



Analysis of Outdoor Thermal Discomfort Over the Kingdom of Saudi Arabia

Key Points:

- Analyze and investigate variability and trends of the outdoor thermal discomfort index (DI) in the Kingdom of Saudi Arabia (KSA)
- Reduced rate of increase in DI was reported in the southwestern region during the last 20 years
- During this period, except Yanbu, Makkah, Madina, and Taif, most cities had an improved DI

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Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract In this study, the variability and trends of the outdoor thermal discomfort index (DI) in the Kingdom of Saudi Arabia (KSA) were analyzed over the 39-year period of 1980–2018. The hourly DI was estimated based on air temperature and relative humidity data obtained from the next-generation global reanalysis from the European Center for Medium-Range Weather Forecasts and in-house high-resolution regional reanalysis generated using an assimilative Weather Research Forecast (WRF) model. The DI exceeds 28°C, that is, the threshold for human discomfort, in all summer months (June to September) over most parts of the KSA due to a combination of consistently high temperatures and relative humidity. The DI is greater than 28°C for 8–16 h over the western parts of KSA and north of the central Red Sea. A DI of >28°C persists for 7–9 h over the Red Sea and western KSA for 90% of summer days. The spatial extent and number of days with DI > 30°C, that is, the threshold for severe human discomfort, are significantly lower than those with DI > 28°C. Long-term trends in the number of days with DI > 28°C indicate a reduced rate of increase or even a decrease over some parts of the southwestern KSA in recent decades (1999–2018). Areas with DI > 30°C, in particular the northwestern regions of the Arabian Gulf and its adjoining regions, also showed improved comfort levels during recent decades. Significant increases in population and urbanization have been reported throughout the KSA during the study period. Analysis of five-years clinical data suggests a positive correlation between higher temperatures and humidity with heat-related deaths during the Hajj pilgrimage. The information provided herein is expected to aid national authorities and policymakers in developing necessary strategies to mitigate the exposure of humans to high levels of thermal discomfort in the KSA.

Plain Language Summary We analyzed the outdoor thermal discomfort using an in-house high-resolution reanalysis generated using an advanced Weather Research and Forecast modeling system and assimilating all available regional observations. We examined the spatiotemporal distribution of thermal discomfort from 1981 to 2018 over Kingdom of Saudi Arabia (KSA). Our results outline changes in livability conditions in terms of the trends of different thermal discomfort thresholds in the last four decades across KSA. Further, we investigate the possible reasons for the increase/decrease of thermal discomfort over different regions of KSA. Our study suggests improved living conditions over some parts of the northwestern Arabian Gulf and their adjoining regions in recent decades and worse conditions over the southeast regions. The detailed information provided here on the hotspots of improved or deteriorated human discomfort will be useful for decision makers to take efficient mitigation measures.

1. Introduction

Climate change due to global warming has numerous effects on the living conditions of humans. Rising temperatures and the impact of urbanization result in heat stress and heat-related mortality (Kleerekoper et al., 2012). In the Kingdom of Saudi Arabia (KSA), changes in weather patterns and a sharp increase in extreme weather events are among the most significant drivers of social vulnerability, considerably threatening the living conditions of humans (Abdul Salam et al., 2014). Rapid growth in urbanization during recent decades and the consequent increase in impermeable surfaces of urban infrastructure surfaces have significantly changed urban ecosystems, substantially impacting the quality of life of urban residents (e.g., Du et al., 2019; Luong et al., 2020; Ren et al., 2008; van Hove, 2015; Warburton et al., 2012; Zhong et al., 2015). The ability of urban dwellers to adapt to varying thermal environments largely depends on the

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external meteorological conditions. However, considering temperature variations alone may not provide a comprehensive picture of the threats posed by heat stress; ambient relative humidity must also be considered as it influences the evaporation of sweat, which helps to naturally maintain human comfort levels (Huang et al., 2020; Qaid et al., 2016). Air temperatures between 18°C and 23°C and relative humidity (RH) levels between 35% and 70% are considered to be the comfortable ranges for livability (Höppe, 1999; Lin et al., 2010). However, these comfortable ranges may vary depending on the outdoor weather conditions and differ among residents from different climatic regions. When the human body is exposed to extreme heat and humidity, its cooling mechanisms, for example, increased heart rate and sweating, are triggered (HNICEM., 2017); these mechanisms can cause discomfort, weakness, loss of stamina, and muscle pains and, in severe cases, even heat strokes and heart attacks (HNICEM., 2017).

The outdoor discomfort index (DI, expressed in units of °C) is a measure of the human heat sensation under different climatic conditions. The DI is computed using temperature and relative humidity, and it represents a quantitative assessment of stress due to heat. The DP helps evaluate how particular atmospheric conditions can affect the sensation of discomfort and the corresponding health risks to the population (e.g., Freitas & Grigorieva, 2015; Roghanchi & Kocsis, 2018; Tom, 1959). To consider cloudy conditions and their effects on longwave radiation scattering, several studies proposed using radiant temperature instead of air temperature when computing DI (e.g., Fanger, 1970; Gan, 2001; Koch, 1962). However, a lack of radiant temperature data for most regions hinders the use of this parameter in assessing human thermal stress (e.g., Ali-Toudert, 2005; Gan, 2001). In the case of KSA, the radiant temperature need not be used to estimation of the thermal comfort because of the prevalence of clear sky conditions and hot and dry climate throughout the year (Ali-Toudert, 2005). Hence, the DI may be computed based on temperature and relative humidity for this region (Anderson et al., 2013; Petitti et al., 2016).

Anderson et al. (2013) computed a heat stress index over several cities in the United States of America (USA) using 21 different methods and reported that calculating the DI based on temperature and humidity is the most robust and more suitable for regions with high temperatures. In other studies, the human health risk factor was calculated by measuring the combined effects of high ambient temperatures and humidity based on the simplified wet-bulb temperature and coarser resolution global data sets (e.g., Dunne et al., 2013; Fischer & Knutti, 2013; Pal & Eltahir, 2016; Zhao et al., 2015). Petitti et al. (2016) computed the DI over the state of Arizona, USA, using temperature and humidity in order to examine the relationship of DI with the mortality and hospitalization. A similar long-term assessment of the DI for the hot and humid climate of the KSA can reveal the effects of thermal stress on the population and the variability of this stress with changes in the climatic conditions and the environment (e.g., urbanization). Such a comprehensive study detailing the variability and trends of DI derived from a reliable long-term, high-resolution data set is still lacking for the KSA.

In most previous studies, the DI was examined using either the Intergovernmental Panel on Climate Change (IPCC) global climate model projections or regional models driven by the global climate models for various regions around the world. Despite the uncertainties associated with the IPCC projections and issues inherent to their downscaling, extreme wet-bulb temperatures projected for the future were suggested to approach and exceed the critical threshold values over the Arabian Gulf and its adjoining regions, which will severely impact human livability (Pal & Eltahir, 2016). Al-Bouwarthan et al. (2019) recently assessed the heat stress over the southeastern KSA during the summer of 2016 using a wet-bulb global temperature index and a temperature-humidity index, suggesting that the temperature-humidity index is the most suitable for evaluating heat stress risks over the KSA.

The objective of the present study is to describe, for the first time, to the best of our knowledge, the DI variability over the KSA based on an in-house atmospheric reanalysis data generated by using an assimilative Weather Research Forecast (WRF) model (Skamarock et al., 2019) over a 39-year period of 1980–2018. This extensively validated reanalysis of the KSA comprises unique information on the long-term weather conditions with a 5-km horizontal resolution grid and hourly intervals over the KSA. We computed the DI at every grid point across the entire study period and assessed its variability over hourly, seasonal, and interannual time scales. In addition, we performed a trend analysis to assess changes in the persistence of DI over time for different regions of the KSA and investigate possible relationships between this trend and changes in population and urbanization. Furthermore, we attempted to establish a link between the available

Table 1
Classification of Human Thermal Discomfort Based on the Discomfort Index (DI)

Sr. No	Human thermal discomfort classification	DI range (°C)
1	No discomfort	<21
2	Under 50% population feels discomfort	21 < DI < 24
3	Over 50% population feels discomfort	24 < DI < 27
4	Most of the population suffers discomfort	27 < DI < 29
5	Everyone feels severe discomfort	29 < DI < 32
6	State of medical emergency	DI > 32

health-related data and changes in DI. The DI and associated trends were also computed using the European Center for Medium-Range Weather Forecasts (ECMWF) next-generation reanalysis (ERA, Copernicus Climate Change Service C3S, 2017) data for comparison.

