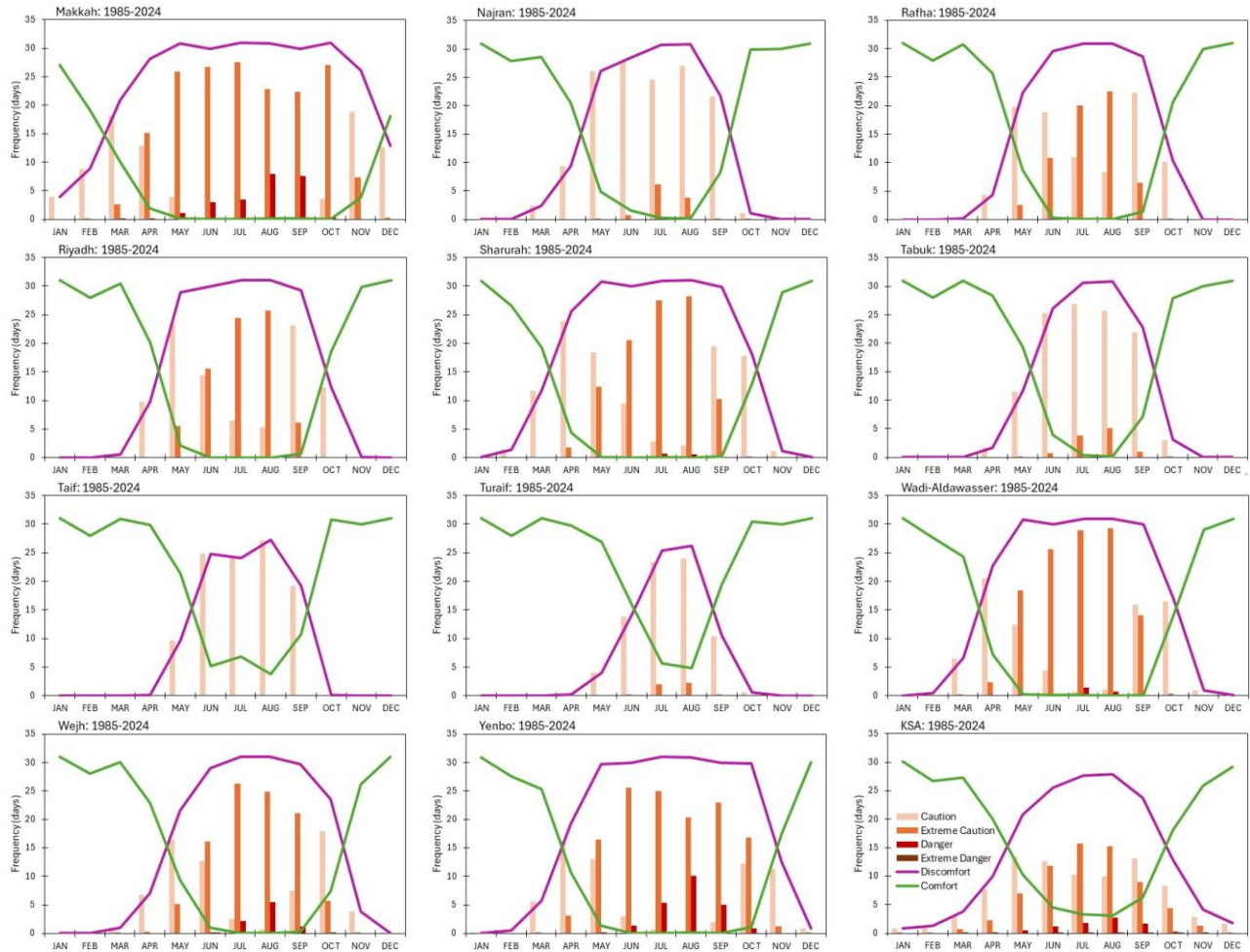


Figure 11. Annual cycle of comfort and discomfort (caution, extreme caution, danger, and extreme danger) days at different station locations in Saudi Arabia averaged over the period 1985-2024.

