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Key Points:

- Future climate change will likely increase the frequency and intensity of heatwaves during Arba'een at Shiite holy sites in Iraq
- An increase in mugginess (measured by wet-bulb temperature) is more pronounced at night than during the day in a warmer climate
- We project a rise in consecutive occurrences of hot days and nights, which could threaten human health during the Arba'een event

Supporting Information:

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

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Heat Stress During Arba'een Foot-Pilgrimage (World's Largest Gathering) Projected to Reach "Dangerous" Levels Due To Climate Change

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Abstract Arba'een, a Muslim pilgrimage, is one of the largest annual mass gatherings in the world, with a date fixed according to the lunar calendar. Most pilgrims start their long walking journey from Basra/Najaf toward Karbala (about 70–500 km) and are significantly affected by outdoor weather conditions during this period. Here, based on simulations performed using carefully-selected climate models, we project that heat stress during the pilgrimage is likely to reach a "dangerous" level, defined according to the US National Weather Service criteria, by the end of this century. Moreover, a significant increase in consecutive occurrence of hot days and hot nights is expected within the coming decades, which may cause a high incidence of heat-related disorders as the human body may not recover from the daytime heat loads. Our study suggests that sound adaptation measures and stringent mitigation actions must be established to ensure a safe pilgrimage in the future.

Plain Language Summary Arba'een is a religious mass gathering, drawing millions of people to the holy city of Karbala in Iraq annually. When this procession occurs in the sweltering summer, it could cause significant heat-related morbidity and mortality. Despite the growing risk of heat stress with global warming, less attention has been paid to heat-related issues during this religious ceremony. Without adequate adaptation and mitigation strategies to climate change, more frequent and severe heatwaves (associated with the consecutive occurrence of hot days and nights) in a warmer world may pose a substantial threat to the Arba'een participants' health.

1. Introduction

Arba'een pilgrimage practiced by Shia Muslims is the largest annual mass gathering globally (Lami et al., 2021). It is held in Iraq to commemorate the martyrdom of Al-Husayn ibn Ali, grandson of the Prophet Muhammad, who was martyred in a battle in Karbala in 680 CE (Husein, 2018). About 20 million people from Iraq and other countries participate in this religious ceremony every year (Al-Ansari et al., 2020; Hamdanieh & Ostadtaghizadeh, 2021; Nikjoo et al., 2021), and the number of participants may continue to grow as Muslims are projected to become the world's largest religious group (Lipka & Hackett, 2017). Multiple activities in this ceremony occur outdoors including a long journey on foot toward the Shrine of Al-Husayn ibn Ali in Karbala (Al-Ansari et al., 2020; Lami, Hameed, et al., 2019; Nikjoo et al., 2021). Among the walking pilgrimage routes, the Najaf-Karbala route is the most popular (72 km) (Al-Ansari et al., 2020; Lami, Hameed, et al., 2019), and the farthest route is the one that starts from Basra, around 500 km southeast of Karbala (Christia et al., 2016). This religious activity, as is the case for other mass gatherings (e.g., Hajj), can raise multiple health concerns related to communicable and non-communicable diseases (Al-Ansari et al., 2020; Albujeer & Almahafdha, 2018; Alqahtani et al., 2021; Hamdanieh & Ostadtaghizadeh, 2021; Lami et al., 2021; Memish, 2010; Memish et al., 2019; Obaid et al., 2020). For example, many pilgrims can be susceptible to temperature extremes due to prolonged exposure to outdoor climates (Kang et al., 2019; Memish, 2010; Noweir et al., 2008; Saeed et al., 2021; Yezli et al., 2019).

To investigate the risks to human health from heat extremes, understanding human adaptability and capacity to regulate body heat is important. Human body temperature can be effectively regulated through evaporative, radiative, convective, and conductive heat exchanges with the ambient environment (Gagge & Gonzalez, 2010). When ambient humidity is high, evaporative and conductive cooling does not occur efficiently, making it difficult to dissipate metabolic heat from the human body, which can cause heat stress (Sherwood & Huber, 2010). Therefore, heat stress is not just caused by extreme temperature but is strongly regulated by a combined measure of temperature and humidity (i.e., wet-bulb temperature; TW) (Choi et al., 2021; Im, Choi, & Ahn, 2017; Im

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et al., 2018; Kang & Eltahir, 2018; Pal & Eltahir, 2016; Raymond et al., 2020). An extreme TW could result in hyperthermia (Sherwood & Huber, 2010), possibly causing heat-related morbidity and mortality during mass gathering events (Kang et al., 2019; Saeed et al., 2021). Therefore, this study analyzed the impact of climate change on Arba'een events by focusing on future change in TW.

