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Future Heat Stress During Muslim Pilgrimage (Hajj) Projected to Exceed "Extreme Danger" Levels

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Abstract The Muslim pilgrimage or Hajj, which is one of the five pillars of Muslim faith, takes place outdoors in and surrounding Mecca in the Saudi Arabian desert. The U.S. National Weather Service defines an extreme danger heat stress threshold which is approximately equivalent to a wet-bulb temperature of about 29.1 °C—a combined measure of temperature and humidity. Here, based on results of simulations using an ensemble of coupled atmosphere-ocean global climate models, we project that future climate change with and without mitigation will elevate heat stress to levels that exceed this extreme danger threshold through 2020 and during the periods of 2047 to 2052 and 2079 to 2086, with increasing frequency and intensity as the century progresses. If climate change proceeds on the current trajectory or even on a trajectory with considerable mitigation, aggressive adaptation measures will be required during years of high heat stress risk.

Plain Language Summary The Hajj is an annual Islamic pilgrimage to Mecca in the Saudi Arabian desert. In this study, we project an increase in the frequency and intensity of future extreme danger heat stress events in Mecca during Hajj under both business as usual and mitigation scenarios.

1. Introduction

Millions of Muslims participate in the Hajj each year, and those who are in good health and can afford it are obligated to participate in it at least once in their lifetime. The followers of Islam represent nearly one quarter of the world's human population, and most of them aspire to perform Hajj as an important part of their faith, with their desire to participate becoming more urgent as their age advances (Gatrad & Sheikh, 2005). As a result, among the two to three million pilgrims participating in Hajj every year for 2 to 3 weeks, a disproportionate fraction is elderly coming from Muslim communities around the world and visits the holy sites around Mecca in the Kingdom of Saudi Arabia (see Figure 1). The ritual of Hajj involves spending roughly 20–30 hr outdoors over a period of about 5 days. The main outdoor activities, which occur in and surrounding Mecca, are (1) Tawaf or praying outside the Great Mosque of Mecca (Alharam) for a few hours on two different occasions, with the most important of the two occurring at the end of the Hajj; (2) Wakuf or standing on the side of Mount Arafat for 1 day between sunrise and sunset, recognized as the most important activity of the Hajj; and (3) Ramy Al-Jamrat or walking in Mina (outskirts of Mecca) for several hours per day called Stoning of the Devil, repeated in a sequence of 3 days. In total, the outdoor activities take place over a period of five prespecified days each year where all the pilgrims in any specific year must participate at the same time, resulting in very high-density crowds. These 5 days are performed every year over the same days of the Muslim calendar, which follows the lunar cycle. Since the lunar year is shorter than the solar year by on average 11 days, Hajj defined within the solar calendar shifts by about 11 days earlier on average every year and cycles back to the same date in the solar calendar after roughly 33 years (supporting information Table S1).

The climate of most of the Middle East including Saudi Arabia, characteristic of its desert environment, is arid with warm winters and hot summers (Hasanean, 2014; Khan & Alghafari, 2018). Since the 1970s, this region has experienced significant upward surface temperature trends (Almazroui et al., 2012; AlSarmi & Washington, 2011; Tanarhte et al., 2012) and increases in the frequency of heat extremes (Donat et al., 2014; Tanarhte et al., 2015). Temperature increases associated with increased atmospheric anthropogenic greenhouse gas (GHG) concentrations are projected much stronger in summer than in winter further exacerbating the extreme nature of summer in the region (Lelieveld et al., 2016; Waha et al., 2017).

Figure 1. Satellite image indicating the location of the Great Mosque of Mecca (Al Haram), Mina, and Arafat in and near Mecca, Saudi Arabia. Map image was obtained from Google Earth.

In order to assess the potential future climate change impacts on heat stress during Hajj, we analyze bias-corrected coupled atmosphere-ocean global climate model (AOGCM) simulations corresponding to the area around Mecca for the period (2006–2100) under Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 adopted by the Intergovernmental Panel Governmental Panel on Climate Change.

2. Methods and Materials

2.1. Climate Change Projections

In this study, we analyze output from three Coupled Model Intercomparison Project 5 (Taylor et al., 2012) coupled AOGCM projections forced by two RCP scenarios: RCP 4.5 and RCP 8.5 (Riahi et al., 2011; Thomson et al., 2011). RCP 8.5 is considered a business as usual scenario with little or no implemented mitigation measures; and RCP 4.5 considers mitigation measures slightly less aggressive than those associated with the Paris Conference of Parties 21 agreement (UNFCCC, 2015). Output from the AOGCM projections is considered for the period 1976 to 2100.

