An adaptability limit to climate change due to heat stress

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Edited by Kerry A. Emanuel, Massachusetts Institute of Technology, Cambridge, MA, and approved March 24, 2010 (received for review November 19, 2009)

Despite the uncertainty in future climate-change impacts, it is often assumed that humans would be able to adapt to any possible warming. Here we argue that heat stress imposes a robust upper limit to such adaptation. Peak heat stress, quantified by the wet-bulb temperature T_W, is surprisingly similar across diverse climates today. T_W never exceeds 31 °C. Any exceedence of 35 °C for extended periods should induce hyperthermia in humans and other mammals, as dissipation of metabolic heat becomes impossible. While this never happens now, it would begin to occur with global-mean warming of about 7 °C, calling the habitability of some regions into question. With 11–12 °C warming, such regions would spread to encompass the majority of the human population as currently distributed. Eventual warmings of 12 °C are possible from fossil fuel burning. One implication is that recent estimates of the costs of unmitigated climate change are too low unless the range of possible warming can somehow be narrowed. Heat stress also may help explain trends in the mammalian fossil record.

climate impacts | global warming | mammalian physiology | paleoclimate

Recent studies have highlighted the possibility of large global warmings in the absence of strong mitigation measures, for example the possibility of over 7 °C of warming this century alone (1). Warming will not stop in 2100 if emissions continue. Each doubling of carbon dioxide is expected to produce 1.9–4.5 °C of warming at equilibrium, but this is poorly constrained on the high side (2, 3) and according to one new estimate has a 5% chance of exceeding 7.1 °C per doubling (4). Because combustion of all available fossil fuels could produce 2.75 doublings of CO_2 by 2300 (5), even a 4.5 °C sensitivity could eventually produce 12 °C of warming. Degassing of various natural stores of methane and/or CO_2 in a warmer climate (6, 7, 8) could increase warming further. Thus while central estimates of business-as-usual warming by 2100 are 3–4 °C, eventual warmings of 10 °C are quite feasible and even 20 °C is theoretically possible (9).

Such worst-case scenarios (along with possible surprise impacts) may be an important or even dominant factor in evaluating the risk of carbon emissions, analogous to situations in which people buy insurance (9). It is widely agreed that warmings of over 6 °C would have disastrous consequences for humankind, but it is very hard to pin down rigorously what the consequences would be, let alone quantify their costs. Thresholds have been proposed for ice sheet and rainforest collapse, for example, but predicting the timing or societal impacts of such events is challenging (10). Economic costs of warming are generally extrapolated from present-day data, but this is clearly unsatisfactory for climates so different from any in human experience. Inability to specify consequences of very large warmings is therefore a hurdle to rational decision-making on climate mitigation.

We propose that a somewhat neglected aspect of global warming, the direct impact on humans and other mammals in the form of heat stress, may provide a climate impacts benchmark that is relatively well-constrained by physical laws. We find a tolerance limit that is well above other oft-cited thresholds, such as the 2 °C target now adopted by many nations, but still reachable if things go badly, therefore an important linchpin for risk estimates.

Heat stress is already a leading cause of fatalities from natural phenomena (11, 12). While fatalities appear associated with warm nights (13), hot days alter the lifestyles and work productivity of those living at low latitudes (14). Both impacts will clearly worsen in warmer climates (15, 16), but most believe humans will simply adapt, reasoning that humans already tolerate a very wide range of climates today. But when measured in terms of peak heat stress—including humidity—this turns out to be untrue. We show that even modest global warming could therefore expose large fractions of the population to unprecedented heat stress, and that with severe warming this would become intolerable.

A resting human body generates ∼100 W of metabolic heat that (in addition to any absorbed solar heating) must be carried away via a combination of heat conduction, evaporative cooling, and net infrared radiative cooling. Net conductive and evaporative cooling can occur only if an object is warmer than the environmental wet-bulb temperature T_W, measured by covering a standard thermometer bulb with a wetted cloth and fully ventilating it. The second law of thermodynamics does not allow an object to lose heat to an environment whose T_W exceeds the object's temperature, no matter how wet or well-ventilated. Infrared radiation under conditions of interest here will usually produce a small additional heating; we err on the side of underestimating stress by neglecting this and assuming that solar heating will be avoided during peak heat stress.