3.6 Regional Discomfort Days

The regional analysis reveals that Jazan experienced the highest number of discomfort days, while Asir had the lowest (Figure 12). Of the 13 regions, six (Gassim, Najran, Eastern, Makkah, Madinah, and Jazan) recorded discomfort days above the country average, while the remaining regions had values below the average. Between 1985 and 2024, discomfort days increased in all regions. The highest increase rate was 14.1 days per decade in Al-Baha, followed by 11.5 days per decade in Jazan, and a slower increase of 2.1 days per decade in Asir. The overall country average increase rate was 7.6 days per decade.

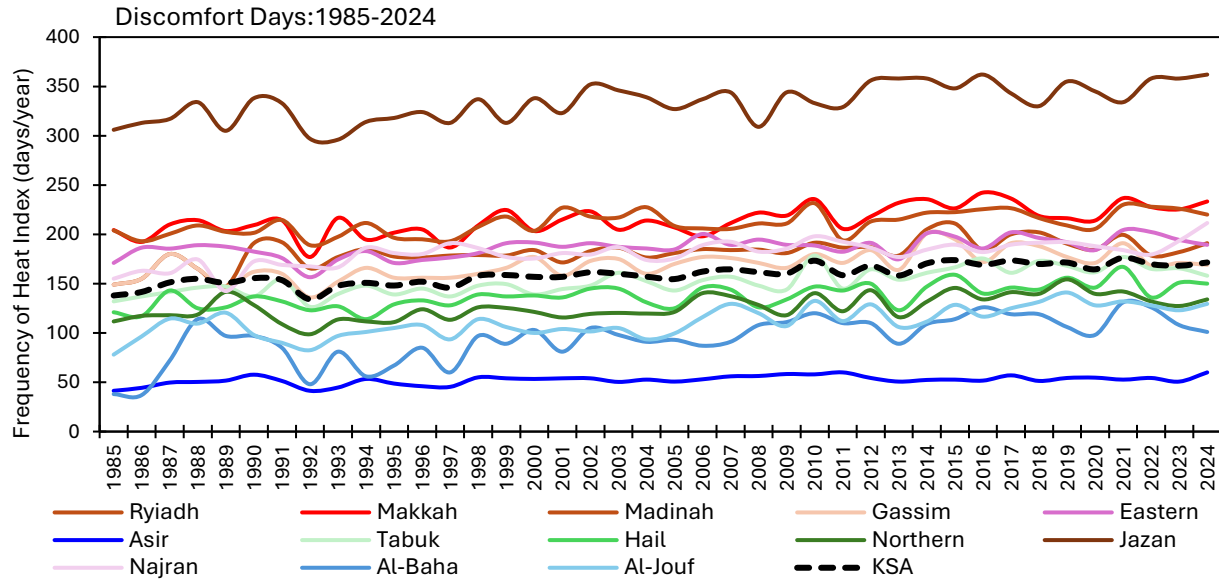


Figure 12. Annual frequency of discomfort (caution, extreme caution, danger, and extreme danger) days at 13 regions in Saudi Arabia averaged over the period 1985-2024.

The number of comfort and discomfort days are inversely related across all regions (Figure 13). Asir region experiences the highest number of comfort days and the lowest number of discomfort days annually, while Jazan shows the opposite character, with the highest number of discomfort days and the fewest comfort days. Jazan also sees a significant number of extreme caution and danger days, while Najran experiences more caution days. This highlights that the most vulnerable region to heat stress is the southwestern region of Jazan, followed by Makkah, Madinah, Eastern, Riyadh, Najran, Gassim, Tabuk, Hail, Northern, and Al-Jouf.