The rest of this study is organized as follows. The methodology for computing DI and the details of the analyzed data sets are presented in Section 2. The results of the DI analysis over the KSA are reported and discussed in Section 3. Finally, a summary and the conclusions of the study are provided in Section 4.

2. Data and Methodology

2.1. Data Sets

We analyzed temperature and relative humidity at a height of 2-m as suggested by the World Meteorological Organization (WMO, 2008) using two different data sources. The 2-m height accounts for the influence of free air, sunshine, and wind, and thus minimizing the effect of grass surfaces, trees, buildings, and other obstructions on measurement instruments (WMO, 2008). The first data set is the ERA global reanalysis (Copernicus Climate Change Service C3S, 2017), available at ~15 km horizontal resolution and for every hour; this data set has been widely used by the research community for several climate studies over the Arabian Peninsula (AP). The second data set is an in-house regional high-resolution reanalysis that was specifically generated to study the climate of the AP using a WRF model assimilating all available regional observations (e.g., Dasari, Desamsetti, Langodan, Attada, et al., 2019; Hoteit et al., 2021; Sanjeev et al., 2020; Viswanadhapalli, Dasari, Dwivedi, et al., 2019; Viswanadhapalli, Dasari, Langodan, et al., 2017). The WRF was configured with 5 km/1 h horizontal/temporal resolutions and used the ECMWF (ERA-Interim) fields as the boundary and initial conditions. This AP reanalysis has been extensively validated using in situ and remote sensing observations; additionally, it has been used in several studies (e.g., Dasari, Desamsetti, Langodan, Attada, et al., 2019; Hoteit et al., 2021; Langodan, Antony, et al., 2020; Langodan, Viswanadhapalli, et al., 2016; Sanjeev et al., 2020; Viswanadhapalli, Dasari, Dwivedi, et al., 2019; Viswanadhapalli, Srinivas, et al., 2019; Viswanadhapalli, Dasari, Langodan, et al., 2017); these studies provide the complete details regarding the methodology used to generate the AP reanalysis and describes its use for studying the regional climate variability and atmospheric and oceanic processes across the AP.

2.2. Computation of Outdoor Thermal DI

We estimated the DI based on temperature and relative humidity, as suggested by Thom (1959). This DI was used as an indicator for the heat stress on humans in several previous studies (e.g., Anderson et al., 2013; Freitas & Grigorieva, 2015; Giles et al., 1990; Roghanchi & Kocsis, 2018; Yasmeen & Liu, 2019). The DI (in °C) is computed as a function of air temperature (T ; °C) and relative humidity (RH; %) as follows:

$$DI = T - 0.05(1 - 0.01RH)(T - 14.5). \quad (1)$$

High DI indicate a high level of thermal human discomfort in humans. The suggested limits of DI according to previous studies (e.g., Anderson et al., 2013; Marina et al., 2005; Mishra et al., 2016, 2013; Nedel et al., 2015; Yasmeen & Liu, 2019) are classified in Table 1.

Herein, we computed the DI using ERA and WRF reanalysis data obtained over the summer months, that is, from June to September (JJAS). We selected these months because of both their extreme heat and the significant changes in summer temperatures reported over the study region during the last few decades (e.g., Attada, Dasari, Chowdary, et al., 2018; Attada, Dasari, Kunchala, et al., 2020; Attada, Kunchala, et al., 2018). We categorized the estimated DI values based on the standard limits (Table 1), and thereafter, we explored its variability and trends over the past four decades.

3. Results

Human DI levels are closely related to the local temperature and relative humidity (RH) conditions. Therefore, we first analyzed the mean and maximum distributions of temperature and RH from both global and regional reanalyses. We also analyzed the changes in population and urbanization throughout the KSA. Subsequently, we examined the computed DI values to assess differences in their persistence and variability. Finally, we analyzed the short-term and inter-decadal trends of DI.

3.1. Analysis of Mean Temperature, Relative Humidity, Population, and Urbanization

First, we analyzed the monthly mean (Figure 1) and maximum (Figure 2) temperatures and the monthly mean of RH (Figure 3) during summer using both ERA and AP reanalyses for the period of 1980–2018. The monthly mean temperature (Figure 1) in July and August are markedly higher than those in June and September. High temperatures are recorded throughout the summer, mainly over the northern KSA and the region extending from Kuwait to Oman. A significant east–west gradient of approximately 6°C–8°C exists over the KSA, with significantly higher temperatures near the Arabian Gulf compared with the Red Sea. Maximum daily temperatures (Figure 2) follow the same distribution as the mean daily temperatures in all four summer months, albeit with a considerably higher (~10°C–12°C) east–west gradient over the KSA. Although ERA and AP reanalyses indicate similar mean temperature patterns, the regional reanalysis temperatures exhibit higher values by approximately 1°C in the northwestern coastal regions of the KSA.

The mean monthly RH (Figure 3) exhibits a different distribution between the coastal and inland regions of the KSA. Higher RH values (more than 80%) dominate over the Red Sea, the Arabian Gulf, and other coastal areas, whereas inland regions experience arid conditions with RH values below 25%. The driest regions (RH < 10%–15%) are located in the central KSA, most significantly in June, following which the RH gradually decreases as the summer progresses; this decrease in RH occurs in conjunction with moisture transport from the Indian summer monsoon (Attada, Kunchala, et al., 2018; Viswanadhapalli, Dasari, Langodan, et al., 2017). Good agreement between the ERA and the regional AP reanalyses confirms that the latter accurately reproduces the large-scale patterns of temperature and RH over the KSA.

Environmental conditions, such as temperature and RH, are critical in determining a region's livability (Al Mayahi, 2019; Liang et al., 2020; Pal & Eltahir, 2016). Considering this, we analyzed population hot spots with vulnerable living conditions in the KSA. The KSA has 13 administrative divisions (Figure 4a), all of which witnessed a consistent increase in population since 1980 (Figure 4b). Of these 13 regions, seven have more than 1 million inhabitants (Figure 4c); Al-Riyadh and Makkah are the most populated regions with more than 6 million inhabitants each, followed by Ash Sharqiyah with approximately 4 million inhabitants, and Madinah, Qassim, Asir, and Jizan with around 1–2 million inhabitants each. Census reports (Census, 2010) indicates a significant increase in population (by about 30%) between 1992 and 2010 in all administrative regions (Figure 4b). This sharp increase in population has promoted rapid urbanization (Carrol, 2007; Lowry, 1990, 1991). Indeed, the urban canopy, which is a measure of urbanization, indicates a substantial extension of nearly two-to three-fold in major cities of the KSA (Figure 5). Most recently, Alahmadi et al. (2019) reported a three-fold increase in urban morphology based on satellite images, mainly over Al-Riyadh, Makkah, and Eastern administrative regions, between 1992 and 2013. They further reported a 30% growth in urbanization during 1999–2006, which increased to 55% during 2006–2013, suggesting a significant increase in urbanization in the KSA in recent years.

Additionally, several million people visit the KSA annually to perform the Hajj pilgrimage. The Hajj season follows the lunar calendar, and between 2014 and 2018, it occurred in the summer months (June to September), when the average temperature and humidity often exceeds 40°C and 80%, respectively (National Hajj Extreme Heat Strategy, 2016). Such high temperatures and humidity increase the heat stress and may cause health issues. For example, the number of heatstroke and heat exhaustion cases reported in each year in five different regions (Makkah, Madinah, Mena, Arafat, and Mozdalifah) during the Hajj period (Table 2) clearly indicate a correlation between the heat exhaustion cases and the high temperatures and humidity. Based on clinical data during the 2016 Hajj season, Abdelmoety et al. (2018) reported that ~29% and ~67.7% of the total cases admitted to hospitals were due to heat stroke and heat exhaustion, respectively, with 6.3% and 0.0% mortality, respectively.