While empirical heat indices such as "wet bulb globe temperature" (WBGT) are typically used to quantify heat stress, tolerance of a given index value varies significantly according to clothing, activity, and acclimatization (14). We consider T_W instead because, unlike other indices, it establishes a clear thermodynamic limit on heat transfer that cannot be overcome by such adaptations.

Humans maintain a core body temperature near 37 °C that varies slightly among individuals but does not adapt to local climate. Human skin temperature is strongly regulated at 35 °C or below under normal conditions, because the skin must be cooler than body core in order for metabolic heat to be conducted to the skin (17). Sustained skin temperatures above 35 °C imply elevated core body temperatures (hyperthermia), which reach lethal values (42–43 °C) for skin temperatures of 37–38 °C even for acclimated and fit individuals (18, 19, 20, 21). We would thus expect sufficiently long periods of $T_W > 35$ °C to be intolerable.

Results

Fig. 1*A* shows area-weighted histograms of three quantities estimated from recent observations over land areas (excluding high latitudes): near-surface air temperature T sampled at all

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Author contributions: S.C.S. designed research; S.C.S. and M.H. performed research; S.C.S. analyzed data; M.H. contributed new reagents/analytic tools; and S.C.S. and M.H. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

See Commentary on page 9483.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.0913352107/-/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.0913352107

