Heat index extremes increasing several times faster than the air temperature

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Many effects of global warming are far removed from the average person’s experience, but anthropogenic global warming is exacerbating heat stress for billions of people where they live today (Mastrucci et al., 2019; Raymond et al., 2020; Baldwin et al., 2023), reducing labor capacity (Dunne et al., 2013), and increasing heat-induced mortality (Vicedo-Cabrera et al., 2021). Therefore, public communication of global warming’s heat-stress implications can serve two important purposes: promoting life-saving adaptation and raising awareness of the benefits of warming mitigation (Patz et al., 2014; Koh, 2016; Cvijanovic et al., 2023).

To communicate the contribution of global warming to an observed heat event, one approach is to calculate how much more likely the event was to exceed a fixed temperature threshold (Shepherd, 2016). While this approach can lead to statements that the probability of exceeding a fixed temperature has, e.g., doubled (Stott et al., 2004), it is often more appropriate to report the change in temperature at a fixed probability of exceedance (e.g., Perkins-Kirkpatrick et al., 2022). Those changes in temperature are typically more modest-sounding because, for more than 90% of the land area between 60° S and 60° N, global warming has increased average daily-maximum temperatures by less than 2 °C (calculated using Berkeley Earth; see Supplementary Material 1.1). On the other hand, we will argue that these relatively modest-sounding changes in temperature have caused large increases in heat stress as quantified by the heat index. Focusing on Texas as a case study, we will show that global warming increased the highest heat index during June, July, and August (JJA) of 2023 by, on average, \(\sim 5-6 \, ^\circ C \, (\sim 9-11 \, ^\circ F)\).

Because of the evaporative cooling of sweat, heat stress is influenced not just by the air temperature, but also by humidity. All else equal, higher humidity reduces evaporative cooling and, therefore, increases heat stress, as clearly evidenced by laboratory studies (e.g., Wolf et al., 2022). While there are many different metrics of heat stress in use (Havenith and Fiala, 2015), the heat index stands out for its basis in physiological modeling (Steadman, 1979) and its validation against laboratory experiments (Lu and Romps, 2023).

Given the actual air temperature \(T\) and water-vapor pressure \(p_v\), the heat index is the air temperature that would feel the same at a reference vapor pressure of 1.6 kPa (Steadman, 1979; Lu and Romps, 2022). Although the heat index is often called a “feels like” temperature, the heat index is based on a model of physiology, not psychology: the heat index is the temperature at 1.6 kPa that would generate the same physiological response as the actual \(T\) and \(p_v\). In other words, the heat index \(T_{HI}\) is defined implicitly by

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\text{physiology}(T_{HI}, 1.6 \text{ kPa}) = \text{physiology}(T, p_v).
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Under the hood, the heat index runs on a mathematical model of human thermoregulation. Originally calculated up to the point where sweat begins to drip off the skin (Steadman, 1979), the calculation has since been extended to all combinations of temperature and humidity (Lu and Romps, 2022). While there have been many studies of global warming’s impact on the heat index, studies have relied on a polynomial extrapolation of originally calculated values (Rothfusz, 1990). That extrapolation has errors as large as 10 °C (Romps and Lu, 2022) and so is not used here. Instead, we calculate the heat index by solving the equations of its underlying thermoregulatory model (Lu and Romps, 2022).

To estimate the impact of global warming on the heat index, we need to know how its two inputs – temperature and humidity – are changing. Any realistic change to the climate will alter mean diurnal cycles as well as distributions of daily-minimum and daily-maximum temperatures. To first approximation, however, we can model the changes to a temperature distribution as if it were simply shifted by the change in its mean (Simolo et al., 2011; McKinnon et al., 2016). In this spirit, a weather station’s temperature reading

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can be mapped to the value it would have been in the absence of global warming by subtracting from it the mean change in temperature from preindustrial to the present. Here, we approximate the local effect of global warming by the observed change in decadal-mean local temperature. Likewise, to first approximation, the distribution of relative humidity does not change with global warming (Held and Soden, 2006; Schneider et al., 2010). Therefore, given an observation of $T$ and RH, we can approximate the conditions that would have prevailed in the absence of global warming, all else equal, by subtracting the mean warming from $T$ and leaving RH unchanged.