Despite the growing risk of heat stress, it is unclear how much future climate change will increase TW at the religious holy sites in Iraq and how this warming trend will affect pilgrims' health during religious ceremonies. In this study, we use carefully selected Global Climate Model (GCM) and Regional Climate Model (RCM) simulations under the Shared Socio-economic Pathways (SSP) scenarios, including SSP1-2.6 and SSP5-8.5 (O'Neill et al., 2016), to investigate the future climate change impacts on heat stress during the Arba'een pilgrimage of the Shia Muslims. The climate projections show that pilgrims participating in the summer season Arba'een are likely to be exposed to a more frequent and more severe humid heat stress due to anthropogenic climate change.

2. Methods and Materials

2.1. Dates of Arba'een

The dates of Arba'een are based on the lunar calendar, which is shorter than the Gregorian calendar. It means that this mass gathering event occurs 11 days earlier on average every year, taking place in different seasons depending on the period considered (Table S1 in Supporting Information S1). Since this study mainly focuses on extreme heatwaves, some of the analysis is mainly performed for the extended summer season (May to September), where extreme temperature events frequently occur (Zittis et al., 2016).

2.2. Observational Datasets

Data on surface pressure, dry-bulb temperature (T), and dew point temperature at 3-hr intervals are taken from the ERA5 reanalysis (Hersbach et al., 2020) to calculate TW using the formulation developed by Davies-Jones (2008) for the period 1976–2019. Based on the US National Weather Service (USNWS), we define caution, extreme caution, danger, and extreme danger thresholds of heat stress (Steadman, 1979), which are assumed equivalent to wet-bulb temperatures of 16°C, 21°C, 24°C, and 28°C, respectively (assuming about 30% relative humidity; see Supplementary Table 6 in Kang et al., 2019). Hot days (respectively hot nights) are defined as events for which daily maximum wet-bulb temperature (TW_{max}) (respectively daily minimum wet-bulb temperature [TW_{min}]) is greater than the USNWS extreme caution (caution) threshold. Tropical nights are defined as when daily minimum T (T_{min}) is greater than 20°C (Fischer & Schär, 2010). Walking pilgrimage during Arba'een may take up to approximately 1 month (Soltani, 2020). Therefore, the event period is assumed to be 30 days in this study. Each year's extreme temperature value (95th percentile) is derived using the T or TW values for the past 30 days, including the event day.

2.3. Climate Change Projections

This study uses three GCM and three RCM simulations. Two future climate change scenarios are considered based on the SSP1-2.6 and SSP5-8.5 scenarios (O'Neill et al., 2016). SSP1-2.6 is considered a mitigation scenario, leading to an approximate radiative forcing level of 2.6 Wm^{-2} in 2100, implying zero emissions in the century's second half. SSP5-8.5 is a high-end scenario with no additional climate policy, leading to an approximate radiative forcing level of 8.5 Wm^{-2} in 2100.

To identify the near-term-future risks of heat stress, MIT Regional Climate Model (MRCM; Im, Pal, & Eltahir, 2017) is applied at a 20-km grid spacing (Choi & Eltahir, 2022). The dynamical core of the MRCM is rooted in the International Center for Theoretical Physics (ICTP) Regional Climate Model version 3 (RegCM3; Pal et al., 2007). The MRCM is characteristically coupled with the Integrated Biosphere Simulator land surface scheme (IBIS; Winter et al., 2009). This model is also incorporated with improved and newly developed physical schemes (Gianotti, 2012; Gianotti & Eltahir, 2014a, 2014b; Marcella, 2012; Marcella & Eltahir, 2012). The latest version of MRCM shows sufficient skill to reproduce the region-specific climate information over various domains, such as North America (Winter et al., 2009), West Africa (Im et al., 2014), Southwest Asia (Pal & Eltahir, 2016), South Asia (Choi et al., 2021; Im, Pal, & Eltahir, 2017), and the Maritime Continent (Im & Eltahir, 2018).

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We apply a stepwise screening process to select the suitable CMIP6 GCMs for use as boundary conditions in the MRCM. The screening process is divided into three steps. As a first step, we select 9 GCMs (out of 30 CMIP6 GCMs) that capture the long-term climate trends (i.e., observed warming and drying trends) in the Mesopotamian basin over the recent decades (Figures S1a and S1b in Supporting Information S1). In a second step, three models (CMCC-ESM2, BCC-CSM2-MR, and KACE-1-0-G) with limited data availability are excluded from further analysis. Finally, we select three models, including MPI-ESM1-2-LR, HadGEM3-GC31-LL, and NorESM2-LM, which have the lowest normalized Root-Mean-Square Error (RMSE) for simulated temperature and precipitation (Figure S1c in Supporting Information S1). Note that only one model with the smallest RMSE is considered from each institution. A more detailed description of the three selected GCMs is provided in Table S2 in Supporting Information S1.

