



Communicating the deadly consequences of global warming for human heat stress

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In December of 2015, the international community pledged to limit global warming to below 2 °C above preindustrial (PI) to prevent dangerous climate change. However, to what extent, and for whom, is danger avoided if this ambitious target is realized? We address these questions by scrutinizing heat stress, because the frequency of extremely hot weather is expected to continue to rise in the approach to the 2 °C limit. We use analogs and the extreme South Asian heat of 2015 as a focusing event to help interpret the increasing frequency of deadly heat under specified amounts of global warming. Using a large ensemble of climate models, our results confirm that global mean air temperature is nonlinearly related to heat stress, meaning that the same future warming as realized to date could trigger larger increases in societal impacts than historically experienced. This nonlinearity is higher for heat stress metrics that integrate the effect of rising humidity. We show that, even in a climate held to 2 °C above PI, Karachi (Pakistan) and Kolkata (India) could expect conditions equivalent to their deadly 2015 heatwaves every year. With only 1.5 °C of global warming, twice as many megacities (such as Lagos, Nigeria, and Shanghai, China) could become heat stressed, exposing more than 350 million more people to deadly heat by 2050 under a midrange population growth scenario. The results underscore that, even if the Paris targets are realized, there could still be a significant adaptation imperative for vulnerable urban populations.

climate change | heat stress | megacities | extreme heat | CMIP5

Air temperatures near the surface of Earth are rising. At the time of writing, 2015 was the warmest year globally since observations began (Fig. 1A). Higher average air temperatures coincide with more frequent periods of extremely hot weather (1, 2), which in turn, have adverse consequences for human well-being and economic productivity (3–5). The health impacts of rising air temperature are compounded by attendant increases in atmospheric water vapor (6), which reduces humans' ability to dissipate heat (7).

Apparent temperature (8) translates the humidity effect into an index that provides a “feels-like” temperature. Although far from the only metric of its type, it is among the most widely used to communicate episodes of extreme heat (9, 10). For example, the US National Weather Service (NWS) approximates apparent temperature with their heat index (HI) (*Materials and Methods*). The NWS issues warnings when forecasted values persist above 105 °F (with HI = 40.6 °C; hereafter HI40.6)—an operational definition of “dangerous” heat. During 2015, annual maxima for HI were well above average across South Asia and around the Persian Gulf (Fig. 1B), with extreme values above 60 °C gaining widespread media attention (11). Some heat-prone megacity regions, such as Karachi (Pakistan) and Kolkata (India), recorded their highest HI values in at least 36 y (Fig. 1B–D). The extraordinary heat had deadly consequences, with over 3,400 fatalities reported across India and Pakistan alone (www.emdat.be).

In the context of a warming climate, occurrence of such extreme HI conditions should not be surprising. By definition, the HI has temperature sensitivity much greater than unity at high values (Fig. S1). This nonlinearity is common to temperature–

humidity heat stress indicators (12), because for a given relative humidity, latent heat cooling capacity decreases at an accelerating rate in response to the rise in vapor pressure governed by the Clausius–Clapeyron relation. Without counteracting reductions in relative humidity, higher air temperatures drive yet greater increments in HI. This temperature sensitivity is underlined in Fig. 2, which shows HI derived from the model integrations of the Coupled Model Intercomparison Project Phase 5 (CMIP5) (13). Comparing the decade 1979–1988 with 2090–2099, it is evident that extreme HI values (here defined as the 99.9th percentile) over land rise much faster in response to global mean air temperature increase than either mean or extreme air temperatures.

Given the threat already posed by heat stress worldwide (14), such temperature sensitivity is of significant concern. Projections of changes in heat stress have accordingly received attention from the research community (9, 10, 15). For upper-bound, end of 21st century warming, heat in some regions could exceed the physiological tolerance of humans (16), with presently rare heat thresholds being crossed far more regularly (15). The frequency of hot extremes has also been observed to be highly sensitive to global mean temperature increase (2), which is expected to drive increasing heat stress for little additional climate change (17). Even limiting warming to 2 °C since preindustrial (PI) is considered unlikely to avoid an intensification of severe heat events (18).