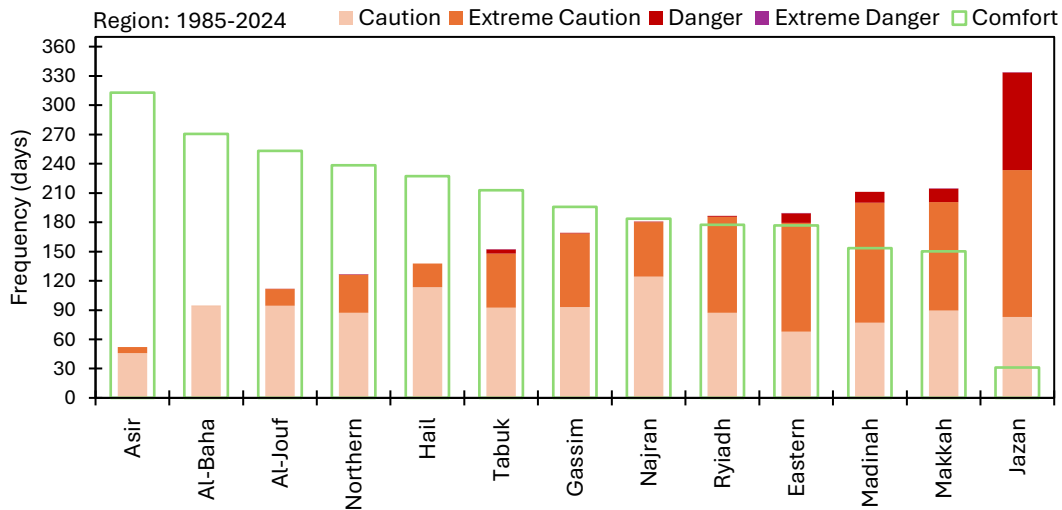


Figure 13. Annual frequency of (a) comfort and (b) discomfort (caution, extreme caution, danger, and extreme danger) days at 13 regions in Saudi Arabia averaged over the period 1985-2024.

In general, coastal regions such as Jazan, Makkah, Madinah and Eastern are more vulnerable to heat stress than the other regions and less vulnerable in the mountainous Asir and Al-Baha regions. Heat stress vulnerability levels differ across various locations within the same region (Figure 14). In the Asir region, Abha and Khamis Mushait are classified as Less vulnerable, whereas Bisha is considered Vulnerable. In the Northern Border region, the vulnerability varies by station: Turaif is Less vulnerable, Arar has a Moderate level, and Rafha is Vulnerable. Similar patterns of variation are observed in other regions that have multiple observation stations.

The vulnerability to discomfort days can be categorized as Extremely vulnerable, Very vulnerable, Vulnerable, Moderate vulnerable, and Less vulnerable. Jazan falls under the Extremely vulnerable category (with more than 300 discomfort days annually), while Makkah, Madinah, and Eastern regions are Very vulnerable (more than 190 discomfort days annually). Riyadh, Najran, Gassim, and Tabuk regions are categorized as Vulnerable (over 150 discomfort days annually), Hail, Northern, and Al-Jouf regions are Moderate vulnerable (over 100 discomfort days annually), and Al-Baha and Asir are Less vulnerable (fewer than 100 discomfort days annually) (Figure 14). It is important to note that while Riyadh's discomfort days are close to those of the Eastern region, it does not experience danger days, placing it in the Vulnerable category. Similarly, Tabuk is categorized as Vulnerable, despite having fewer discomfort days than Riyadh, due to the presence of Danger days in Wejha, as indicated in the station-wise discomfort day distribution. While Asir is categorized as less vulnerable, Bisha station experiences significant discomfort days during the summer months (see Figure 6).

Furthermore, examining the diurnal variation of heat stress across different regions and stations is crucial. However, due to the lack of hourly surface observational data, heat stress can be calculated using Automatic Weather Stations (AWS) and reanalysis gridded datasets. Notably, the AWS data is available only for a few years, suitable for case study and not for long-term climatology. Remarkably, heat stress projections are essential for long-term planning. For future research, it is recommended to use climate model simulations for both historical and projection periods, in addition to reanalysis datasets.