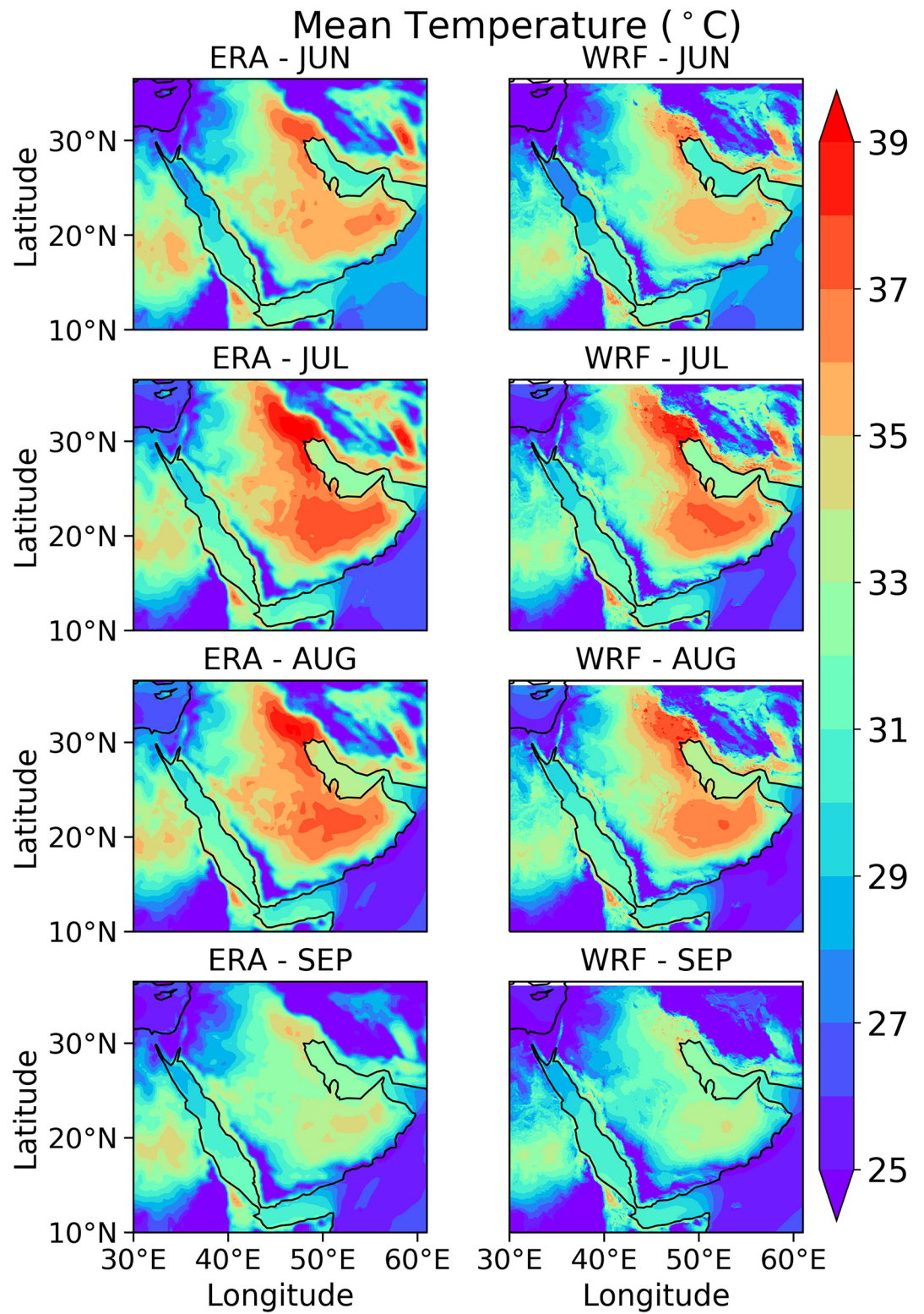


Figure 1. Mean monthly surface temperatures (°C) across the Kingdom of Saudi Arabia (KSA) from ERA and regional Arabian Peninsula (AP) reanalysis for June, July, August, and September.

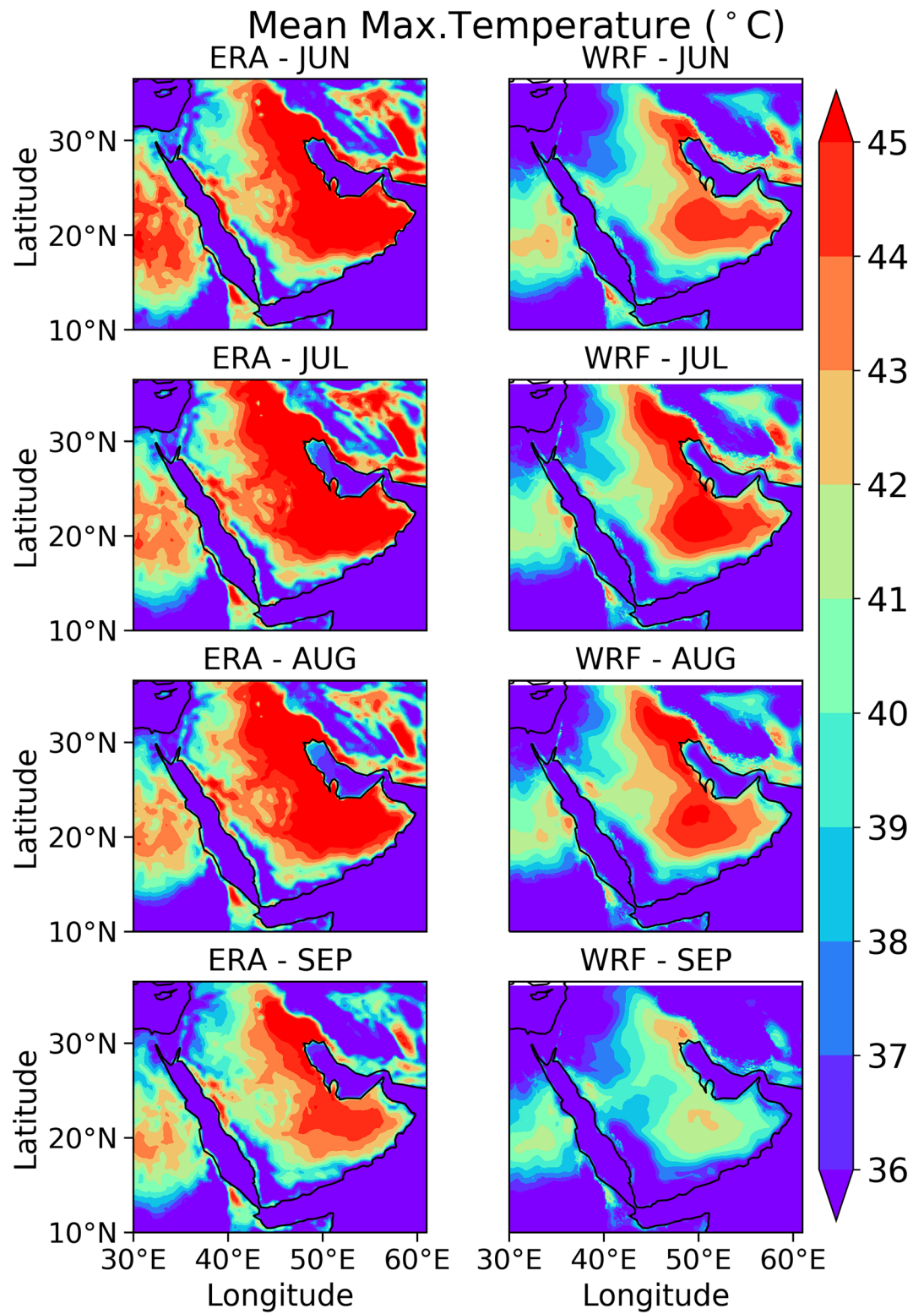


Figure 2. Mean monthly surface maximum temperatures (°C) across the KSA from ERA and regional AP reanalysis for June, July, August, and September.