Mindful of these impacts and sensitivity, we examine the extent to which the global warming limits of 1.5 °C and 2 °C agreed on in Paris by the international community (19) may avoid dangerous climate change from a heat stress perspective. The issue is explored by assessing heat stress projections as a function of global temperature change. This approach has been applied elsewhere in climate impacts research and permits quantification of sensitivity

Significance

Extremely hot weather can have deadly human consequences. As the climate warms, the frequency and intensity of such conditions are expected to increase—among the most certain negative impacts expected under global warming. Concerns about dangerous climate change have encouraged the international community to commit to limiting global temperature changes to below 2 °C above preindustrial. Although lauded as a great achievement to avoid dangerous climate change, we find that, even if such aspirations are realized, large increases in the frequency of deadly heat should be expected, with more than 350 million more megacity inhabitants afflicted by midcentury. Such conclusions underline the critical role for ambitious adaptation alongside these climate change mitigation targets.

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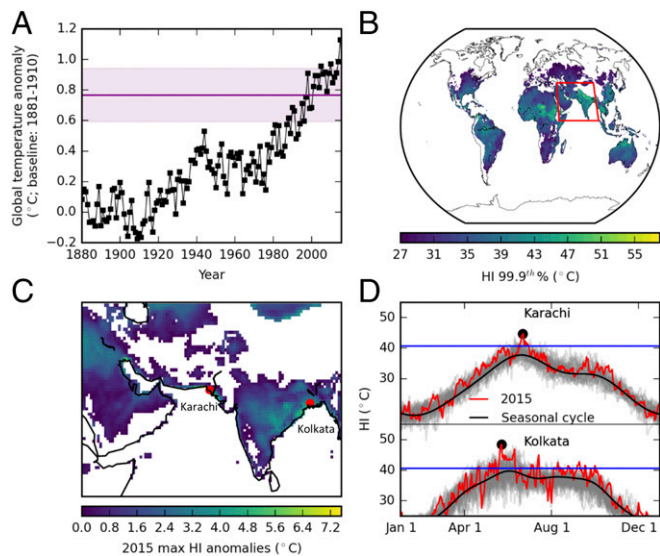


Fig. 1. Mean air temperatures and recent HI extremes. (A) Global mean air temperature series defined as the average of the BEST, HadCRUT4, and GISTEMP records. The purple line gives the 1986–2015 mean, with the shaded area representing ± 1 SD. (B) The 99.9th percentiles of daily HI values, with values < 27 °C masked (the lower limit of the HI warning category indicating “caution” to heat stress). (C) HI anomaly of 2015 relative to the mean of the annual maximums 1979–2015; negative anomalies are masked as are positive anomalies where absolute HI < 27 °C. Note that the domain of C is indicated in B by the red box. (D) Daily mean HI values for the respective regions (1979–2015). Gray curves are individual years 1979–2014; red is 2015.

across a range of policy-relevant warming targets (20–22). We also use temporal and spatial analogs to facilitate communication of these results to the wider public. The use of analogs assumes that conditions already experienced may present similar challenges when manifesting elsewhere or in the future and has been used widely by the climate research community (23). The allure of analogs stems from their potential to educate a wide range of non-specialists about the complex impacts of climate change, providing a first step to comprehending the unknown (24).

An emphasis on communication is necessary, because warming consistent with the Paris targets has been described as sounding modest enough for the urgency of the situation to be lost on non-experts (25). Such interpretation may downplay the risk of climate change, which in turn, could make individuals less willing to take action to reduce climate change (26). In reality, the period 1986–2015 was ~ 0.8 °C above PI (here defined as 1881–1910) (Fig. 1A). Hence, the 1.5 °C and 2 °C Paris targets allow for only another 0.7 °C and 1.2 °C warming [although a global mean temperature rise of 2.7 °C is expected under the current set of intended nationally determined contributions (INDCs)]. In other words, the ambitious targets still commit to between 1.9 and 3.4 times the warming already experienced since the Industrial Revolution, which in turn, propagates into much greater changes in the severity of extreme HI conditions (Fig. 2). Our analysis highlights combined temperature–humidity heat stress impacts as a reason for concern and draws on analogs to illustrate the challenges that may be ahead.