The MRCM domain covers the Mesopotamian basin with a central latitude of 35°N and longitude of 41°E (Figure S2 in Supporting Information S1). The vertical coordinate is a terrain-following sigma coordinate, and a Lambert Conformal projection is used for the horizontal coordinate. MRCM simulations are available for the 1975–2050 period under the SSP1-2.6 and SSP5-8.5 scenarios. Reference (1989–2002) and near-term future (2021–2034) periods, when the summer Arbae'en event occurs, are mainly analyzed. We demonstrate that MRCM is superior in reproducing the spatial distribution of the temperature over Mesopotamia compared to the forced GCMs. Specifically, topography-induced temperature patterns are well reproduced against the corresponding observation (Figures S3 and S4 in Supporting Information S1).

GCM data are interpolated to a 1.0° × 1.0° grid for multi-model ensemble analysis. To assess the impacts of climate change at Basra, Najaf, and Karbala, we consider the nearest grid point to the individual stations from each simulation. Note that, due to coarse resolution, the selected grid points on the GCM grid are slightly different from those of the MRCM (Figure S2 in Supporting Information S1).

To eliminate systematic biases in the GCM and MRCM outputs, we applied the equidistant quantile-mapping bias correction procedure under the assumption that the bias does not change over time, following the previous studies (Choi et al., 2021; Li et al., 2010). The ERA5 data is used to correct the bias in simulated *T* and TW at Basra, Najaf, and Karbala in Iraq.

3. Results

T and TW show clear upward trends in Basra, Najaf, and Karbala in recent decades in response to increasing atmospheric CO2 concentration (Figure 1). *T* in the three cities increased by 1.6°C between 1979 and 2019, well above the global average (IPCC, 2021). As expected from the Clausius–Clapeyron relation, the observed atmospheric warming increases the near-surface atmospheric humidity (Figure S5 in Supporting Information S1), resulting in pronounced warming of TW (about 0.6°C per decade during the last four decades) (Figure 1). The rate of TW increase is slightly higher than that of *T*, suggesting enhanced humid heat stress.

Based on the GCM projections, the Arba'een pilgrimage would expose many pilgrims to danger-level heat events by the end of this century (Figure 2 and Figure S6 in Supporting Information S1). TW_{max} above the danger threshold of 24°C is seldomly observed in the present climate, except for Basra (Figure 2). However, GCM projections exhibit significant increases in daily maximum temperature and near-surface specific humidity under the high-end scenario (Figures S7–S9 in Supporting Information S1), which result in a distinct shift of the TW_{max} distribution toward warmer conditions, exceeding 28°C for the period 2086–2099 (Figures 2a–2c). At the scale of individual religious events, humid heat stress may become more severe during the Arba'een pilgrimage occurring in summers (from May to September). The mean TW_{max} during the summer season is projected to increase by about 1°C for 2021–2034, by about 2°C for 2054–2067, and by about 3–4°C for 2086–2099 relative to 1989–2002, regardless of the city. Significant differences in heat stress between two Shared Socioeconomic Pathways (SSP1-2.6 and SSP5-8.5) occur toward the end of this century. It implies that the frequency of occurrences of danger-level heat events is likely to increase proportionally to atmospheric Greenhouse Gas (GHG) concentrations (Figure S6 in Supporting Information S1).

The regional climate simulations by the MRCM (which perform significantly better in reproducing fine-scale climate information over Iraq) agree on significant warming trends at the three places in the coming few decades (Figure 3). The mean *T* and TW in Mesopotamia are likely to increase by about 2°C and 1°C in the near-term period against the reference period, respectively, regardless of the emissions scenario (Figures S10 and S11 in Supporting Information S1). The rise in TW may lead to a more frequent and severe humid heat stress during the