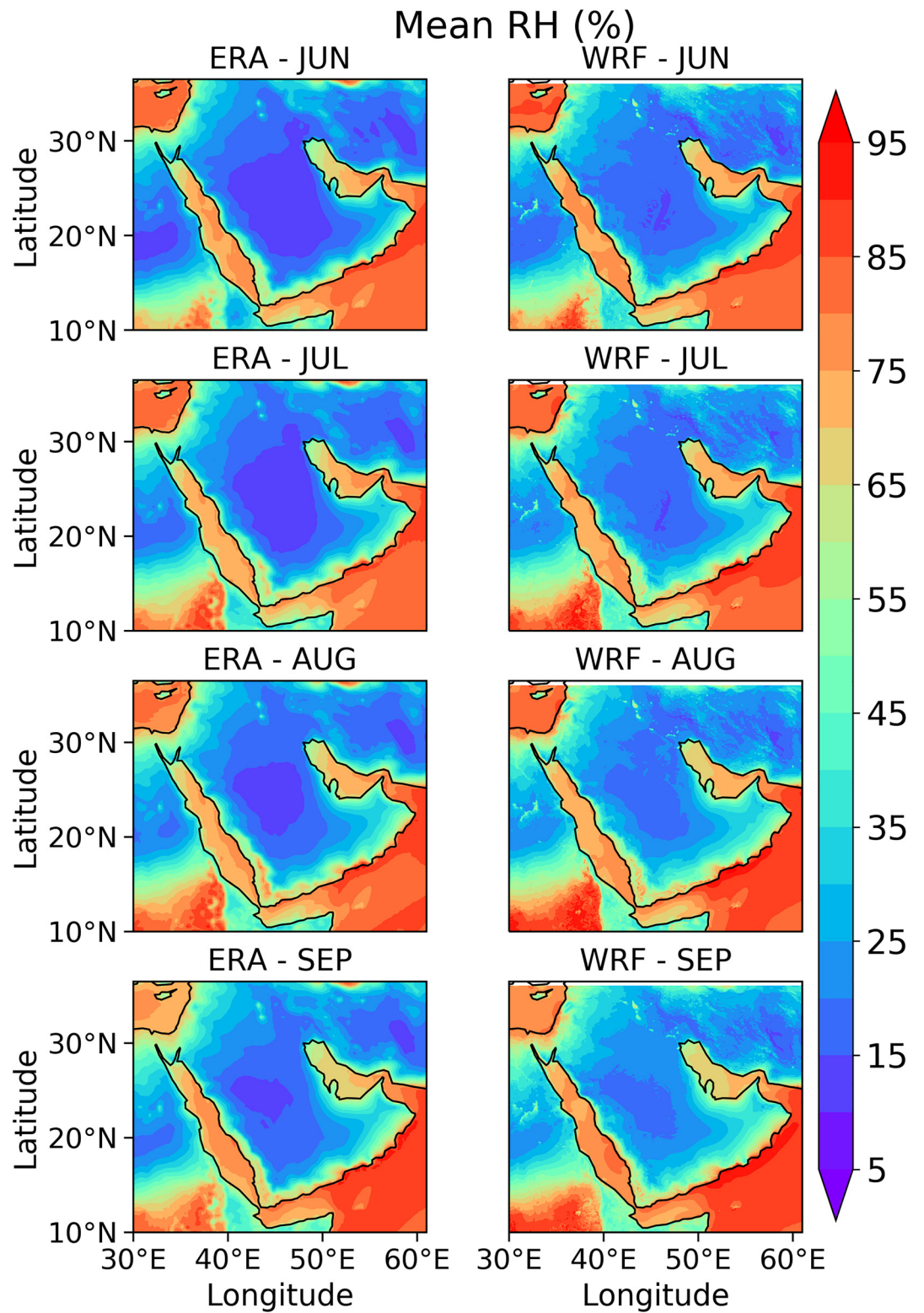


Figure 3. Mean monthly relative humidity (%) across the KSA from ERA and regional AP reanalysis for June, July, August, and September.

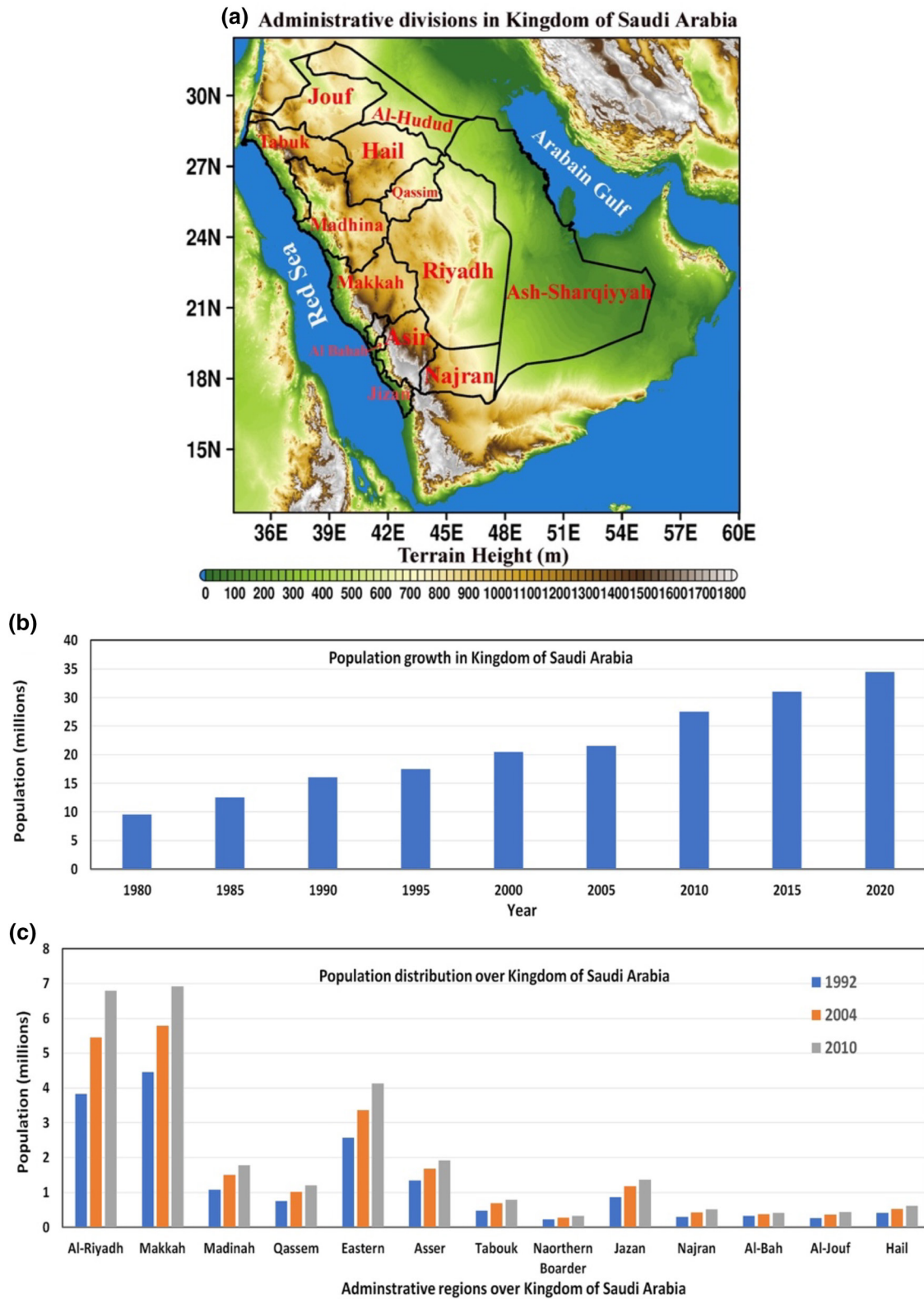


Figure 4. Population distribution across the Kingdom of Saudi Arabia (KSA). (a) Administrative regions of the KSA, (b) population changes in the KSA, and (c) population in the different administrative regions in 1992, 2004, and 2010.