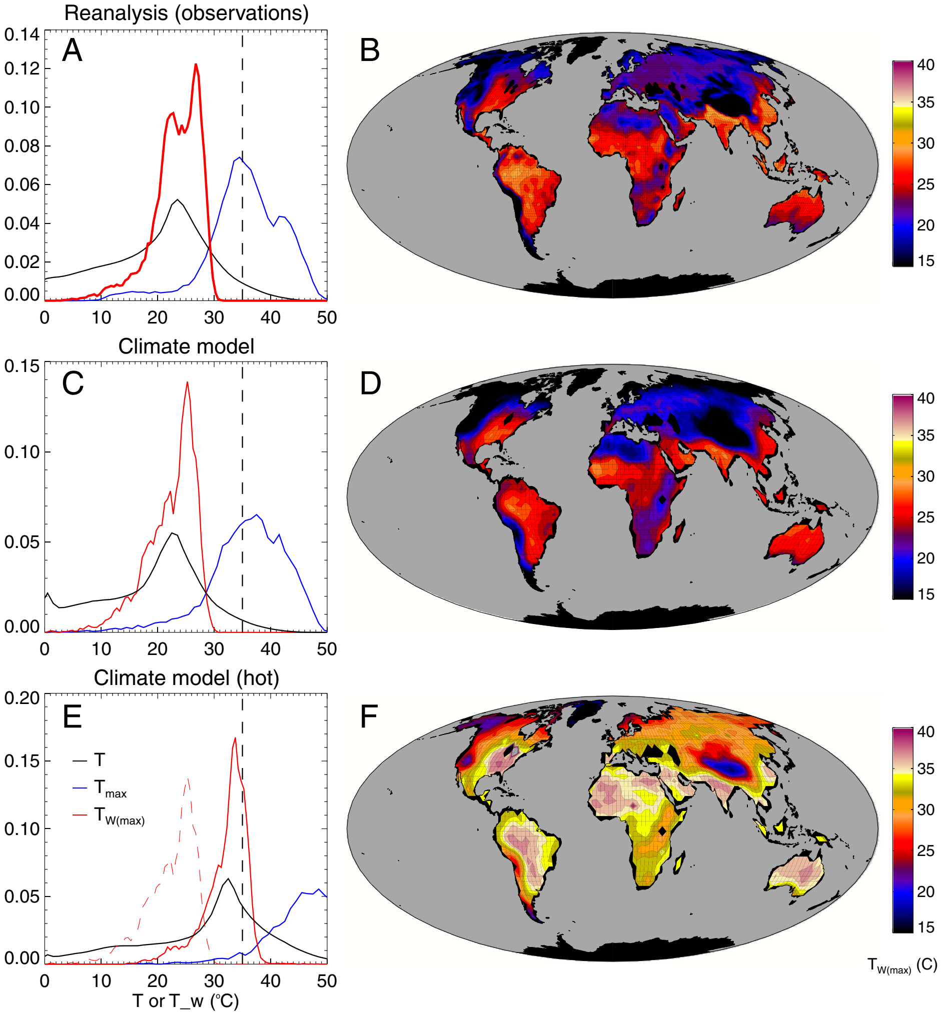

Fig. 1. (*A*) Histograms of 2-meter *T* (*Black*), $T_{\max}$ (*Blue*), and $T_{W(\max)}$ (*Red*) on land from 60S–60N during the last decade (1999–2008). "Max" histograms are annual maxima accumulated over location and year, while the *T* histogram is accumulated over location and reanalysis time. Data are from the ERA-Interim reanalysis 4xdaily product (similar results are found for the 50m level from the NCEP reanalysis, see *SI Text*). (*B*) Map of $T_{W(\max)}$. (*C* and *D*) Same as *A* and *B* but from a slab-ocean version of the CAM3 climate model that produces global-mean surface temperature close to modern values. (*E* and *F*) Same as *C* and *D* but from a high-CO_2 model run that produces a global-mean *T* 12 °C warmer; accounting for GCM bias, the $T_{W(\max)}$ distributions are roughly what would be expected with 10 °C of global-mean warming relative to the last decade (see text). Dashed line in *E* is $T_{W(\max)}$ reproduced from *C*. White land areas in *F* exceed 35 °C.

locations and times, the annual maximum $T_{\max}$ of this sampled in all locations and years, and annual maximum wet-bulb $T_{W(\max)}$. The distribution of T is broad, with a most-common value near 25 °C and a thin tail reaching to 50 °C (albeit with very few points above 40 °C). The distribution of $T_{\max}$ shows that a large majority of locations reaches 30 °C at some point during a typical year, and a few reach close to the 50 °C global record. Shifting either of these curves warmer by a few degrees would only move a tiny fraction of their area into uncharted territory (above 50 °C).

By constrast, the highest instantaneous T_W anywhere on Earth today is about 30 °C (with a tiny fraction of values reaching 31 °C). The most-common $T_{W(\max)}$ is 26–27 °C, only a few degrees lower. Thus, peak potential heat stress is surprisingly similar across many regions on Earth. Even though the hottest temperatures occur in subtropical deserts, relative humidity there is so low that $T_{W(\max)}$ is no higher than in the deep tropics (Fig. 1*B*). Likewise, humid midlatitude regions such as the Eastern United States, China, southern Brazil, and Argentina experience $T_{W(\max)}$ during summer heat waves comparable to tropical ones, even though annual mean temperatures are significantly lower. The highest values of T in any given region also tend to coincide with low relative humidity. Maxima of $T_{W(\max)}$ over the decade are higher than those shown by nearly 1 °C in most tropical regions and up to 2 °C in midlatitudes (though still never exceeding 31 °C), so our focus on annual events may underestimate the danger. Also, we use six-hourly data, which has a similar but smaller effect.

The likely reason for the apparent ceiling on T_W is a convective instability mechanism. We find essentially identical results for quantities near or 50 m above the surface (see *SI Text*). The equivalent potential temperature θ_e, a measure of air buoyancy and atmospheric stability, is a monotonic function of T_W and air pressure. Values that exceed a threshold determined by temperatures aloft will produce storm activity that cools air near the surface, limiting θ_e (22). The corresponding ceiling on T_W increases with pressure, explaining why $T_{W(\max)}$ is positively correlated with this ($r = 0.71$), and why equator-ward of 45 N/S, most locations where $T_{W(\max)} < 26$ °C are above 650 m elevation. Most other locations are in areas of very low storm activity and rainfall. Because $T_{W(\max)}$ and human population are both larger at low elevations and in rainy regions, 58% of the world's population in 2005 resided where $T_{W(\max)} \geq 26$ °C (population data obtained from Columbia University, sedac.ciesin.columbia.edu/gpw).

The simplest prediction of global warming's effect on $T_{W(\max)}$ is to assume a uniform upward shift of the T_W distribution. A 4 °C increase in T_W would then subject over half the world's population annually to unprecedented values and cut the "safety buffer" that now exists between the highest $T_{W(\mathrm{Max})}$ and 35 °C to roughly a quarter. A shift of 5 °C would allow $T_{W(\max)}$ to exceed 35 °C in some locations, and a shift of 8.5 °C would bring the most-common value to 35 °C. It has been similarly pointed out that a few degrees of warming will produce unprecedented temperature and agricultural stresses in the tropics (23).