The three AOGCMs are selected from 40 Coupled Model Intercomparison Project 5 AOGCMs based on a rigorous screening process. As a first requirement, the considered AOGCM must represent the Red Sea as a water body, which was determined based on the land sea fraction. Of the 40 AOGCMs analyzed, only seven of them met this requirement and were therefore considered for further analysis. Using those seven AOGCMs, a rigorous evaluation of performance in simulating temperature (T), wet-bulb temperature (TW; computed using the formulation developed by Davies-Jones, 2008), and relative humidity in the region was performed using a similar procedure to that of Pal and Eltahir (2016). AOGCMs meeting an acceptable bias and root mean square error criteria were included in the analysis: Community Climate System Model version 4 (Meehl et al., 2012), Max-Planck-Institute Earth System Model (Giorgetta et al., 2013), and Norwegian community Earth System Model (NorESM1-M; Bentsen et al., 2013).

2.2. Bias Correction

Despite the rigorous screening process outlined above, the AOGCM simulations of historical climate contain uncertainties and biases largely originating from misrepresentations of physical processes as well as the

chaotic behavior of the climate system (Ehret et al., 2012; Liang et al., 2008). Furthermore, there is also a scale gap when in situ station data are directly compared to coarse-resolution model grid averages (Maraun et al., 2015). For climate change impacts studies, bias corrections are often applied with the assumption that the bias from the historical climate remains constant in the future climate. In this study, in situ observations from the Mecca (MAKKAH [station number: 410300], 21.43°N, 39.77°E) station from the Integrated Surface Database (Smith et al., 2011) are considered. To minimize the inclusion of missing values in the Mecca station data, the reference period of consideration is limited to the most recent available 30 years (1984–2013). AOGCM simulation output is extracted for the 30-year period 1976–2005 at the grid point closest to the Mecca station.

To perform the bias correction, we apply a Parametric Quantile Mapping (Piani et al., 2010) to simulated daily maximum dry-bulb temperature (T_{max}) and wet-bulb temperature (TW_{max}). The Parametric Quantile Mapping algorithm involves a transfer function between Gaussian cumulative distribution functions of the observations and output from each AOGCM simulation during a reference period and future periods ($F_{o,r}$, $F_{m,r}$, and $F_{m,f}$). To do so, we calculate absolute changes in quantiles between reference and future periods ($\Delta_m(t)$) for T_{max} and TW_{max} for each month using raw output from each AOGCM ($Raw_{X_{m,f}}(t)$), as follows:

$$\Delta_m(t) = Raw_{X_{m,f}}(t) - F_{m,r}^{-1}\left[F_{m,f}^{(t)}\left\{Raw_{X_{m,f}}(t)\right\}\right] \tag{1}$$

Based on the computed changes, we then obtain bias-corrected future projections ($BC_{X_{m,f}}(t)$) by adding $\Delta_m(t)$ to reference bias-corrected value:

$$BC_{X_{m,f}}(t) = F_{o,r}^{-1}\left[F_{m,r}\left\{Raw_{X_{m,f}}(t)\right\}\right] + \Delta_m(t) \tag{2}$$

3. Results

In this study, we consider the physically relevant thermodynamic variable called wet-bulb temperature (TW), which is defined as the temperature to which a parcel of air will cool when moisture is evaporated into it until saturation. It therefore increases with increasing temperature and humidity and is a measure of "mugginess" (Sherwood & Huber, 2010). TW in excess of 35 °C is considered lethal for all humans and has been projected for regions along the Persian/Arabian Gulf and in Indus and Ganges Valleys (Im et al., 2017; Pal & Eltahir, 2016). Observations of T and TW, from Mecca meteorological station, indicate a significant warming trend during the last 30 years of close to 2 °C, which is well above the global average and largely attributed to increased anthropogenic atmospheric GHG concentrations (IPCC, 2013; Figure 2). The U. S. National Weather Service (USNWS) defines an extreme danger heat stress threshold (Steadman, 1979) that is approximately equivalent to a wet-bulb temperature of about 29.1 °C at 45% relative humidity (Im et al., 2017)—a combined measure of temperature and humidity. During this analysis period, while there were several TW events exceeding the USNWS danger threshold of 24.6 °C, no events exceed the extreme danger threshold of 29.1 °C (Figure 2c).