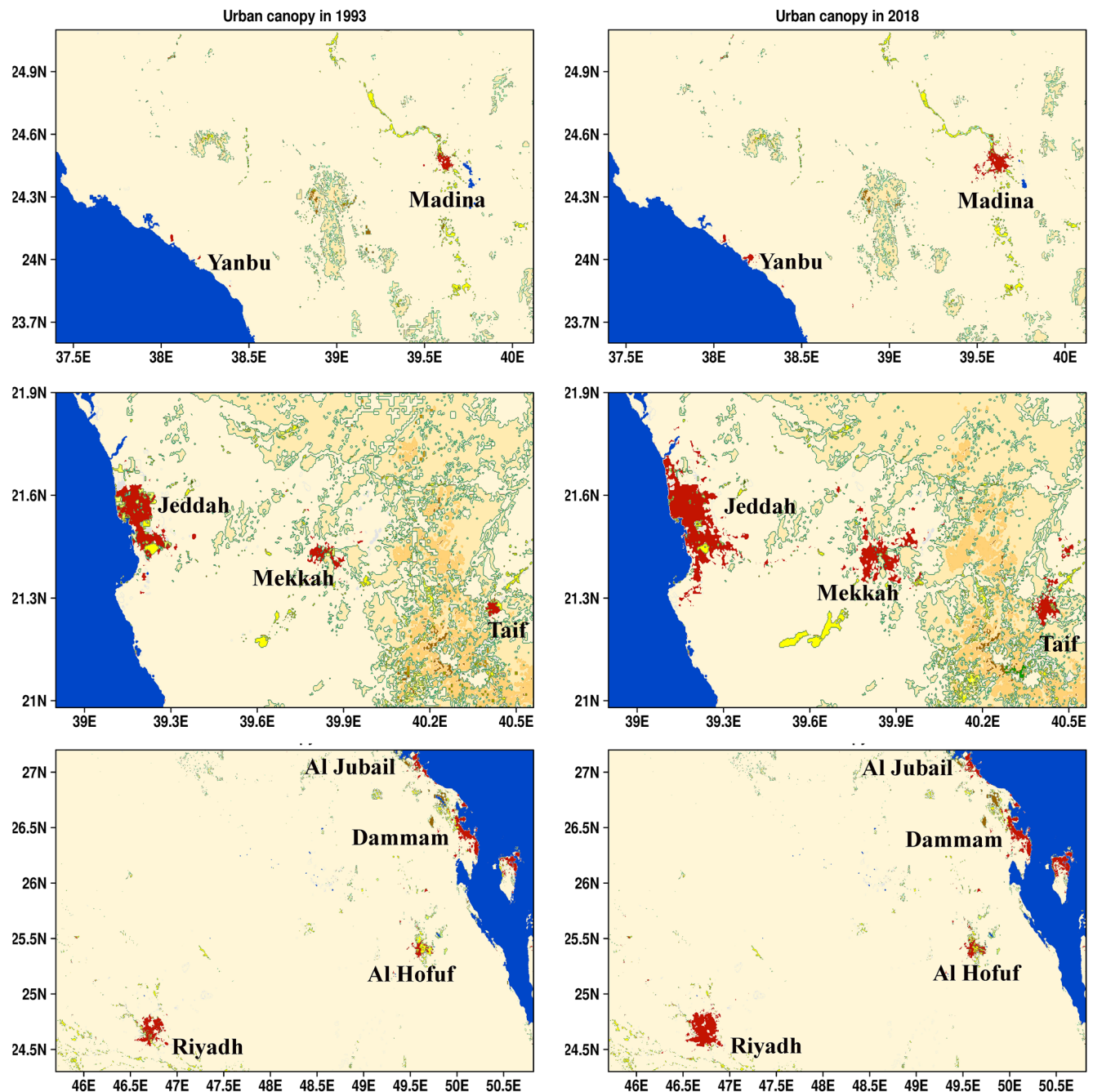


Figure 5. Changes in urban canopy (shown in red color) in various regions of the KSA. The left and right panels show data for the years 1993 and 2018, respectively.

Several studies have also reported that construction workers in the KSA are increasingly susceptible to critical health effects owing to heat exposure (e.g., El-Shafei et al., 2018; Horie, 2013; Inaba & Mirbod, 2007; Jia et al., 2016). These effects include chronic health problems such as psychological distress (e.g., Smith et al., 1997; Tawatsupa et al., 2010), and cardiovascular (e.g., Vangelova et al., 2006) and kidney diseases (e.g., Luo et al., 2014; Tawatsupa et al., 2012). Therefore, analyzing the long-term DI and its variability and trends in relation to the rapid urbanization and increasing population of the KSA is crucial.

Table 2
Total Number of Cases of Heat Stroke (Heat Exhaustion) Cases Reported in Four Different Regions During the Hajj Season

Region	2014	2015	2016	2017	2018
Makkah	8 (7)	163 (38)	16 (15)	38 (15)	15 (17)
Madinah	1 (2)	2 (1)	3 (3)	0 (1)	0 (8)
Mena	57 (186)	324 (630)	70 (337)	170 (535)	130 (649)
Arafat and Mozdalifah	16 (214)	228 (345)	8 (171)	57 (180)	18 (187)
Total	82 (409)	717 (1014)	97 (526)	265 (731)	163 (861)

Source: Ministry of Health (2019).

3.2. Analysis of the Mean DI

The monthly mean DI values as computed from ERA and AP reanalyzes using Equation 1 for the summer months are presented in Figure 6. The mean spatial patterns from both data sets indicate that the DI exceeds 29°C over the most parts of the western KSA and the Red Sea regions. The highest values are recorded in July and August over the Arabian Gulf, probably because of the Shamal winds, which reach their maximum strength during these months (Viswanadhapalli, Dasari, Dwivedi, et al., 2019). These winds transport heat and moisture toward the AP. The entire east coast of the Red Sea, extending from the northwest to the southwest of the KSA, exhibits relatively lower DI values (~22°C–29°C) compared with other regions in the KSA.

The mean number of hours per day with DI > 28°C and DI > 30°C are shown in Figures 7 and 8, respectively. The results obtained from both ERA and AP reanalyzes suggest that DI > 28°C persists for around 8–10 h per day over the western KSA and about 14–16 h per day over Oman and the adjoining regions (Figure 7). The number of hours per day with DI > 28°C is relatively consistent over the western KSA throughout the summer, and it spatially extends during July and August. The southern Red Sea and the Arabian Gulf experience DI > 28°C for about 14–16 h per day.

The mean number of hours per day with DI > 30°C is shown in Figure 8. These results suggest that the Arabian Gulf experiences DI > 30°C for about 6–8 h per day. The areal extent of DI > 30°C for 6–8 h per day is larger over the northwest part of the KSA and adjoining countries; this extent may be related to the clear sky conditions over this region (Dasari, Desamsetti, Langodan, Attada, et al., 2019; Dasari, Desamsetti, Langodan, Karumuri, et al., 2020; Gandham et al., 2020; Kunchala, Attada, Dasari, Ramesh, Abualnaja, et al., 2019; Kunchala, Attada, Dasari, Ramesh, Langodan, et al., 2018), as well as the dominant land use and vegetation coverage (Gandham et al., 2020). The eastern region of the KSA mainly comprises arid land with highly urbanized areas characterized by a higher specific heat capacity than the moderately vegetated hilly regions of the western KSA. The southern Red Sea coast of Sudan and the Arabian Gulf experience DI > 30°C for ~8–14 h per day during July and August, indicating a severe level of human discomfort during these months. The high DI in this region may be associated with the channeling of the Indian summer monsoon winds and the associated transport of moisture, resulting in increased humidity, and subsequently, a high DI.

We further computed the mean number of days during which DI > 28°C persisted for 4–6 h and 7–9 h per day for each summer month using the global and regional reanalyzes (Figures S1 and S2). The corresponding results are presented and discussed in the supporting information; these results provide information on the spatial patterns of the number of days with persistently high DI, and it can help policy makers in various sectors to adopt necessary precautionary measures related to business hours, health conditions, energy balance, and heat stress, among other factors.

The mean number of days during which DI > 28°C persists for 4–6 h and 7–9 h per day for each month in the major cities of the KSA are listed in Table 3. The results indicate that the number of days with DI > 28°C is greatly lower for the cities located in the central KSA region, including Makkah, Madina and Taif. The number of days with DI > 28°C is relatively higher (lower) over Jeddah and Yanbu provinces than over the central (eastern) cities. The maximum number of days with DI > 28°C were recorded over the eastern parts of KSA, in the Al-Riyadh, Al-Hofuf, Dammam, and Al Jubail provinces.