The shift ratio of the $T_{W(\max)}$ distribution per °C of global-mean T might be different from unity, however, or the shape of the distribution might change—due either to changes in relative humidity [though unlikely a priori and not observed with recent warming (24)], dynamics, or spatially inhomogeneous warming. To investigate, we ran the Community Atmospheric Model version 3.1 coupled to a mixed-layer ocean model, with a variety of CO_2 levels (see *SI Text*). Fig. 1 *C* and *D* shows the same quantities as in Fig. 1 *A* and *B*, from a simulation having a global-mean surface temperature close to observed. The simulated and observed distributions have similar shape. $T_{W(\max)}$ is biased 1–2 °C too low (due to a low bias in humidity during heat extremes), whereas $T_{W(\max)}$ is too high in some midlatitude regions, but the simulation seems sufficient for the intended purpose.

Comparison of the peak in $T_{W(\max)}$ vs. global temperature among different model simulations (Fig. 2) shows that $T_{W(\max)}$ near the surface consistently tracks tropical surface temperature. The rise rate is then only 0.75 °C per 1 °C increase in global-mean temperature, because the tropics warms more slowly than higher latitudes. One example simulation, globally warmer than the one in Fig. 1 *C* and *D* by about 12 °C, is shown in Fig. 1 *E* and *F*. The $T_{W(\max)}$ distribution is slightly narrower but not greatly changed in this simulation except for an upward shift of 9 °C, or about 7 °C above observations. Its $T_{W(\max)}$ distribution is therefore what we might expect with a global-mean warming of approximately 10 °C. In this simulation, several regions experience 35 °C wet-bulb values each year, and even Siberia reaches values exceeding anything in the present-day tropics.

The ability of climate models to represent extremes or the details of Fig. 1*F* is arguable. However, the link of $T_{W(\max)}$ to tropical temperatures is a plausible consequence of the dynamical links between air in the tropics and aloft in midlatitudes (25), and the polar amplification of warming predicted here compares reasonably to that observed over the twentieth century. Thus, the 0.75 factor obtained here should not be too far off.

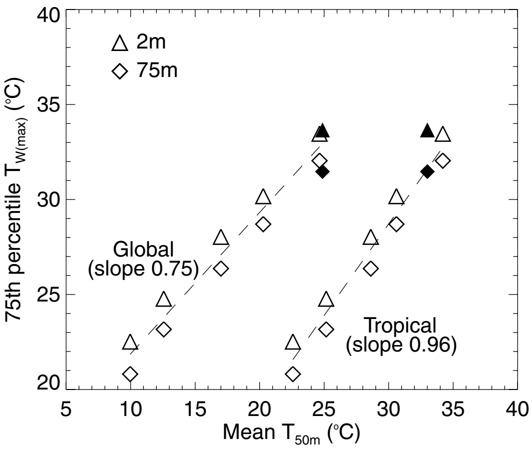

Fig. 2. The 75th percentile value of $T_{W(\max)}$ (a measure of the peak occurrence value) at two or 75 meters above ground vs. global or tropical mean 75-m temperature in CAM3 simulations. Solid symbols are for a simulation representing possible Eocene conditions. Dashed lines show best linear fits, with slopes given (Eocene run not included in fit).

Discussion

Could humans survive $T_W > 35$ °C? Periods of net heat storage can be endured, though only for a few hours (see *SI Text*) and with ample time needed for recovery. Unfortunately, observed extreme-T_W events ($T_W > 26$ °C) are long-lived: Adjacent nighttime minima of T_W are typically within 2–3 °C of the daytime peak, and adjacent daily maxima are typically within 1 °C. Conditions would thus prove intolerable if the peak T_W exceeded, by more than 1–2 °C, the highest value that could be sustained for at least a full day. Furthermore, heat dissipation would be very inefficient unless T_W were at least 1–2 °C below skin temperature (see *SI Text*), so to sustain heat loss without dangerously elevated body temperature would require T_w of 34 °C or lower. Taking both of these factors into account, we estimate that the survivability limit for peak six-hourly T_W is probably close to 35 °C for humans, though this could be a degree or two off. Similar limits would apply to other mammals but at various thresholds depending on their core body temperature and mass.