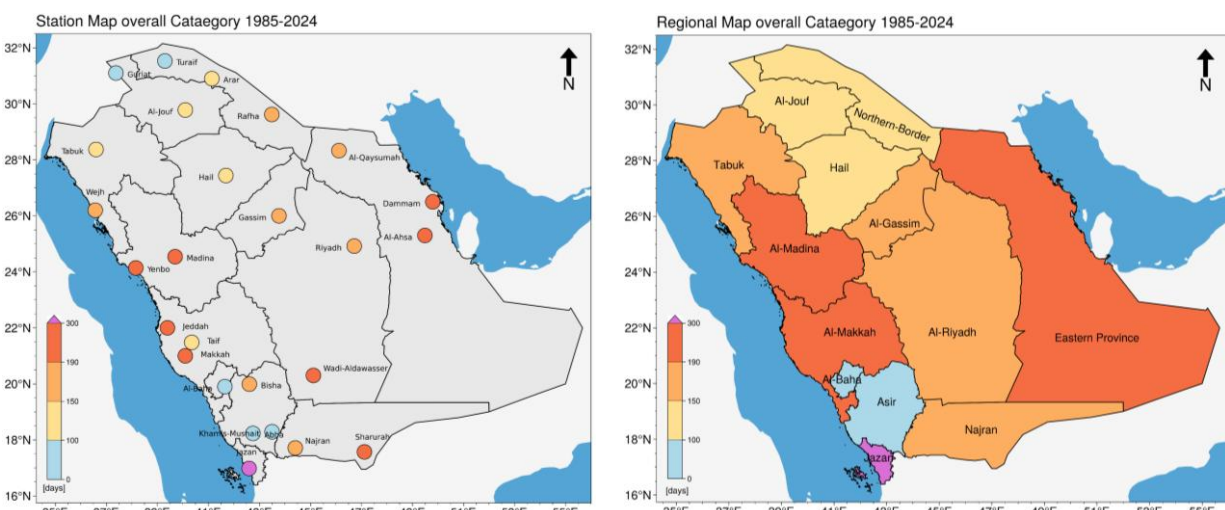
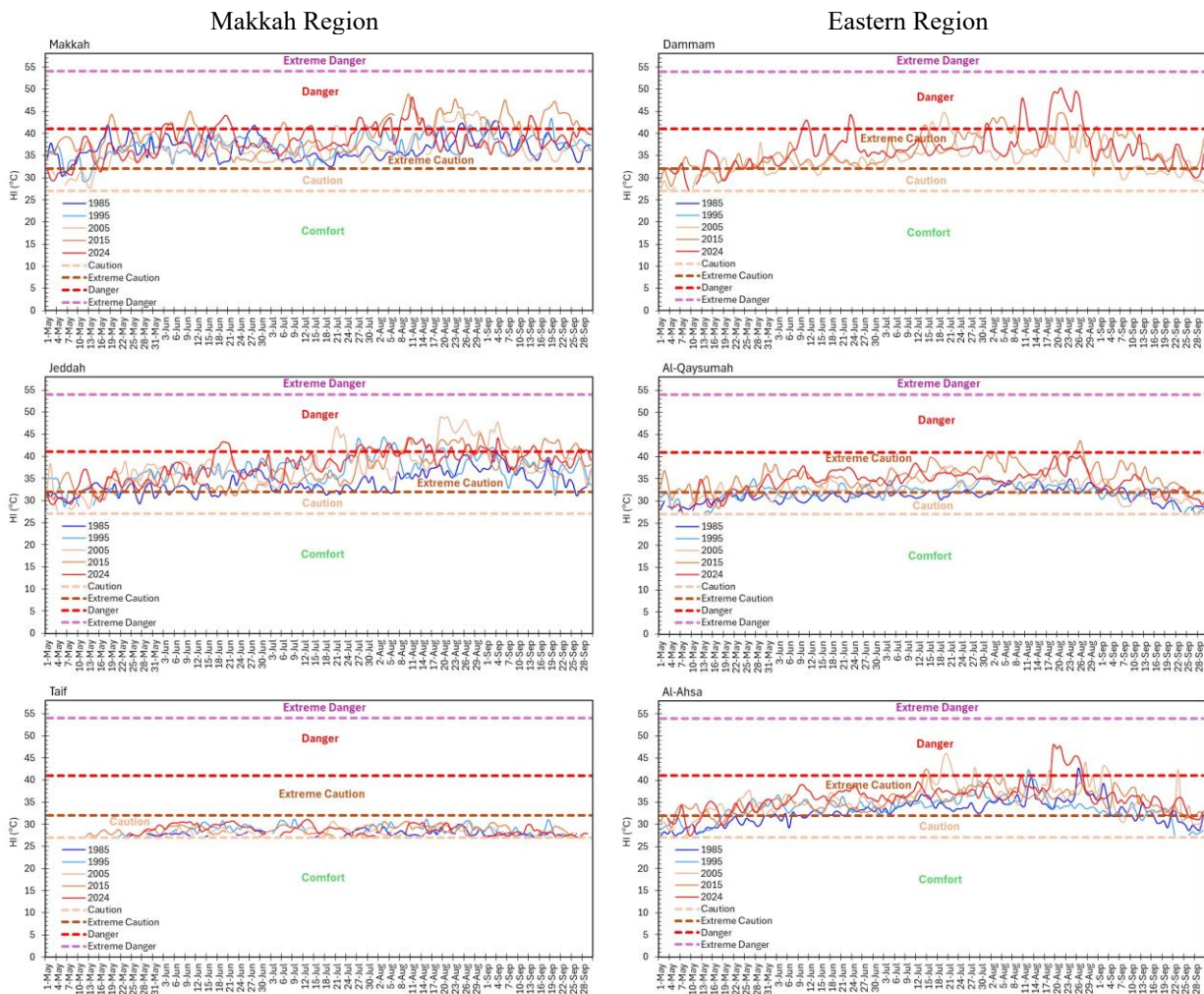