We show the global-scale sensitivity of HI in terms of threshold exceedances (Fig. 3A). Sliding 30-y samples of changes in global mean temperature since 1881–1910 from transient CMIP5 simulations are plotted against concurrent changes in bias-corrected global heat stress [defined here as the area-weighted average number of days per year with mean HI ≥ 40.6 °C (nHI40.6)]; the spatial detail behind these projections is illustrated in Fig. S2. The relationship between the global heat stress burden (HSB) and

global mean air temperature exhibits nonlinearity that is robust to variants of our method, with higher heat stress sensitivity under increasing temperatures also evident when (i) threshold exceedances of 35 °C simplified wet bulb globe temperature (SWBGT) are used [another common heat stress metric (5)] and (ii) the transient CMIP5 projections are replaced by pattern-scaled temperature observations and fixed relative humidity (SI Text, section 4 and Fig. S3). Notably, the frequency of extreme values increases slower for a reference dry bulb (DB) temperature of 37.6 °C (with equivalent rarity to HI40.6 during the 1979–2005 observational record) as the climate warms. Hence, assessments based on sensitivity of heat extremes’ frequency to global temperature change through DB (2) should be regarded as conservative projections of human heat stress.

The spatially-explicit heat stress projections (Fig. S2), highlight that, as global air temperatures rise, the land area experiencing dangerous HI values increases, with poleward expansion particularly evident in the Northern Hemisphere. The frequency of dangerous HI values also increases for those regions that are already impacted. The combined effect of increased area and frequency explains why global heat stress should be expected to follow a nonlinear relationship with global mean air temperature over the range considered here. With the area-weighted mean heat stress defined as $A\bar{N}$ (where A is the fraction of the Earth’s land surface experiencing dangerous HI and \bar{N} is the area-weighted mean number of days experienced within this region), nonlinearity will result if both terms are a function of global air temperature (as evident from the product rule of calculus). The practical implication of this relationship is that societies will be disproportionately impacted by heat stress as global temperature increases. Larger populations will be exposed to dangerous HI values, and those people already affected will be subjected to harmful conditions more often and with greater severity.

This nonlinearity also means that any change in global HSB experienced from warming to date will be smaller compared with the same additional warming realized in the future. Such nonlinearity has two implications. First, vulnerable communities may be insufficiently prepared to manage a nonlinear growth in extreme heat risk (27). Second, there could be progressively heavier impacts if the Paris warming targets are missed. According to the median CMIP5 HI curve in Fig. 3A, under 1.5 °C global warming, the HSB will be 5.7 times that experienced during the reference period (1979–2005), rising to between ~ 12 and 26 times the reference heat stress under 2 °C and 2.7 °C warming, respectively. The avoided impacts of mitigation are shown in Fig. 3A, Inset by continuing the curves in Fig. 3A to 4 °C of global warming. Under

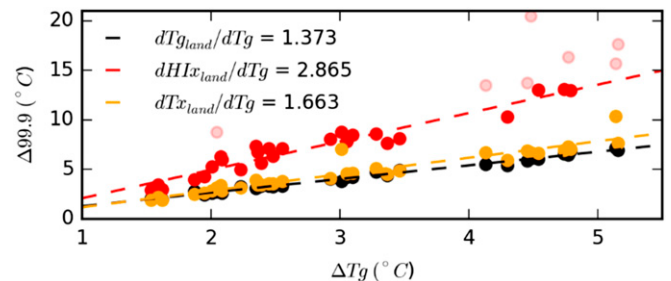


Fig. 2. Relationship between CMIP5 modeled changes in global mean air temperature (ΔT_g) and changes in mean air temperature over land ($T_{g_{land}}$), extreme temperatures over land ($T_{x_{land}}$), and HI values over land ($HI_{x_{land}}$). Extremes are defined as the 99.9th percentile, and the changes are calculated by differencing the respective values in the last decade of model simulations (2090–2099) relative to the simulated values over the period 1979–1988. Note that we mask HI values > 50 °C when computing the regression slope (shown in lighter shading), because this value is the upper limit of the range considered by ref. 8.