Mammals have survived past warm climates; does this contradict our conclusions? The last time temperatures approached values considered here is the Paleogene, when global-mean temperature was perhaps 10 °C (26) and tropical temperature perhaps 5–6 °C warmer than modern (27, 28), implying T_W of up to 36 °C with a most-common $T_{W(\mathrm{Max})}$ of 32–33 °C. This would still leave room for the survival of mammals in most locations, especially if their core body temperatures were near the high end of those of today's mammals (near 39 °C). Transient temperature spikes, such as during the PETM or Paleocene-Eocene Thermal Maximum (26), might imply intolerable conditions over much broader areas, but tropical terrestrial mammalian records are too sparse to directly test this. We thus find no inconsistency with our conclusions, but this should be revisited when more evidence is available.

On evolutionary time scales we might expect taxa stressed by heat to undergo adaptive increases in surface-area-to-mass ratio to aid heat dissipation relative to metabolic rate. While data from the tropics are sparse, the major mammalian taxa heavier than 1 kg—carnivora, artiodactyls, and perissodactyls—were indeed about a factor of 10 less massive on average during the early Eocene than during cooler, later periods (29, 30), part of a growth trend known as "Cope's law" (31). Similarly, "transient dwarfing" of midlatitude mammals occurred during the PETM (32). Both phenomena have been attributed to changes in food supply but could also be explained as an adaptation to changing heat stress.

In principle humans can devise protections against the unprecedented heat such as much wider adoption of air conditioning, so one cannot be certain that $T_{W(\mathrm{Max})} = 35$ °C would be uninhabitable. But the power requirements of air conditioning would soar; it would surely remain unaffordable for billions in the third world and for protection of most livestock; it would not help the biosphere or protect outside workers; it would regularly imprison people in their homes; and power failures would become life-threatening. Thus it seems improbable that such protections would be satisfying, affordable, and effective for most of humanity.

We conclude that a global-mean warming of roughly 7 °C would create small zones where metabolic heat dissipation would for the first time become impossible, calling into question their suitability for human habitation. A warming of 11–12 °C would expand these zones to encompass most of today's human population. This likely overestimates what could practically be tolerated: Our limit applies to a person out of the sun, in gale-force winds, doused with water, wearing no clothing, and not working. A global-mean warming of only 3–4 °C would in some locations halve the margin of safety (difference between $T_{W\max}$ and 35 °C) that now leaves room for additional burdens or limitations to cooling. Considering the impacts of heat stress that occur already, this would certainly be unpleasant and costly if not debilitating. More detailed heat stress studies incorporating physiological response characteristics and adaptations would be necessary to investigate this.

If warmings of 10 °C were really to occur in next three centuries, the area of land likely rendered uninhabitable by heat stress would dwarf that affected by rising sea level. Heat stress thus deserves more attention as a climate-change impact.

The onset of $T_{W\max} > 35\,^{\circ}\mathrm{C}$ represents a well-defined reference point where devastating impacts on society seem assured even with adaptation efforts. This reference point constrasts with assumptions now used in integrated assessment models. Warmings of 10 °C and above already occur in these models for some realizations of the future (33). The damages caused by 10 °C of warming are typically reckoned at 10–30% of world GDP (33, 34), roughly equivalent to a recession to economic conditions of roughly two decades earlier in time. While undesirable, this is hardly on par with a likely near-halving of habitable land, indicating that current assessments are underestimating the seriousness of climate change.

Methods

The observational estimates of wet-bulb and dry-bulb temperature extremes were derived from six-hourly 2-meter temperature, humidity, and pressure data from the ERA-Interim dataset. Results from this dataset were corroborated by similar results from the NCEP-DOE reanalysis II dataset. Simulations of present-day and hot climates were performed using the NCAR (National Center for Atmospheric Research) Community Atmosphere Model with varying levels of carbon dioxide. Quantities were computed from the model using the same variables and formula as for the reanalysis data.

A more detailed explanation and justification of data and methods is given in the *SI Text*. Further discussions can also be found there to support claims as to the limits of tolerable heat stress.

ACKNOWLEDGMENTS. S.C.S. completed part of this work while at Yale University; he thanks G. Havenith and T. Kjellstrom for useful discussions. We acknowledge the Columbia University CIESIN, the United Nations FAO, and the CIAT for providing population data, and the ECMWF and NCEP/NCAR/NCDC for making the reanalysis datasets available. M.H. thanks the Institute of Geological and Nuclear Sciences in New Zealand for providing a conducive work environment while he was on a sabbatical from Purdue University and the National Science Foundation for providing funding for research under Grants 090278-ATM and 0902882-OCE.

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