The climate of the area around Mecca is arid, warm in winter and hot in summer, characteristic of the desert environment in this region (Hasanean, 2014; Khan & Alghafari, 2018). Its proximity to the Red Sea promotes relatively high humidity conditions when westerly winds transport humid air into the region. The seasonality of dry-bulb temperature (T, commonly referred to as temperature) and humidity conditions is the most important factor dictating the levels of heat stress during Hajj (Figure 3). Severe conditions are often experienced when the Hajj occurs within summer, while pleasant conditions prevail when Hajj occurs in winter (Aleeban & Mackey, 2016; Noweir et al., 2008). High T conditions occur from April to October season, especially in early summer months. During the late summer and early autumn months, August through October, high combined temperature and humidity conditions prevail reflecting the combined seasonal flux of warm humid air from the Red Sea and local heating (see Figure 3 and Text S1).

High heat stress events are not uncommon when the Hajj occurs during the boreal summer. Over the 30-year historical record of analysis, the USNWS 24.6 °C danger threshold is exceeded in 60% of years (58% of years
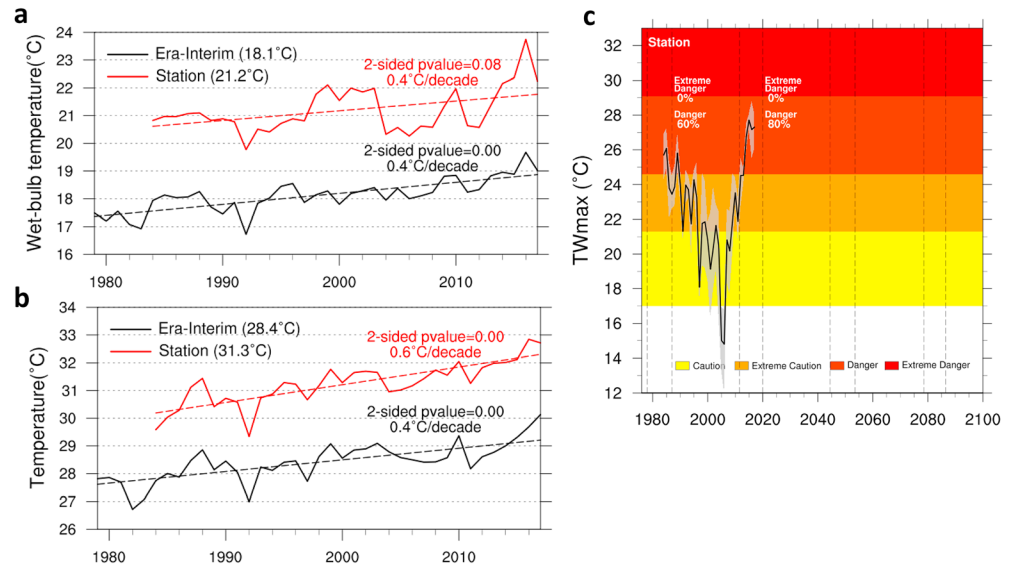
Figure 2. Time series of annual mean (a) TW and (b) T and (c) daily TW_{max} (°C) during Hajj. In (a) and (b), station and ERA-Interim data with trendlines are indicated in red for the period 1984–2017 and black for 1979–2017, respectively, and the values represent the average, two-sided Mann-Kendall *p* values, and decadal trend. In (c), the black line represents the 5-day TW_{max} average of the station observations during Hajj; shading indicates the maximum and minimum; background colors indicate U.S. National Weather Service heat stress risk level equivalents at 45% relative humidity in Figure S8; and vertical dashed lines indicate bounds of Hajj periods occurring during August through October.