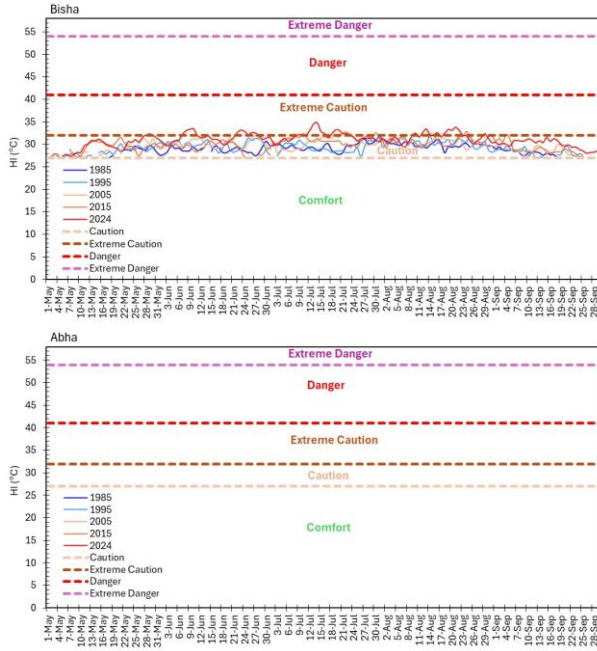
Figure 14. Heat stress discomfort (caution, extreme caution, danger, and extreme danger) days vulnerable stations and regions in Saudi Arabia.

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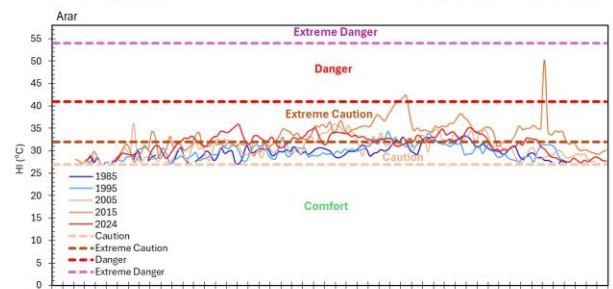
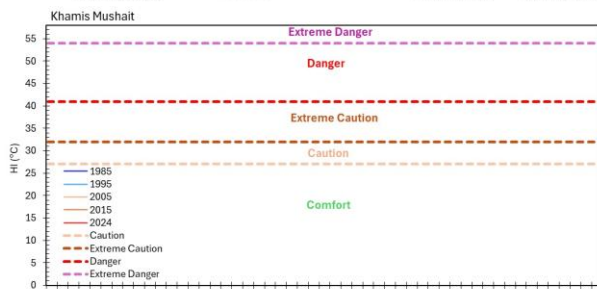
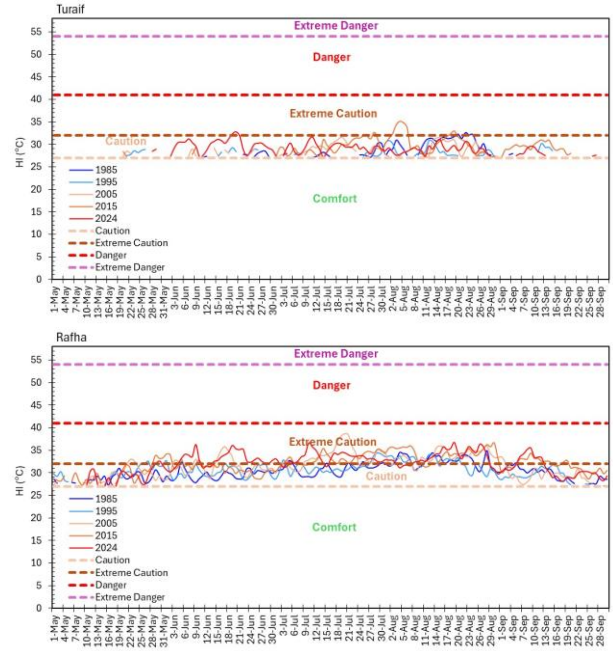
314 The daily heat stress in different regions over Saudi Arabia shows variations in region to region and station to station
315 within a region (Figure 15). Makk region shows extreme caution to danger for Makkah and Jeddah station while only
316 caution in hilly Taif station. Eastern region shows extreme caution to danger almost in all stations. In this region
317 Dammam has data missing for 1985 and 1995. Asir is the relatively comfortable region except caution in Bisha station
318 while Abha and Khamis Mushait have no discomfort days. Northern, Hail, and Al-Baha regions experience mostly
319 caution dation with some extreme caution in Rafha, Arar, and Hail. Madinah and Riyadh regions experience mostly
320 extreme caution with danger in Yenbo. Tabuk, Najran, and Gassim regions have mostly extreme caution while danger
321 can reach for few days in Sharurah. Al-Jouf is mostly caution with a few days in extreme caution. Jazan region
322 experiences mostly danger days with some extremely caution days. In general, the level of discomfort increases from
323 early years to recent years as seen for the years 1985, 1995, 2005, 2015 and 2024 exhibited in Figure 28. One can
324 argue on the leveling of HI-based thermal scales. In this study the threshold 54 °C is used for extreme danger; however,
325 51 °C is also used for the same classification (<https://www.weather.gov/ama/heatindex>) but there will not change on
326 the status of extreme danger days as seen in Figure 28.