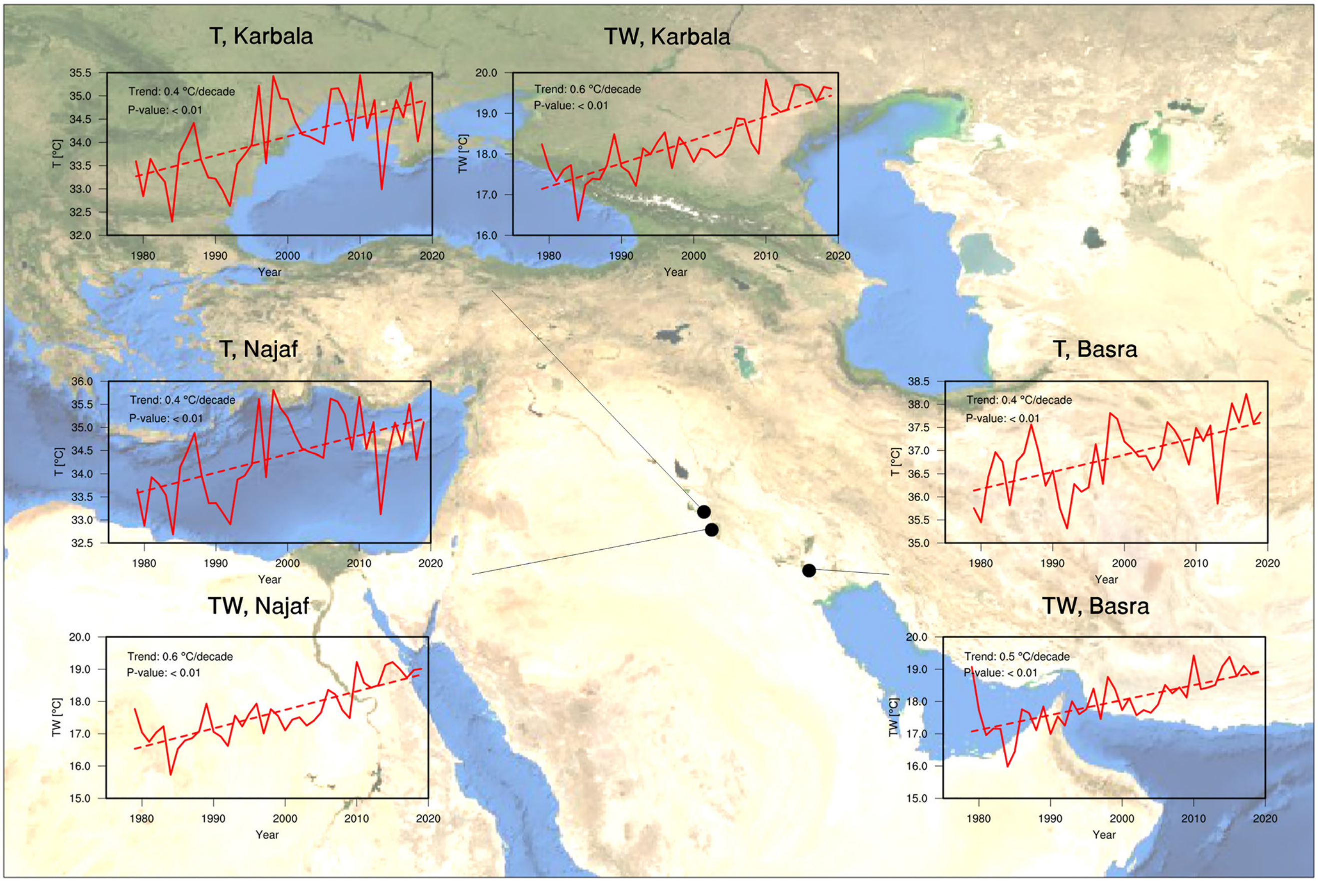

Figure 1. Time series of summer (May to September) mean dry-bulb (*T*; unit: °C) and wet-bulb (TW; unit: °C) temperatures at Basra, Najaf, and Karbala stations in Iraq for 1979–2019. *T* and TW are derived from ERA5. Red dashed lines highlight linear trends. Trend and corresponding *p*-value (based on a nonparametric Mann–Kendall test) are annotated in the top left of each panel. The background image was obtained from NASA Visible Earth.

pilgrimage (Figures 3a–3c). In a warmer summer within the next few decades, the shift of extreme TW_{max} distribution is evident toward higher values, leading to more frequent heat extremes with TW_{max} exceeding the extreme caution threshold of 21°C (Figures 3a–3c). The incidence of extreme-caution-level heatwaves is 16%–23% in the current climate, but approximately doubles (35%–44%) in the near-term future (Figures 3d–3f). Notably, Basra, a city close to the Persian Gulf, stands out due to its extreme TW_{max} values (above extreme danger threshold of 28°C). Note that similar conclusion can be drawn when considering all seasons in which Arba'een may occur (Figure S6 in Supporting Information S1). Although more frequent heatwaves in the danger category are expected over Basra in the low-concentration scenario than in the high-concentration scenario, this difference is small and insignificant (Figure 3).

The TW increases are more pronounced at night than during the day (Figure 4). Projected changes in the diurnal cycle of TW are shown in Figure 4 under the relatively low and high GHG emissions scenarios (SSP1-2.6 and SSP5-8.5). The three MRCM simulations show a robust pattern despite inter-model spread. TW is expected to increase by about 1.2°C at night and by about 1.0°C during the day by 2034 across the three cities compared to the present climate, implying an increased frequency of occurrence of combined hot days and nights. This warming asymmetry might be due to the water vapor greenhouse effect (Figure S12 in Supporting Information S1): additional water vapor as a result of climate change would cool the surface by blocking incoming solar radiation during the day, while trapping heat close to the ground at night (Cox et al., 2020; Easterling et al., 1997).