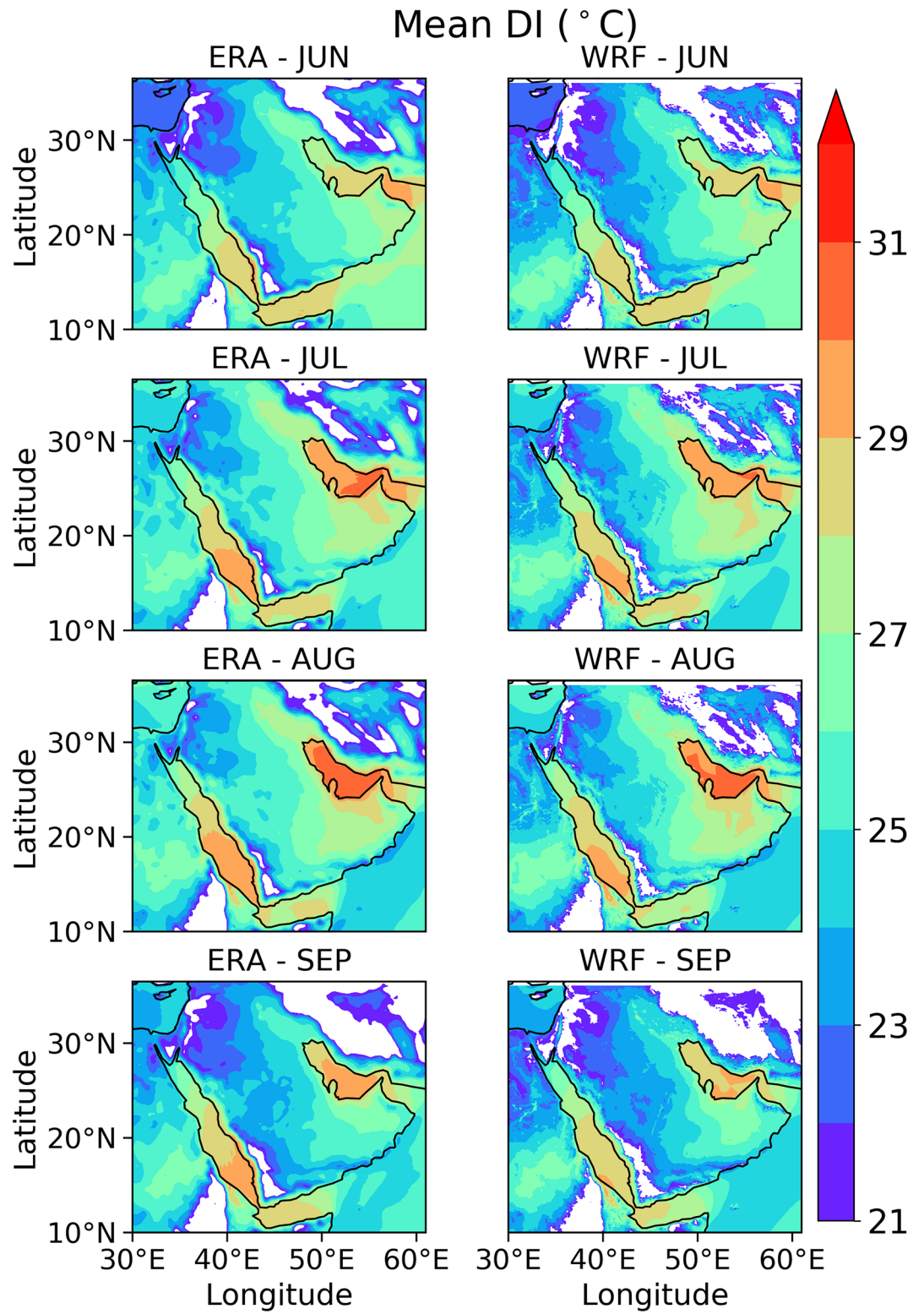


Figure 6. Mean monthly discomfort index (°C) across the KSA from ERA and regional AP reanalysis for June, July, August, and September.

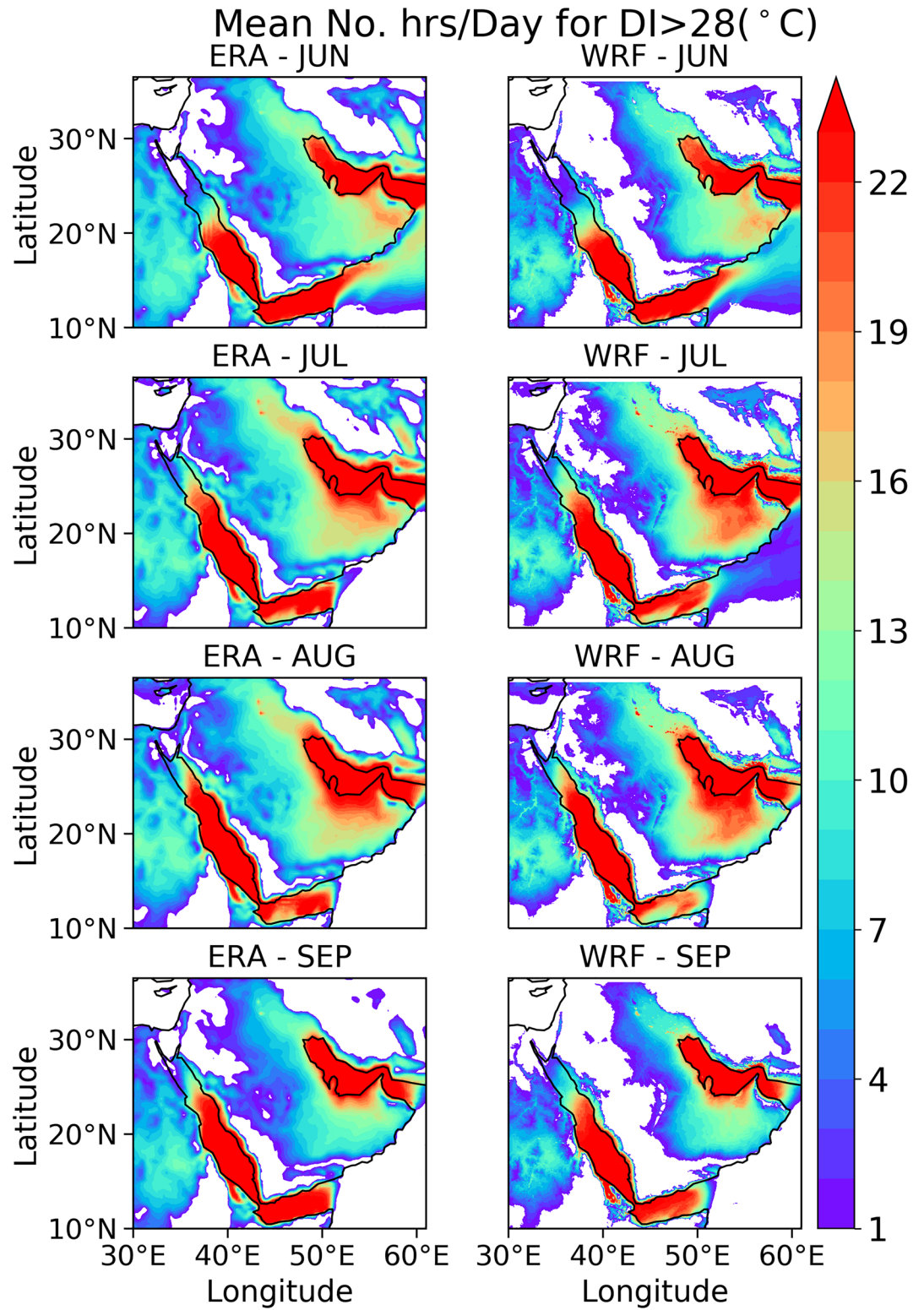


Figure 7. Mean number of hours per day with a discomfort index (DI) greater than 28°C across the KSA from ERA and regional AP reanalysis for June, July, August, and September.