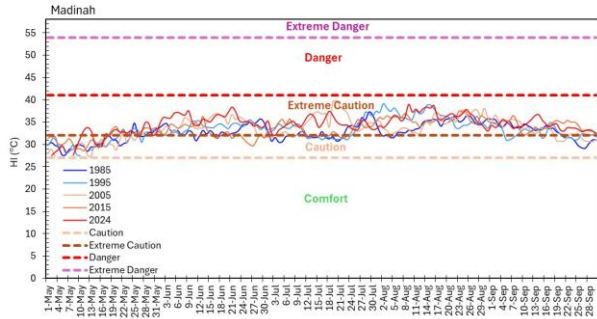
Asir Region



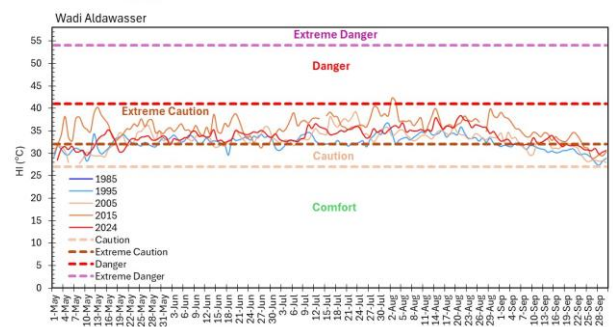
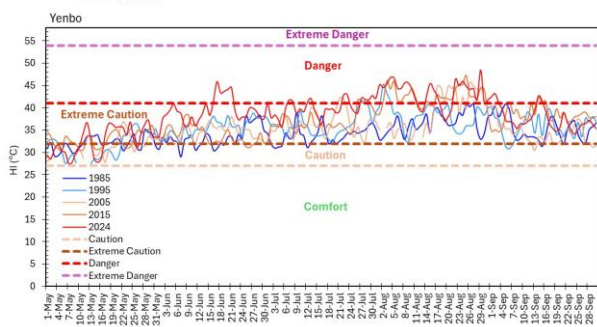
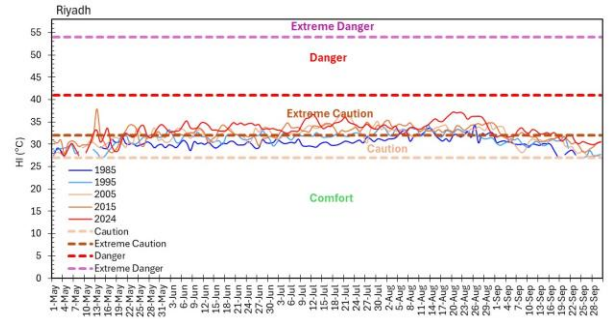
Northern Region