in historical simulations) when Hajj coincides with the summer (Figure 4). Daily TW_{max}, however, has never exceeded the 29.1 °C extreme danger threshold. Consistent with high heat stress events, but not necessarily related, past stampede incidents resulting in significant death among pilgrims occurred during Hajj in 1990 and in 2015 both during summer events associated with TW in excess of the USNWS danger threshold (Figure 2c). On 2 July 1990, 1,426 pilgrims died in a stampede (Al-Mughrabi, 2015; Benedictus, 2015) when maximum temperature (T_{max}) reached 41.7 °C and wet-bulb temperature (TW_{max}) reached 25.1 °C. Similarly, on 24 September 2015, more than 2,000 pilgrims (Gambrell, 2015; Kasolowsky, 2016) perished when T_{max} and TW_{max} reached 48.3 and 27.3 °C, respectively. The exact cause of these stampedes is not known (Salamati & Vafa, 2016); however, adverse weather conditions are likely to have contributed to their severity and death toll (Anderson, 1989).
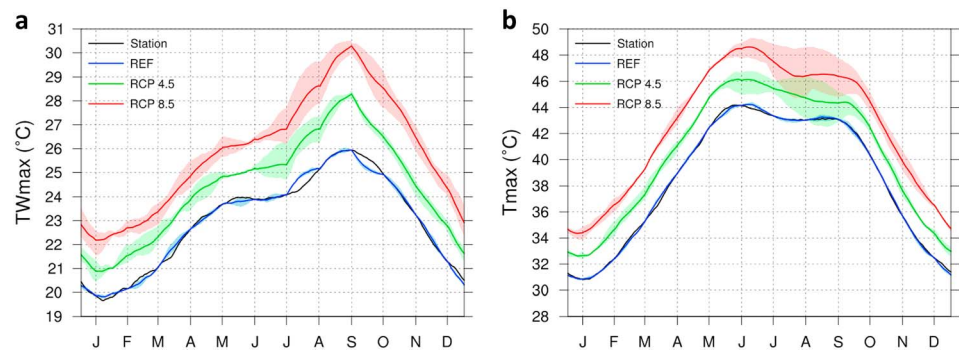

Figure 3. The 30-year mean seasonal cycle of (a) TW_{max} and (b) T_{max}. Station data are represented by the black line for the period 1984–2013. The blue, green, and red colors represent the reference simulation for the period 1976–2005 and Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 projections for the period 2071–2100, respectively. The blue, green, and red lines represent the atmosphere-ocean global climate model ensemble mean, and the shading represents the atmosphere-ocean global climate model ranges.
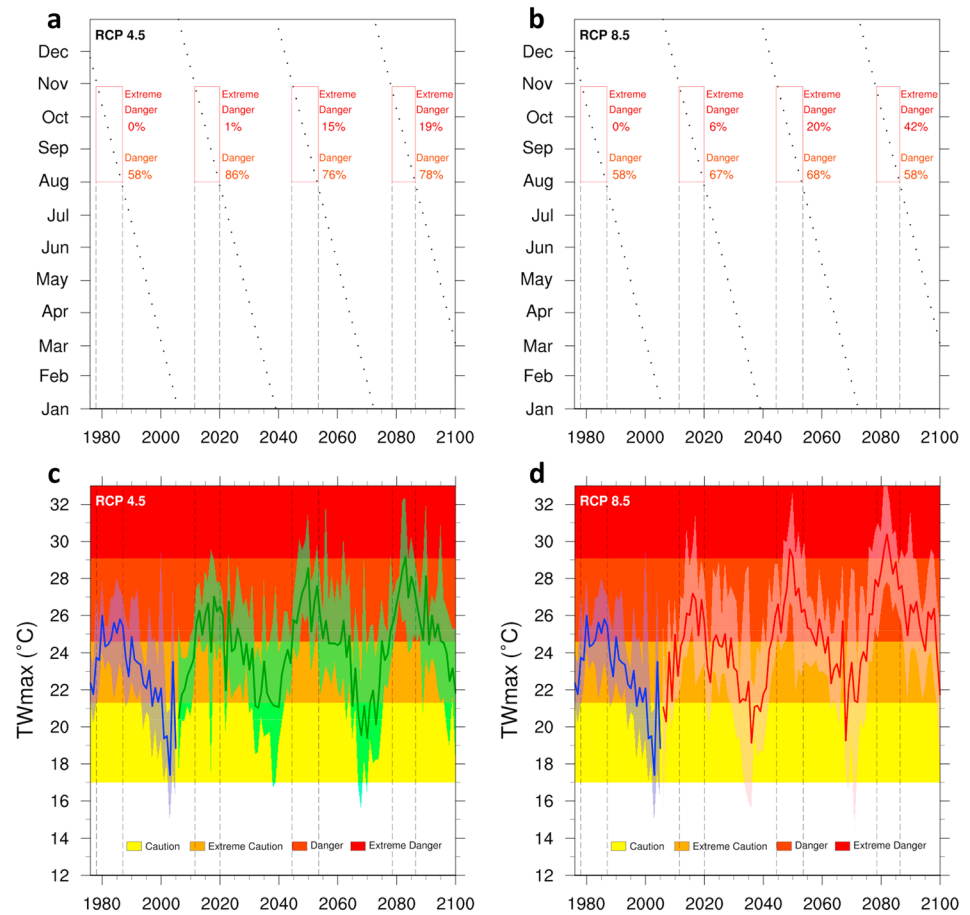
Figure 4. Daily TW$_{max}$ during Hajj and date of Hajj. (a) Date of Hajj from 1976–2100 with frequency of occurrence between Danger and Extreme Danger (orange values) and exceeding extreme danger (red values) during August-September-October under the HIST and Representative Concentration Pathway (RCP) 4.5 scenarios; (b) same as (a) but for RCP 8.5; (c) same as Figure 2c but for HIST (blue) and RCP 4.5 (green); and (d) same as (c) but for RCP 8.5. The shading represents the atmosphere-ocean global climate model ranges during Hajj, and the vertical dashed black lines indicate bounds of Hajj periods occurring during August through October.