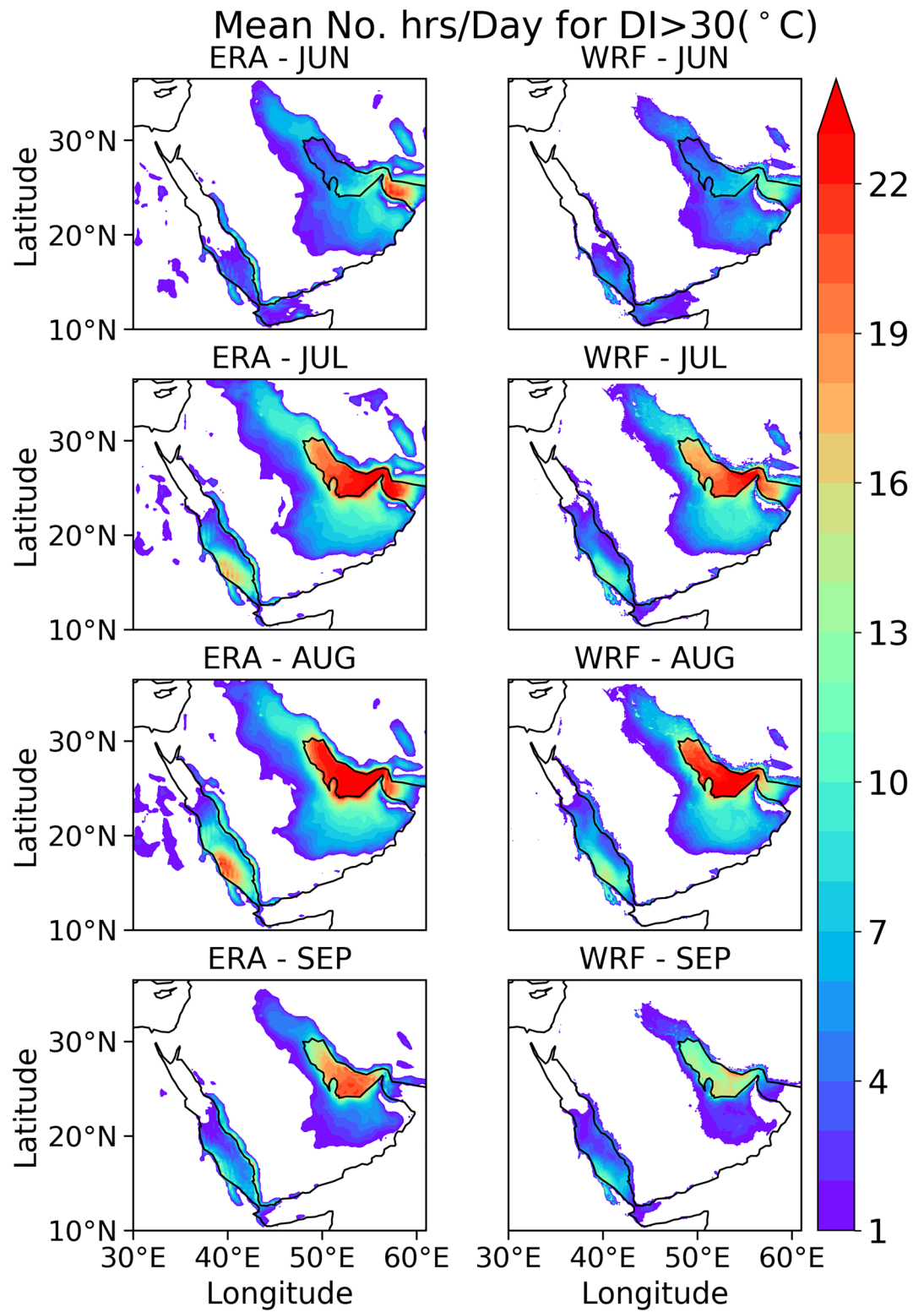


Figure 8. Mean number of hours per day with a discomfort index (DI) greater than 30°C across the KSA from ERA and regional AP reanalysis for June, July, August, and September.

Table 3
Mean Number of Days in Each Month in Which DI > 28°C Persisting for 4–6 h/day (7–9 h/day) Over the Major Cities of in the Kingdom of Saudi Arabia (KSA)

Urban regions	No. of days in which DI > 28°C persisted for 4–6 h/day (7–9 h/day)			
	June	July	August	September
Al-Riyadh	15 (8)	26 (15)	24 (16)	9 (6)
Al-Hofuf	16 (11)	26 (23)	25 (22)	11 (5)
Dammam	20 (11)	26 (22)	27 (23)	13 (8)
Al Jubail	15 (8)	24 (20)	25 (13)	12 (4)
Jeddah	10 (6)	16 (13)	17 (14)	14 (12)
Makkah	2 (1)	2 (1)	3 (1)	2 (1)
Taif	2 (1)	3 (1)	3 (1)	2 (1)
Madinah	2 (1)	3 (1)	2 (1)	2 (1)
Yanbu	12 (6)	13 (7)	16 (12)	11 (6)

The above climatological analysis of the distribution of DI > 28°C and DI > 30°C indicates that the level of human thermal discomfort during summer is higher in the western KSA (i.e., the Arabian Gulf and its adjoining regions) and the southern Red Sea than in the other regions of the KSA. Further, the human thermal discomfort in the southeast regions of the KSA and its adjoining countries, including the United Arab Emirates (UAE), Oman, Bahrain, and Kuwait, is higher than that in the northern and northwestern regions of the KSA.

3.3. Changes in the DI During 1980–2018

To assess changes in human thermal discomfort throughout the KSA during the past four decades, that is, 1980–2018, we analyzed the linear trends with a 95% confidence level over the entire study period and for different sub-periods therein. We computed the linear trends for the number of hours per day with DI > 28°C and DI > 30°C at every grid point, and obtained the results at the 95% confidence level based on a Student's t-test (Panofsky & Brier, 1968). To identify recent changes in DI compared to the DI in past four decades, and to further understand the recent changes influencing human thermal discomfort, we divided the study period (1980–2018) into two subperiods: The past, that is, 1980–1998 and the recent, that is, 1999–2018 periods. The year 1998 was selected for demarcation is based on previous studies that reported drastic changes in the Walker and Hadley circulation around this time as a result of the mega El-Nino Southern Oscillation (ENSO) event during that year (Wang, Liu, Kim, Webster, & Yim, 2012; Wang, Liu, Kim, Webster, Yim, & Xiang, 2013). Furthermore, the KSA has witnessed significant industrialization since 1998 (Belloumi & Alshehry, 2016). Therefore, we expect urban areas, which have developed together with industrialization, to be more adversely affected in terms of human thermal comfort in the recent decades. Herein, we present only the trend analysis for the DI derived from the regional AP reanalysis for the major populated regions of KSA (shown in Figure 5). The spatial distributions of DI trends from both the AP and ERA reanalyses are provided in Figures S2–S7.

The trends of the mean number of days in summer with DI > 28°C persisting for 4–6 h per day over the major cities of the KSA are shown in Figure 9. The trends (days/decade) for the individual months are listed in Table 4. The mean number of days with thermal discomfort significantly increased (at the 95% confidence level) during recent decades in Taif, Makkah, Madina, and Yanbu, suggesting a significant deterioration in the thermal discomfort during the latest two decades in all four summer months. The other cities showed an increase at the 95% confidence level during the 1980–1998 period followed by a nonsignificant decrease in the 1999–2018 period. Makkah and Madina experienced a slight decrease in the number of days with DI > 28°C persisting for 4–6 h per day in September, and a significant increase in June, July, and August during the recent decades. These results clearly suggest that the levels of outdoor thermal discomfort have improved over most of the major cities of the KSA during the recent decades, with the exception of high-altitude cities, such as Makkah, Madina, and Taif, where the DI has deteriorated over time. Although these