To illustrate the effect of this mapping on the heat index, we will focus on Texas as a case study. The area-weighted average of daily-mean Texas surface-air temperatures during JJA has warmed by 1.5 °C from preindustrial (1850-1859) to present (2013-2022) (Berkeley Earth; see SM 1.1). To analyze the recent heat extremes in Texas, we use hourly Automated Surface Observing Systems (ASOS) station data archived by the Iowa Environmental Mesonet (see SM 1.2). There were 210 stations reporting temperature and relative humidity from June 1 to August 31 of 2023 (see Table S1). For each station, we calculate its maximum hourly mean temperature and maximum hourly mean heat index (Lu and Romps, 2022) during those three months. To calculate changes in these quantities since the preindustrial, we are unable to use ASOS time series directly because the median age of ASOS stations is only 20 years. Instead, for each station, we can estimate what the maximum heat index in JJA 2023 would have been in the absence of global warming, i.e., if the relative humidities had been the same, but if all the temperatures had been lower by 1.5 °C.

Figure 1a plots each station’s maximum temperature during JJA 2023 against that same temperature minus 1.5 °C. Here, the approximate impact of global warming on maximum temperatures is visualized by the departure of the points from the one-to-one line, shown by the dashed curve. Figure 1b plots each station’s maximum heat index (during JJA 2023) against the maximum heat index that would have been achieved if temperatures were 1.5 °C cooler, i.e., in the absence of global warming. This plot allows us to see how global warming has affected recent heat-index values. At lower temperatures, the effect of humidity on physiology becomes less pronounced, and $T_{HI}$ asymptotes to $T$. Consistent with this, at lower values on the abscissa, the points are elevated above the one-to-one line by close to 1.5 °C, similar to Figure 1a. At higher values on the abscissa, however, we see large departures from the one-to-one line. For example, the highest observed heat index of 75 °C (at Houston’s Ellington Airport on July 23) would have been about 6 °C lower at a value of 69 °C in the absence of global warming. Assuming constant relative humidity, the 1.5 °C of global warming has increased these maximum heat-index values by an average of 6 °C.

A heat index of 75 °C might sound unrealistic and unsurvivable, but it is, in fact, both realistic and – for a young, healthy individual – survivable. To understand why, we must recall that the heat index is the physiologically equivalent temperature, assuming wetted skin, at a reference water-vapor pressure of 1.6 kPa. For comparison, at 1.6 kPa, an air temperature of 75 °C has a wet-bulb temperature of only 31 °C (see SM 1.3 and Figure S1). The energy budget of a wet human is similar to that of a wet bulb: in both cases, the temperature of the wetted surface is largely set by the need to balance sensible and radiant heat flowing in and latent heat flowing out. For a person, however, there is the additional metabolic heat that must be shed to the environment, leading to a somewhat higher temperature of the wetted surface for a sweaty person than for a wet bulb. In particular, 75 °C and 1.6 kPa induces (for a young, healthy person in steady-state heat balance) a skin temperature of 38 °C, which is far less than 75 °C, and which corresponds to a dangerous, but survivable, state of hyperthermia. Thus, the large latent heat of water postpones hyperthermia to a high value of the heat index for the same reason that the wet-bulb temperature can deviate by several tens of degrees from the dry-bulb temperature.