4. Discussion and Conclusion

Arba'een is one of the largest annual mass gatherings, drawing millions of people to the holy city of Karbala in Iraq. A persistent increase in temperature is generally expected in the surrounding region, including most of Iraq, due to climate change (Safieddine et al., 2022; Zittis et al., 2016, 2019, 2021). The increase in temperature may

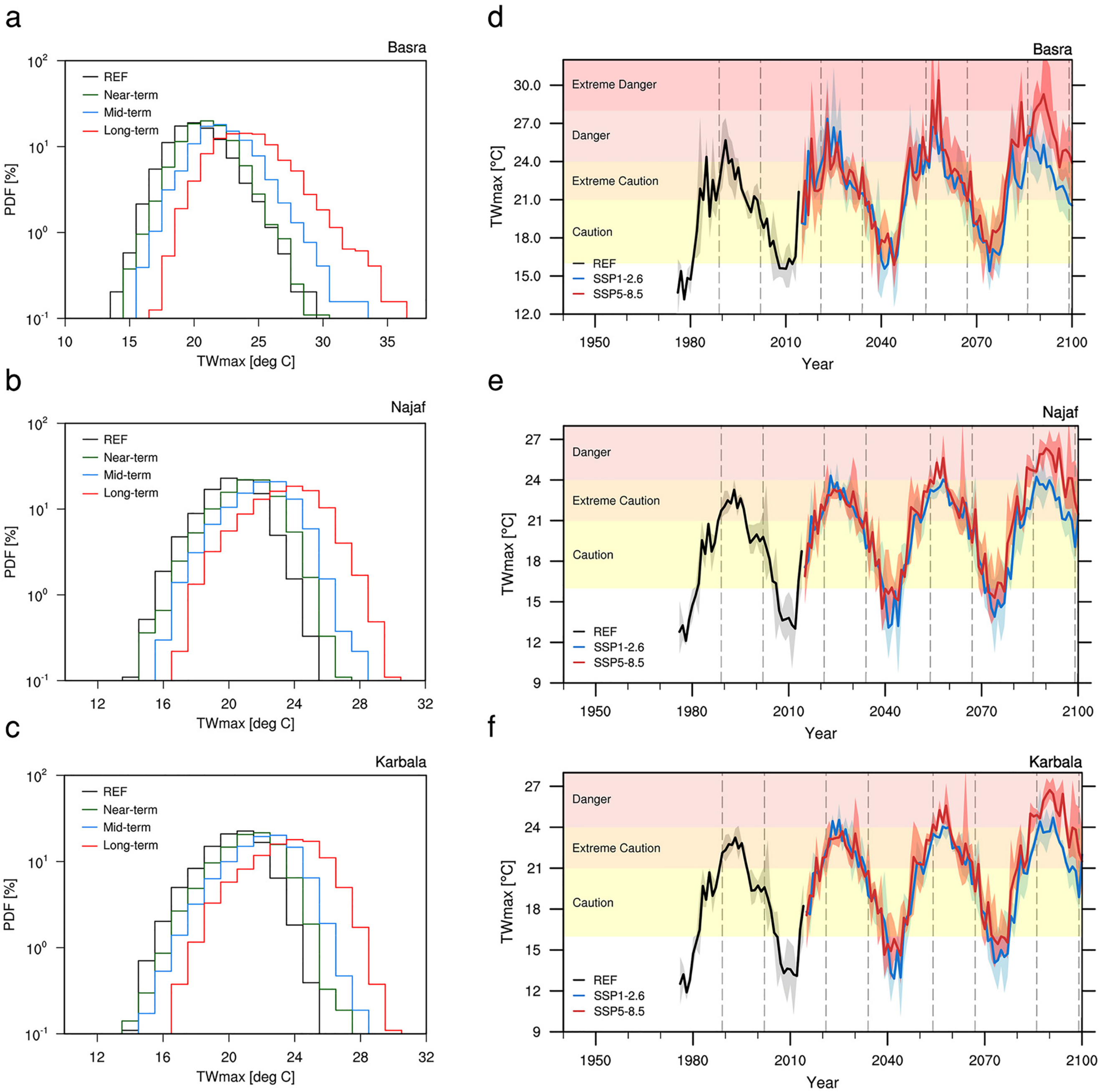

Figure 2. (a–c) Histogram of daily maximum wet-bulb temperature (TW_{max}; unit: °C) during summer (May to September) at Basra, Najaf, and Karbala stations in Iraq for reference (1989–2002), near-term (2021–2034), mid-term (2054–2067), and long-term (2086–2099) periods under SSP5-8.5 scenario. (d–f) Time series of the annual 95th percentile of TW_{max} (°C) during Arba'een under reference, SSP1-2.6 and SSP5-8.5 scenarios. TW_{max} is derived from bias-corrected Global Climate Model simulations (MPI-ESM1-2-LR [MPI], HadGEM3-GC31-LL [HAD], and NorESM2-LM [NOR]). Multi-model mean is displayed with thick solid line and shading indicates the inter-model spread in (d–f). Background colors in (d–f) indicate U.S. National Weather Service heat stress risk level. Vertical dashed lines in (d–f) denote bounds of Arba'een periods occurring from May to September.

possibly enhance heat-related morbidity and mortality during the Arba'een period when it coincides with future summers. Despite the growing risk of heat stress, it has received less attention in the past decades because this religious ceremony has been banned in the last few decades due to political reasons. As the pilgrimage is resumed and attention is focused on it, a persistent increase in the number of participants is expected over the next few decades. Therefore, it is essential to project the climate change impacts on heat stress during this annual mass gathering event.