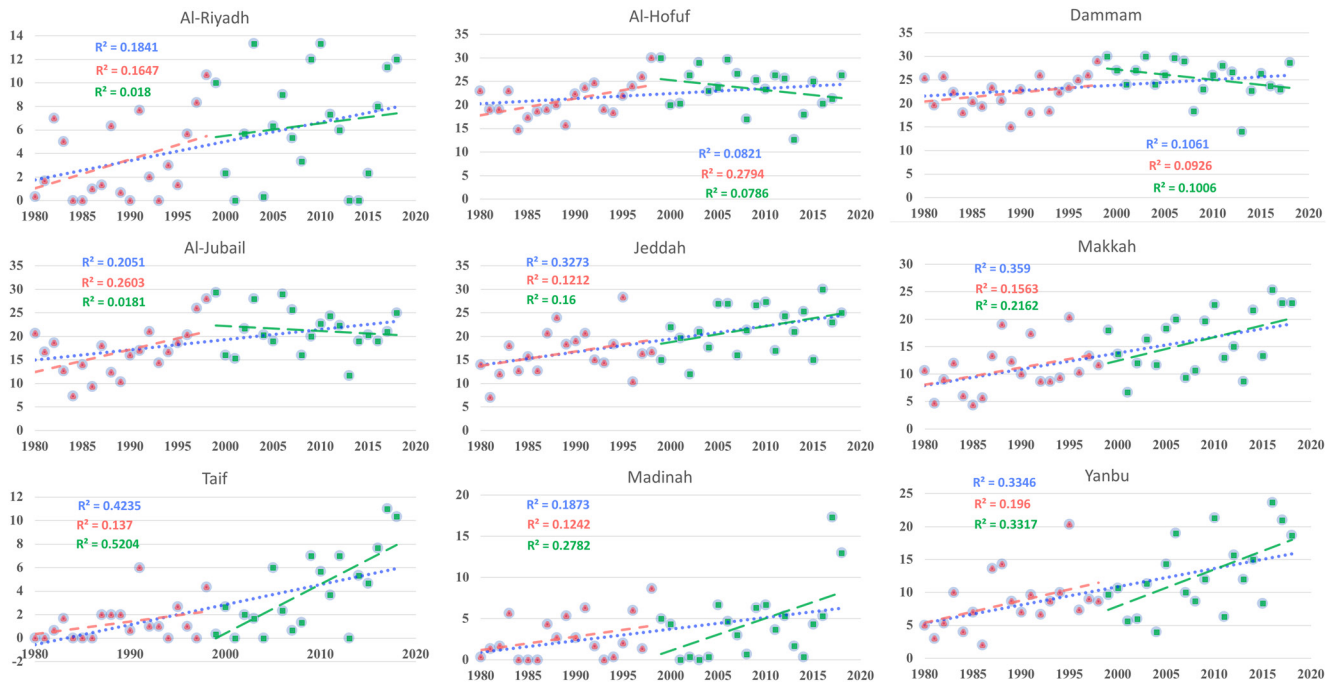


Figure 9. Long-term trends in the mean number of days in summer with a DI greater than 28°C persisting for 4–6 h/day over the study period (1980–2018, blue), the first two decades (1980–1998, red), and the last two decades (1999–2018, green) in the major cities of the KSA.

cities exhibited relatively small number of days with DI > 28°C persisting for 4–6 or 7–8 h per day (Table 3) before 1998, this number has significantly increased (at the 95% confidence level) throughout the recent decades.

4. Summary and Conclusions

Herein, we analyzed the discomfort index (DI), which is a measure of outdoor thermal discomfort, during the summer months (i.e., June to September) across the KSA between 1980 and 2018. The DI was computed based on temperature and relative humidity (RH) data from two independent data sources: a regional

Table 4
Trends of the Number of Days per Decade With DI > 28°C Persisting for 4–6 h per day Over the Major Cities of the KSA

Urban regions	Trends of the number of days for which DI > 28°C persisted for 4–6 h/day											
	1980–2018				1980–1998				1999–2018			
	June	July	August	September	June	July	August	September	June	July	August	September
Al-Riyadh	2.5	2.25	2.1	2.0	2.1	−1.2	2.1	1.9	−0.4	−0.2	0.3	2.1
Al-Hofuf	0.9	0.2	0.4	1.2	1.7	−1.5	1.2	2.1	−0.6	0.1	−0.3	−0.5
Dammam	1.7	0.5	1.4	1.2	2.2	−0.8	2.3	0.1	−0.4	−0.1	−0.2	−0.1
Al Jubail	1.75	0.2	1.2	1.2	2.1	−0.8	0.2	0.4	−0.3	−0.2	−0.1	1.1
Jeddah	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	−0.1	−0.1	−0.1	−0.1
Makkah	0.6	1.5	1.2	0.6	0.7	0.3	1.3	−0.2	1.3	1.2	1.4	−0.2
Taif	1.6	1.9	1.8	0.5	1.7	0.6	1.9	0.4	1.6	1.8	1.1	1.1
Madinah	1.4	2.4	2.6	0.2	0.2	−0.7	2.8	−0.1	1.6	2.6	−0.5	−0.2
Yanbu	0.9	2.1	2.4	1.2	0.2	1.1	2.6	1.6	1.8	2.2	0.3	0.3

Note. The number of days shown in shaded boxes indicate those with more than 95% confidence level.

atmospheric reanalysis generated using an assimilative WRF model configured with 5-km horizontal resolution and the global reanalysis ERA. We conducted detailed comparisons of the estimated DI values to confirm their consistency. The DI time series computed at every grid point over the entire study period were analyzed to investigate the variability and associated trends at different time-scales throughout the KSA.

The analysis results suggest that the majority regions across the KSA experienced $DI > 28^{\circ}\text{C}$ in summer (i.e., June to September), which is associated with high surface temperatures and RH. $DI > 28^{\circ}\text{C}$, a condition at which most people experience discomfort, persisted for $\sim 8\text{--}16$ h per day over the KSA throughout the summer months. We found that on around 90% of the total summer days, $DI > 28^{\circ}\text{C}$ persisted for 7–9 h per day over the Red Sea and western KSA during all four months. We also detected similar spatial patterns and trends for $DI > 30^{\circ}\text{C}$, which is an indicator of extreme human discomfort. These higher DI values were mainly concentrated over the neighboring regions of the Arabian Gulf and some parts of the southern Red Sea.

The trend analyses of $DI > 28^{\circ}\text{C}$ and 30°C revealed a significant improvement in the human thermal discomfort in recent decades over the southern Red Sea, some parts of the northwestern Arabian Gulf, and their adjoining regions. The results revealed a reduced rate of increase, or even a decrease in the number of days with a persistently high DI for these regions in the last 20 years (i.e., 1999–2018). In contrast, human thermal discomfort over the southeast regions of the KSA, UAE, Oman, and Qatar have exhibited a positive trend in recent decades. Changes in DI over recent decades can be attributed to variations in meteorological and/or microclimatic conditions, and requires further detailed analysis.

Knowledge of the variability and trends of outdoor thermal discomfort over the KSA will provide a reference for policy makers and urban planners. The development of a comprehensive understanding of the region's climatology and its effects on the long-term trends of DI enables authorities to determine which regions of the KSA are and may remain comfortable for the population in the future. Additionally, it will also provide engineers with important information for designing efficient infrastructure with effective ventilation and cooling capacity by updating the existing protocols to meet adequate conditions for the safety, health, and comfort of the population. Detailed knowledge of the DI is further critically important for supporting the ongoing developments of several large-scale projects that are being developed in the KSA, for example, NEOM (<https://www.neom.com>), the Red Sea Project (<https://www.theredsea.sa>), and AMAALA (<https://www.amaala.com/en/home>), among others, providing crucial information about the regional environment for optimizing the design and the operations of these new developments. The framework developed herein is a stepping-stone toward developing a forecasting system that could provide important information for outdoor and sports activities, energy consumption management, military planning, tourism, the mining industry, street vendors, and outdoor workers, among many other parties.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data sets of the European Center for Medium-Range Weather Forecasts (ECMWF's) next-generation reanalysis (Copernicus Climate Change Service C3S, 2017), Saudi Arabia population data (Census, 2010), and clinical data reported during Hajj (National Hajj Extreme Heat Strategy, 2016) are freely available and properly cited in the manuscript. All remaining data sets used in this study are deposited, under GeoHealth FAIR data policy, at https://figshare.com/articles/dataset/Datasets_for_the_GeoHealth_2020GH000370/14388170.

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