Although the very high heat index of 75 °C was bumped up by global warming by ~6 °C, some other heat-index values were affected much more. For example, on June 20, 2023, the city of Nacogdoches had an hourly mean heat index of 60 °C. At the time, the temperature was 31 °C with a relative humidity of 91%. Had the relative humidity been the same, but the temperature lower by 1.5 °C, the heat index would have been lower by 18 °C. This large sensitivity to temperature is caused by the heat and humidity approaching those conditions that would induce hyperthermia in a young, healthy adult. According to the heat index model, in the conditions at Nacogdoches, the global-warming-induced temperature increase of 1.5 °C increased a person’s skin blood flow by 0.5 l min$^{-1}$ (compared to a basal rate of about 0.6 l min$^{-1}$) so as to avoid hyperthermia. At 1.6 kPa, the temperature would need to increase by 18 °C (from 42 °C to 60 °C) to induce the same physiological stress (i.e., the same skin blood flow; see SM 1.4 and Figure S2). This high sensitivity is caused by the approach to the physiological limit: for the observed relative humidity of 91%,
Figure 1: (a) Maximum temperature at each ASOS station in Texas during JJA 2023, plotted against the approximate temperature it would have been in the absence of global warming, which is 1.5 °C lower than observed. (b) Maximum heat index at each ASOS station in Texas during JJA 2023, plotted against the approximate heat index it would have been in the absence of global warming (calculated by subtracting 1.5 °C from the temperature while holding relative humidity fixed). For visual reference, the one-to-one line is marked by a dashed curve in both panels. Colors denote the approximate global-warming impact: the difference between the observed value and the approximate value it would have been in the absence of global warming.
no amount of skin blood flow can prevent hyperthermia at temperatures over 34 °C (Lu and Romps, 2022).

To corroborate these estimated changes in the heat index, we can turn next to the ERA5 reanalysis (Hersbach et al., 2020). We use hourly data in the local afternoon (17 UTC to 22 UTC) during all days of JJA from grid cells centered within Texas from 1942 to 2023 (values for 1940 and 1941 were discarded as outliers; see SM 1.5 and Figure S3). In the analysis of the ASOS station data, we used two approximations that we can check using the ERA5 data: 1. that the temperatures at the time of maximal heat index have been affected by global warming the same as the mean annual temperature, and 2. that the relative humidities at the time of maximal heat index have remained roughly constant. In the ERA5 data, the temperature at the time of each grid cell’s annual maximum heat index increased, from 1942-1951 to 2014-2023, by an average of 0.8 K, which is nearly identical to the mean annual temperature increase during that time (1.0 K from ERA5 and 0.9 K from Berkeley Earth), corroborating the first approximation. Regarding the second approximation, the average relative humidity at the time of the maximal heat index did not decrease: in fact, it actually increased slightly, from 31% to 35%.

In the analysis of ERA5 heat index, we do not need to use either of those two approximations because we can calculate the time series of the heat index directly. Overall, the mean of the annual grid-point maximum heat index increased in ERA5 from 1942-1951 to 2013-2022 by 3 °C. To estimate the change since preindustrial, we can multiply this number by the warming since preindustrial divided by the warming since 1942-1951, which gives a mean increase in maximum heat index of 5 °C. This is illustrated in Figure 2, which plots the mean (over grid cells) of annual maximum heat index. In 2023, this mean was 7 °C above preindustrial. In summary, both station data and reanalysis are consistent with global warming having increased the most extreme values of the heat index in Texas by ~5-6 °C (~8-11 °F).

In public communications, global warming is typically quantified in terms of the dry-bulb temperature,
but that fails to convey the true impact on heat stress. A person’s typical experience of diurnal temperature variations is in association with approximately constant specific humidity, biasing the perception of the implications of +1.5 °C. Global warming, on the other hand, can generate temperature increases with roughly constant, or even increasing, relative humidity. At an air temperature of 30 °C and 90% relative humidity, a 1.5 °C increase in air temperature at fixed specific humidity increases a person’s skin blood flow by about 12%. On the other hand, with a more realistic depiction of global warming as occurring with fixed relative humidity, that same 1.5 °C increase in air temperature increases a person’s skin blood flow by 58%. The heat index rises by 15 °C in this case, reflecting the approach to hyperthermic conditions and the amplification of heat stress from constant relative humidity. Communicating the impact of global warming in terms of changes to the heat index gives the public a more accurate picture of the extent to which global warming has increased heat stress.

**Competing interests**

The author declares no competing interests.
References


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