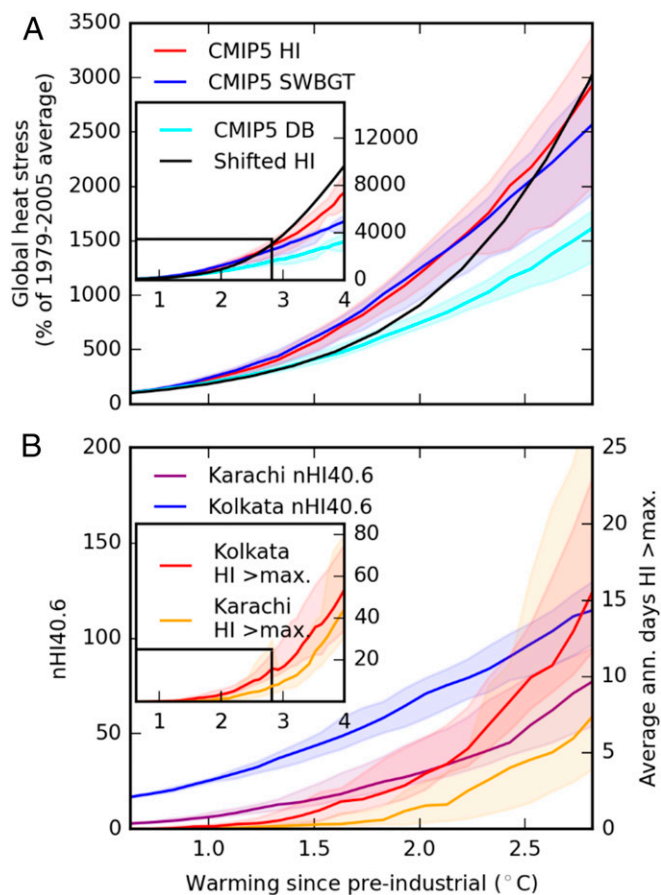


Fig. 3. Global and regional heat stress projected as a function of global warming amounts. (A) Global (land) heat stress sensitivity to global air temperature changes, in which lines are medians calculated from the CMIP5 ensemble and the shaded regions span the 25th–75th percentiles. Note that heat stress is defined here as the mean annual number of days exceeding a threshold temperature (40.6 °C, 35 °C, and 37.6 °C for the HI, SWBGT, and DB temperatures, respectively). At this global scale, these metrics are area-averaged. *A, Inset* continues the curves to 4 °C warming above PI, with limits in *A* indicated by the black box. (B) The same as in *A* but for the named locations, with different units on the y axes. Series on *B, Inset* axes continues the respective curves from *B* to 4 °C.

these temperatures, HSB as defined by CMIP5 HI reaches more than 75 times the reference value for \overline{AN} .

The possible consequences of these projections can be made more tangible by using the recent heatwaves of Karachi and Kolkata as analogs. Because HI40.6 is already expected each year at these locations, likely resulting in some degree of acclimatization (28), we show in Fig. 3*B* counts of annual exceedance of the historical maximum daily mean HI on record alongside HI40.6. The results indicate that HI values in excess of the deadly record set in 2015 would become commonplace in the absence of mitigation efforts (Fig. 3*B, Inset*), with more than 40 (50) d per year (a^{-1}) expected in Karachi (Kolkata) under global warming of 4 °C. Although effects are much reduced if warming is limited to levels consistent with the INDCs or the 1.5 °C and 2 °C targets, we highlight that there will likely be significantly increased heat stress, even if mitigation does successfully hold global warming to the ambitious 1.5 °C target. According to the ensemble median, a global warming of 1.5 °C would imply that Kolkata experiences, on average, conditions equivalent to the 2015 record every year; Karachi would experience the same deadly heat about once every 3.6 y. Under 2 °C of global warming, both regions could expect such heat on an annual basis. The potential societal impacts

of extreme heat are well-documented (3, 4), and some of these were manifested in Karachi and Kolkata during 2015. Conservative estimates suggest that there were 1,200 heat-related deaths in Karachi and enhanced mortality and economic disruption in Kolkata (29, 30). In this context, the projections of Fig. 3*B* are evidently of significant concern.

We explore the broader potential societal impacts of global warming on heat stress by examining projections for other megacity regions. These locations were identified according to the 21st century population projections from ref. 31, focusing on cities within the top 101 by population size for all three shared socio-economic pathways (SSPs) (32) and all time slices considered by the authors (2010–2100) (*Materials and Methods*). Our subset of 44 cities accounted for 0.4 billion people in 2010 and is projected to reach between 0.94 and 1.1 billion by 2100 depending on the SSP. For each of these megacities, we identified under which warming scenarios they may begin to experience heat stress annually (using the criteria from the CMIP5 ensemble median projection of $nHI40.6 \geq 1$) [full information of this city-level assessment, including identification of heat-stressed cities, is in *SI Text, section 3* (Tables S1–S4)]. We also show in Tables S2–S4 the historical spatial analogs (megacities) that best match the conditions ($nHI40.6$ and values of the HI 99.9th percentiles) in cities projected to become newly heat stressed.