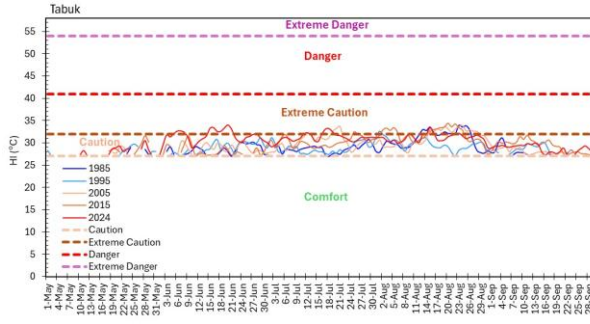
Madinah Region



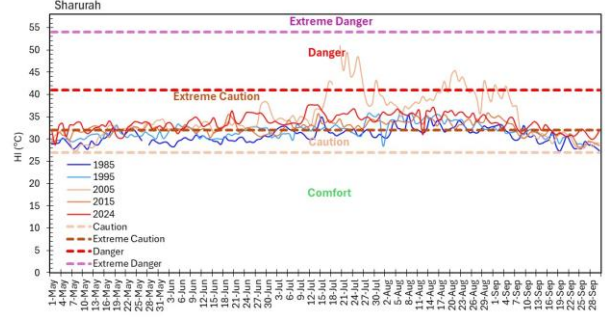
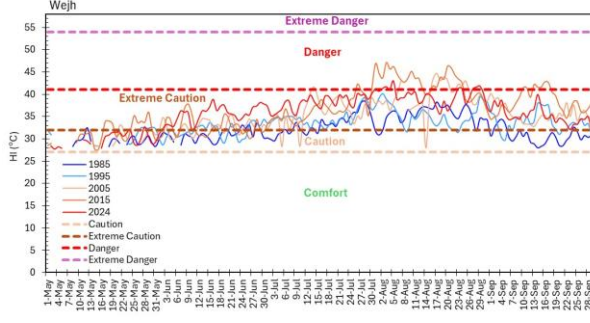
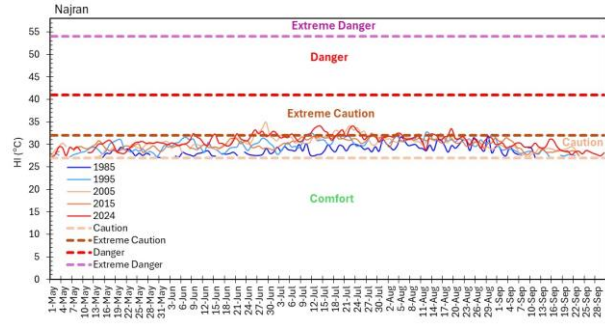
Riyadh Region



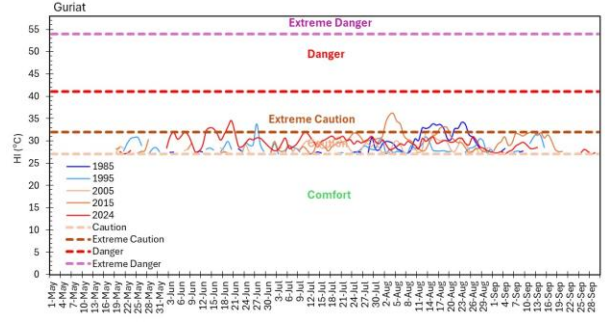
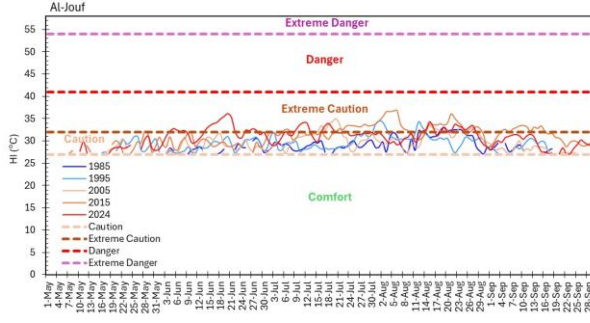
Tabuk Region