Based on bias-corrected AOGCM simulations, average T$_{max}$ and TW$_{max}$ are projected to increase as the century progresses. The impacts of climate change on the seasonal cycles of TW$_{max}$ and T$_{max}$ are shown in Figures 3a and 3b, respectively. For the historical simulations, daily TW$_{max}$ never exceeds the 29.1 °C USNWS extreme danger threshold but exceeds the 24.6 °C danger threshold 58% of years when Hajj coincides with the boreal summer (Figure 4). Under the RCP 8.5 business-as-usual (BAU) scenario, heat stress levels are projected to exceed the extreme danger threshold 6%, 20%, and 42% and the danger threshold 73%, 88%, and 100% sometime during Hajj events in the periods up to 2020, 2045–2053, and 2079–2086, respectively. The intensity and frequency of exceedance of these events substantially increase as the century progresses. In fact, events occur outside of August to October during the 2079–2086 period. In addition, all Hajjes, regardless of the part of the year in which they fall, are project to have events exceeding USNWS extreme caution (TW > 24.3 °C). Mitigation efforts associated with RCP 4.5 are projected to substantially reduce the occurrences to 1%, 15%, and 19% for extreme danger; however, the danger threshold is exceeded 87%, 91%, and 97%, respectively. By the end of the century, all but a few years exceed the extreme caution threshold. It is important to note that differences in heat stress events between RCP 4.5 and RCP 8.5 emerge only in the latter period when the differences in atmospheric GHG concentrations are the largest (IPCC, 2013). Such heat stress levels around Mecca have not been observed in the station observation analysis period. Furthermore, the projected heat stress events during the specified at-risk periods are projected to be associated with T$_{max}$ conditions approaching 50 °C (Figure S1).

4. Discussion and Conclusion

The human health risk during Hajj depends on both the intensity and duration of the natural hazard as well as the level of vulnerability of the pilgrims in any specific year. The factors that shape this vulnerability include structural factors such as the capacity of the Hajj facilities and quality of transportation logistics and nonstructural factors such as the age distribution, health, and number of pilgrims. If anthropogenic GHG emissions and associated atmospheric concentrations remain unabated, the hazard associated with the future projected intensity, frequency, and duration of heat stress during Hajjes will require carefully planned strategies, especially in summer, and measures in order to avoid serious risk to human health during Hajj in the future. As Islam is the world's fastest-growing major religion and is projected to continue to be (Lipka & Hackett, 2017), strategies manage associated increases in those interested in performing Hajj are expected to be challenging, even in absence climate change. Should pilgrims shift their preference of when they observe Hajj to milder climatic months avoiding the summer, these infrastructural challenges would likely be considerably amplified due to further increase in the number of those interested in performing Hajj during nonsummer months. Any mitigation efforts favoring something similar to or more robust than RCP 4.5 will likely have significantly positive impacts by reducing the projected heat stress intensity and frequency. Nevertheless, the risk of heat stress increases substantially regardless of the scenario. In recent years, Hajj facilities and logistics have been significantly expanded and improved to help provide refuge from extreme weather conditions, and similar continued and perhaps more aggressive efforts are likely to happen in the future. However, a well-planned strategy would be required to manage the nonstructural human vulnerability factors as well. One such strategy would be to reduce the number of pilgrims during the high-risk decades identified above and limit Hajj only to those pilgrims performing obligatory Hajj in good health.

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