Fig. 4*A* indicates that, with 1.5 °C of global warming, a number of city regions in West Africa and South and East Asia can expect to experience heat stress for the first time. Lagos (Nigeria), for example, would be newly heat stressed according to our definition and could expect $nHI40.6$ similar to that endured by Delhi (India) during the reference climate of 1979–2005. The closest historical analog for Shanghai (China)—also newly heat stressed—would be Karachi. Globally, over 40% of these 44 largest cities would be annually heat stressed for a warming of 1.5 °C (Fig. 4*B*), representing a doubling relative to the reference period. With temperatures 2 °C above PI, no additions are made to the list of newly heat-stressed cities, but this absence reflects the spatial distribution of our sampled locations. Under even higher temperature change scenarios, new cities annually experiencing heat stress continue to emerge. For the INDC level of 2.7 °C warming, for example, the largest city in the world at present (Tokyo, Japan) and the Chinese megacity of Beijing could be among those affected. With 4.0 °C warming, nearly 80% of the 44 megacities could be annually heat stressed, including New York and Rio de Janeiro.

Fig. 4*C* suggests that those cities already accustomed to extreme heat can expect larger increases in extreme HI values under the respective warming scenarios (consistent with information in Fig. S1). Use of these city exemplars reinforces the point that, for progressively higher warming amounts, not only will heat stress spread to new populations but those already exposed will be challenged by the largest increases in HI intensity.

The heat stress threat posed by climate change is accentuated by assumed population growth over the coming century. To explore the combined effect of warming and population change in these 44 cities, we defined a population-weighted HSB as the CMIP5 ensemble median $nHI40.6$ multiplied by the population for each city. By computing the metric using HI projections for different amounts of global warming combined with population projections for a plausible range of years (Fig. 5*A*), we provide insight into the possible effects of specified climates prevailing during particular time periods (Fig. 5*B*). By averaging over all combinations (of years/warming amounts) and SSPs, we can then rank the cities according to their projected HSB over the 21st century (*Materials and Methods* has more details of this procedure; Fig. 5*C*). Note that our method yields insight into conditions beyond the range of specific representative concentration pathways (RCPs) driving the CMIP5 ensemble. For example, the time-evolving impact of stabilizing temperatures at 1.5 °C above PI can be assessed (by simply reading the relevant x coordinate in Fig. 5*B*).