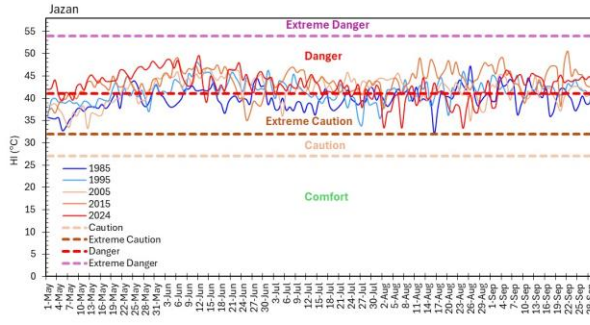
Najran Region



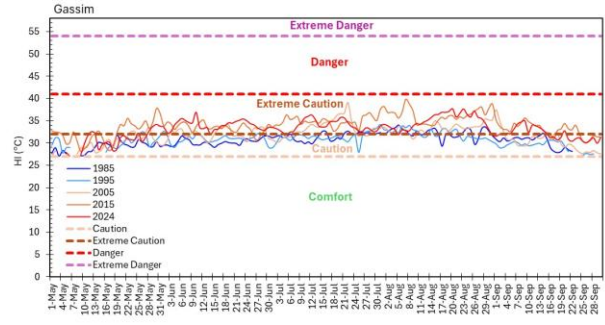
Al-Jouf Region



Jazan Region



Gassim Region



Hail Region

Al-Baha Region

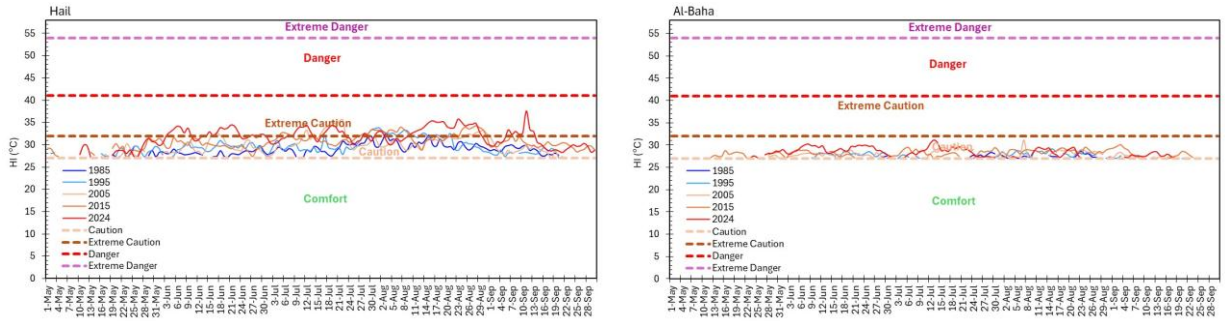


Figure15. Daily heat stress discomfort (caution, extreme caution, danger, and extreme danger) days during May to September at different stations under 13 regions in Saudi Arabia.

4. Conclusions

This study provides valuable insights into the patterns of heat stress across Saudi Arabia, highlighting the significant vulnerability of certain regions to extreme thermal discomfort. The analysis of 26 surface observation manned stations over a 40-year period (1985-2024) has revealed a clear regional variation in heat stress, with Jazan, Makkah, and Jeddah being the most affected, while Asir and Al-Baha experience comparatively lower discomfort levels. The classification of regions based on thermal comfort indicates that Jazan is the most vulnerable, facing the highest frequency of discomfort days, followed by other regions such as Makkah and Madinah, which are also highly vulnerable. This trend of increasing discomfort days over time, especially in regions like Al-Baha and Jazan, underlines the growing concern about heat stress as a natural hazard, with potential implications for public health, urban planning, and energy consumption.

The findings also emphasize the importance of understanding seasonal and regional variations in discomfort days, with specific months such as May, September, and July being critical periods for extreme heat exposure. While extreme danger days were rare, their occasional occurrence highlights the severity of heat stress during certain periods, especially in coastal cities. Ultimately, the classification of regions based on vulnerability provides a foundation for the impacts of heat stress, protect vulnerable populations, and promote sustainable development through further research in the face of an increasingly hotter climate. Further research on heat stress is required using hourly records from manned stations, Automatic Weather Stations, reanalysis datasets, and climate model simulations for the long-term planning purposes.

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