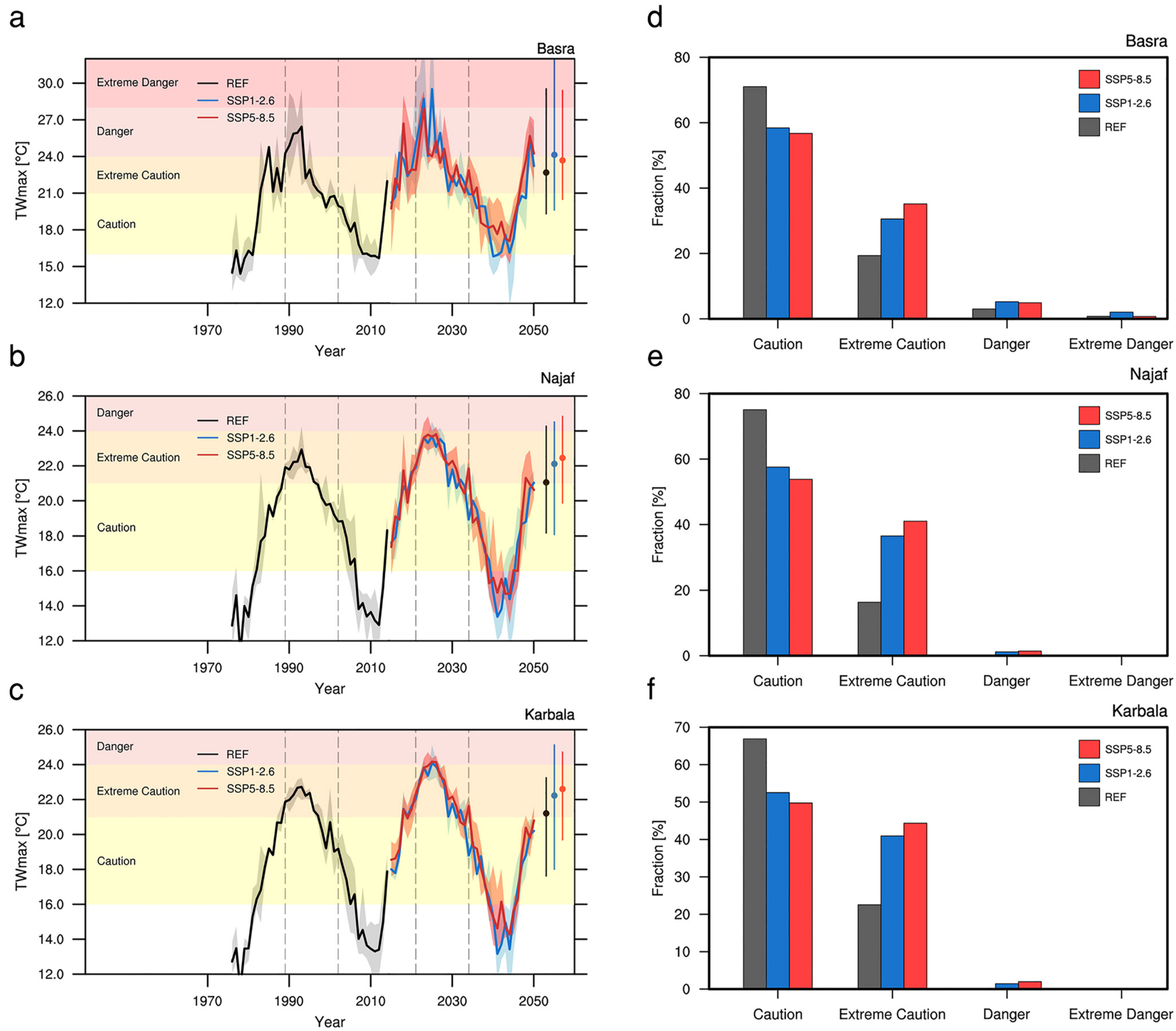

Figure 3. (a–c) Time series of the annual 95th percentile of TW_{max} (°C) during Arba'een at Basra, Najaf, and Karbala stations in Iraq under reference, SSP1-2.6 and SSP5-8.5 scenarios. (d–f) Probability distribution of heat stress with different risk levels during Arba'een occurring from May to September under reference (1989–2002), SSP1-2.6 and SSP5-8.5 (2021–2034) scenarios. TW_{max} is derived from bias-corrected Regional Climate Model simulations driven by MPI, HAD, and NOR. Multi-model mean is displayed with thick solid line and shading indicates the inter-model spread in (a–c). Background colors in (a–c) indicate U.S. National Weather Service heat stress risk level. Vertical dashed lines in (a–c) denote bounds of Arba'een periods occurring from May to September.