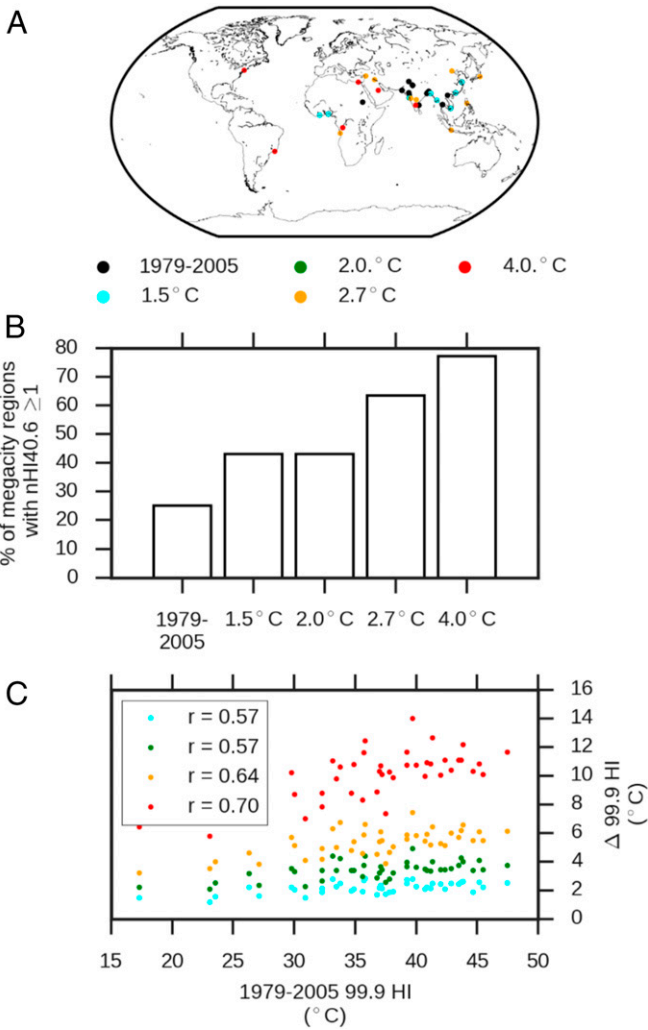


Fig. 4. Changes in heat stress for global city regions under various scenarios of global warming. (A) City regions experiencing annual heat stress ($nHI_{40.6} \geq 1$) for the first time under different warming amounts according to the CMIP5 ensemble median. Black circles mark locations already experiencing heat stress during the 1979–2005 reference period. Note that the names of these cities are available in [Tables S1–S4](#). (B) CMIP5 ensemble median percentage of megacities experiencing common heat stress under the respective warming amounts. (C) Changes in the CMIP5 ensemble median 99.9th HI percentile as a function of the observed 99.9th HI percentile during the 1979–2005 reference period. Values for HI > 50 °C have been masked out of this plot and the correlations in *Inset* (see [Fig. 2](#) legend). These correlations (r values) quantify the strength of the positive relationship plotted. Note that the critical r value for rejection of the null hypothesis ($r = 0$) is ± 0.30 for 42 df at the 0.05 level; hence, all reported values are interpreted as significant.

This analysis suggests that South Asian cities will remain the most heat stressed over the coming century, because 6 of the top 10 by HSB are located in Pakistan, India, or Bangladesh. African cities also feature prominently, with Lagos (Nigeria), Abidjan (Ivory Coast), and Khartoum (Sudan) taking 3 of the remaining 4 spots in the top 10. Notably, Lagos and Abidjan are also projected to realize some of the largest relative changes in HSB (the largest and third largest, respectively; Ho Chi Minh is projected to experience the second largest change), which is because of a combination of rapid population growth and sharp increases in $nHI_{40.6}$. For example, under 1.5 °C warming, the CMIP5 ensemble median projects that Lagos could see a 106-fold increase in $nHI_{40.6}$ relative to 1979–2005; under SSP2, population in Lagos peaks during 2070–2099,

with an 11-fold increase relative to 1995. A 1.5 °C warmer climate at the end of this century would, therefore, result in an HSB more than 1,000 times greater than the recent past for Lagos. Across all megacities, we estimate that, with this level of warming under SSP2 and as early as the middle of the 21st century, more than 350 million more people (a fourfold increase) could be exposed to heat stress annually compared with the 1979–2005 reference period.

In summary, we emphasize that the potentially deadly consequences of heat stress linked to global warming, even if limited to the 1.5 °C Paris target, should not be overlooked. More of the Earth’s land surface could experience dangerous heat, and those regions already exposed could encounter such conditions more often. Although the challenge of reaching a universal definition of dangerous heat is acknowledged—in terms of metric, timing, and duration—the fact remains that conditions that have historically challenged (and overwhelmed) those living in some of the most heat-stressed regions on Earth could become much more frequent. Population growth in vulnerable regions will add to the challenge. We used megacities to quantify the impacts of these combined climate and societal pressures but acknowledge that the spatially coarse climate models used cannot resolve the specific city-scale microclimates (33) in detail. Nonetheless, we consider it unlikely that projections for cities are overly pessimistic given that heat stress amplification associated with global warming is believed to be no less severe in urban environments (34). Indeed, our frequency-based analysis of heat stress likely provides a conservative perspective on projected heat stress. We have also shown that regions characterized by historically higher HI extremes can anticipate larger increases in the HI with global temperature rise, meaning more intense heat stress could also result as the 40.6 °C threshold is exceeded by greater amounts.

The high sensitivity to global temperature rise translates into a further doubling of global heat stress moving from 1.5 °C to 2 °C above PI (5.7 and ~ 12 times greater than 1979–2005, respectively), which from a human health perspective, provides a strong incentive for limiting global warming to the lower of these targets. However, with a possible 350 million more people exposed to deadly heat by the middle of the century even if this target is met, our analysis shows the critical role for adaptation alongside mitigation to manage the potential societal impacts. In this aspect, urban centers, including the megacities used here to communicate projected heat stress, are recognized as key focal points for action on mitigating and adapting to climate change (35). Some city authorities are already taking steps to limit the effects of extreme heat. For instance, Ahmadabad (India) recently implemented South Asia’s first comprehensive heat action plan, which may soon be expanded across the region (36). Given the dual pressures of climate change and population growth on heat stress identified here, we foresee a need for such plans to be adopted more widely across vulnerable regions.

Materials and Methods

HI and Climate Model Simulations. The NWS HI was calculated using the algorithm in [ref. 37](#). The index was evaluated using daily mean modeled fields from CMIP5 for the period 1979–2099, obtained through the Earth System Grid Federation (an inventory of the runs used is shown in the table in [SI Text, section 1](#)). Model experiments from 2006 onward reflect the RCPs; results for 1979–2005 were taken from the RCPs’ constituent “historical” model runs and identified and spliced using available metadata. HI computation requires values of air temperature and relative humidity. The former was available directly from the CMIP5 archive, whereas relative humidity (RH) was derived from specific humidity and surface pressure (P_s):

$$RH = \frac{qP_s}{\varepsilon e_0 \exp\left[\frac{L}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right]} \times 100, \quad [1]$$

where q is specific humidity (g/g), ε is the ratio of gas constants for water vapor and dry air (0.622 $g_{\text{vapor}}/g_{\text{dry, air}}$), e_0 is 610.8 Pa, L/R is 5,423 K (latent heat of vaporization divided by the gas constant for water vapor), T_0 is

We also obtained the 1995 population for each city from ref. 43 to compute the reference HSB over the period 1979–2005. These burdens were calculated by multiplying nHI40.6 for a specified warming amount for each city ($nHI40.6_{City}$) by the respective population (P_{City}). The term $nHI40.6_{City}$ was computed as a function of global warming amounts in 0.1 °C increments analogous to the global-scale metrics (*Materials and Methods, Heat Stress as a Function of Air Temperature Changes*) but without the spatial-averaging step. The ensemble median $nHI40.6_{City}$ was then multiplied by all possible running 30-y population averages for each city, giving insight into the HSB for a wide range of scenarios. We masked combinations of warming amounts (which control $nHI40.6_{City}$) and years that required faster rates of warming than the maximum recorded across the CMIP5 ensemble (Fig. 5A). The average 21st century HSB for each SSP was, therefore, calculated from

$$HSB_{City,SSP} = \frac{1}{\sum_i \sum_j H(T_g, i, j)} \sum_i \sum_j nHI40.6_{City} \times P_{City} \times H(T_g, i, j),$$

where the subscripts i and j index the global warming amounts and years, respectively; $H(T_g, i, j)$ is a Heaviside function that evaluates to one (zero) if the warming amount i is less (more) than the maximum CMIP5 global warming (T_g) for the 30-y period j . Averaging $HSB_{City,SSP}$ across three SSPs yields the 21st century HSB plotted in Fig. 5C. Reference HSB was calculated by multiplying the observed (1979–2005) $nHI40.6_{City}$ by the 1995 population.

In the text, we also cite the number of megacity inhabitants with ensemble median $nHI40.6 \geq 1$ for a +1.5 °C climate ($n_{1.5}$), which was computed as

$$n_{1.5} = \sum_{City} H(nHI40.6_{City}, 1.5^\circ\text{C}) \times P_{City,2050},$$

where the Heaviside function evaluates to one (zero) if $nHI40.6$ for the respective $City$ is ≥ 1 . $P_{City,2050}$ denotes the 30-y mean population projection (according to SSP2 for this location and the 30-y period centered on 2050).

Data and Code Availability. The CMIP5 data underpinning our analysis can be downloaded from any of the nodes of the Earth System Grid Federation (e.g., <https://esgf-data.dkrz.de/projects/esgf-dkrz/>), whereas the observational (WFDEI) dataset is available via ftp from <ftp://iiasa.ac.at>. The HadCRUT4, GISTEMP, and BEST global air temperature series can be sourced from <https://crudata.uea.ac.uk/cru/data/temperature/>, <https://data.giss.nasa.gov/gistemp/>, and berkeleyearth.org/data/, respectively. The SSP megacity population projections were obtained from the authors of ref. 31, and the 1995 population from ref. 43 is available at <https://esa.un.org/unpd/wup/CD-ROM/> (file 12). All processed data and computer code used in the analysis are available from the authors on request.

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