Based on the global and RCM simulations, we project a worsening of humid heat stress in the coming decades. That is, the mean TW_{max} during the extended summer season could increase by about 1°C for 2021–2034, by about 2°C for 2054–2067, and by about 3–4°C for 2086–2099 relative to 1989–2002 at Basra and the holy cities of Najaf and Karbala in Iraq. In particular, an increasing number of pilgrims from many countries with diverse backgrounds are projected to experience severe heatwaves, with TW_{max} exceeding the USNWS danger threshold by the end of the century. Although the increase in temperature in the near-term future (2021–2034) does not stand out compared to the end of this century (2086–2099), heat stress may also be exacerbated by the combination of hot days followed by hot nights in the coming few decades.

Physiologically, a hot night interferes with the pilgrims' comfortable sleep and can also inhibit the recovery from the daytime heat loads. Thus, the consecutive occurrence of hot days and hot nights may exacerbate the heat-related morbidity and mortality during the Arba'een events. In the present climate (1989–2002), the

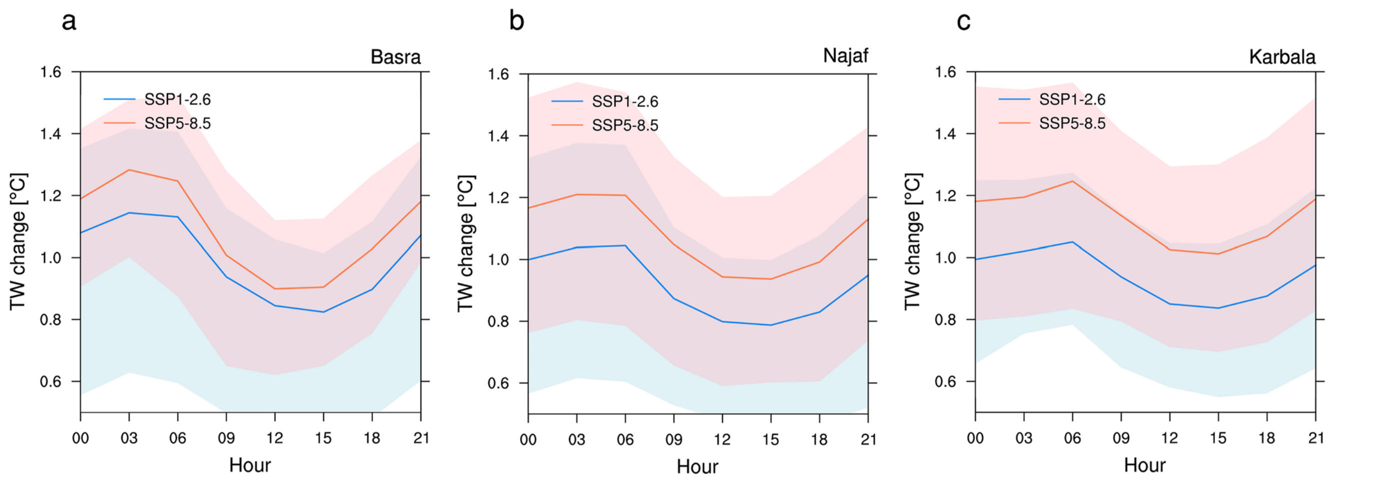

Figure 4. Projected change (2021–2034 minus 1989–2002) in diurnal cycle of TW (°C) during summer (May to September) at Basra, Najaf, and Karbala stations in Iraq under SSP1-2.6 and SSP5-8.5 scenarios. The solid line and shading indicate an ensemble mean and inter-model spread, respectively. TW is derived from bias-corrected Regional Climate Model simulations driven by MPI, HAD, and NOR.

probability of consecutive hot days and nights is about 11%, 16%, and 21% at Najaf, Basra, and Karbala, respectively. However, they are projected to be 37%–45% for the period 2021–2034 under the high-end scenario (Figure 5). A similar conclusion can be drawn when considering tropical nights rather than hot nights (Figure S13 in Supporting Information S1). This health risk is severe, especially for vulnerable pilgrims, like elderly (Fischer & Schär, 2010; Memish, 2010), those with pre-existing conditions (e.g., cardiovascular and pulmonary disease) (Fischer & Schär, 2010; Memish, 2010), and pregnant women (Zhang et al., 2017). The secondary effects of warming temperatures (e.g., changes in infectious disease ecology, food and water insecurity) may further exacerbate this health risk (e.g., Carlson et al., 2022; Ebi et al., 2021).

Physical mechanisms behind the warming trends have been well documented in previous studies (e.g., IPCC, 2021; Zittis et al., 2021). Widespread warming in the Mesopotamian basin is mainly caused by increasing GHG concentrations in the atmosphere (IPCC, 2021). The warmer climate, in turn, increases the near-surface atmospheric water-holding capacity as described by the Clausius-Clapeyron relation, while the water vapor feedback further intensifies the warming. The increases in water vapor and regional warming are expected to enhance the risk and severity of heat stress. On the other hand, dynamic contribution (i.e., changes in atmospheric circulation)

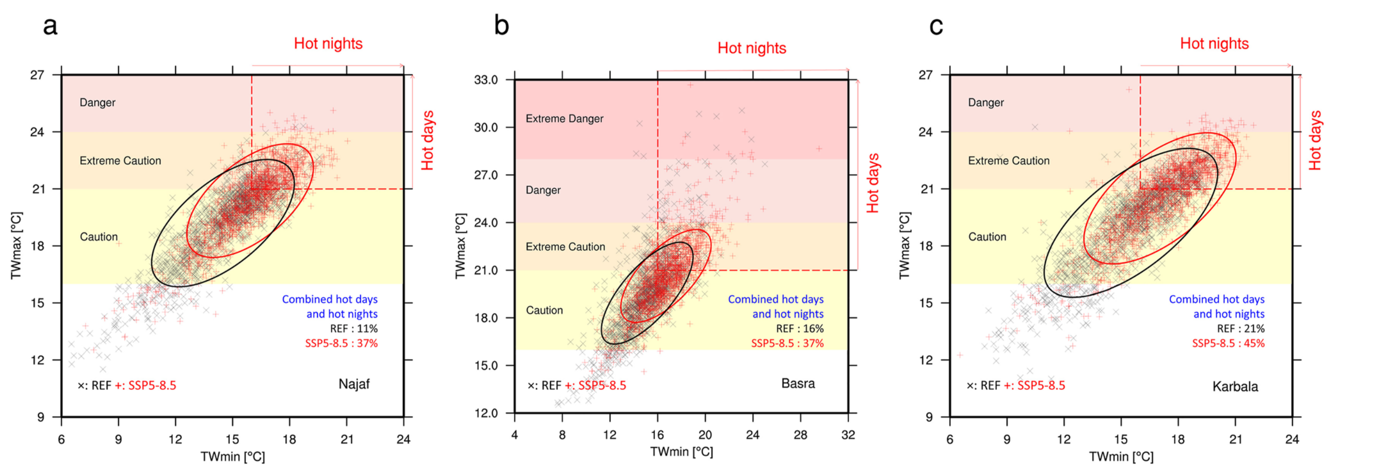

Figure 5. Daily minimum wet-bulb temperature (TW_{min}; unit: °C) versus daily maximum wet-bulb temperature (TW_{max}; unit: °C) at Basra, Najaf, and Karbala stations in Iraq during Arba'een under reference (REF; 1989–2002) and SSP5-8.5 (2021–2034) scenarios. TW_{min} and TW_{max} are derived from bias-corrected Regional Climate Model simulations driven by MPI, HAD and NOR. Background colors indicate U.S. National Weather Service heat stress risk level. The frequency of occurrence of combined hot days ($TW_{max} > 21$°C) and hot nights ($TW_{min} > 16$°C) are annotated in the bottom right of each panel.

may drive severe heat stress. For instance, an intensified thermal low near the eastern Mediterranean gives rise to anomalous southerly wind, reducing the advection of cold air from Europe and amplifying regional warming in the Mesopotamian basin (Figure S14 in Supporting Information S1; Lelieveld et al., 2016). Strengthened moisture advection from the surrounding water bodies (the Mediterranean Sea and the Black Sea) may also contribute to the enhanced heat stress. Although not considered in this study, the extra warming from the urban heat island effect can exacerbate pilgrims' exposure to heat extremes (Ebi et al., 2021; IPCC, 2021).

We acknowledge that the health risk during Muslim pilgrimage depends on not only climate conditions but also other factors, like the capacity of the facilities, the age distribution, food safety, personal hygiene, and health and number of pilgrims (Karampourian et al., 2018; Lami, Asi, et al., 2019; Lami, Hameed, & Arbaji 2019; Lami, Radhi, et al., 2019; Peyravi et al., 2020; Soltani, 2020; Soltani et al., 2021). Despite the significant expansion of facilities over the decades, it is still not enough to adequately provide health care to the explosively growing number of participants each year (Karampourian et al., 2018; Lami, Hameed, & Arbaji, 2019; Peyravi et al., 2020). Therefore, this study suggests that current preventive measures need to be supplemented and sound adaptation measures should be established based on accurate projections of future conditions.

Conflict of Interest

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

Data Availability Statement

ERA5 reanalysis data were obtained from the European Center for Medium Range Weather Forecasts (ECMWF) (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview; Hersbach et al., 2020). CMIP6 data (MPI-ESM1-2-LR (Wieners et al., 2019), HadGEM3-GC31-LL (Ridley et al., 2018), and NorESM2-LM (Seland et al., 2019)) are available online (https://esgf-node.llnl.gov/projects/cmip6/). Regional climate simulations needed to reproduce key results presented throughout this paper are available on Harvard Dataverse at https://doi.org/10.7910/DVN/Y8PZLN (Choi & Eltahir, 2022).

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