

An adaptability limit to climate change due to heat stress

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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 CO₂ 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 CO₂ 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. 1A 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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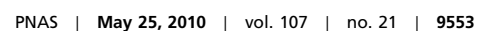
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increase in T_W would then subject over half the world's population annually to unprecedented values and cut the "safety buffer" that now exists between the highest $T_{W(\text{Max})}$ and 35 °C to roughly a quarter. A shift of 5 °C would allow $T_{W(\text{max})}$ 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 $T_{W(\text{max})}$ 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. $T_{W(\text{max})}$ is biased 1–2 °C too low (due to a low bias in humidity during heat extremes), whereas $T_{W(\text{max})}$ is too high in some midlatitude regions, but the simulation seems sufficient for the intended purpose.

Comparison of the peak in $T_{W(\text{max})}$ vs. global temperature among different model simulations (Fig. 2) shows that $T_{W(\text{max})}$ near the surface consistently tracks 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 $T_{W(\text{max})}$ 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 $T_{W(\text{max})}$ 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 $T_{W(\text{max})}$ 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.

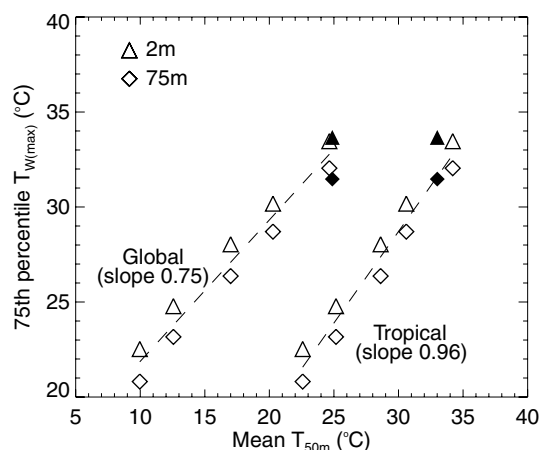


Fig. 2. The 75th percentile value of $T_{W(\text{max})}$ (a measure of the peak occurrence value) at two or 75 meters above ground vs. global or tropical mean 75-m temperature in CAM3 simulations. Solid symbols are for a simulation representing possible Eocene conditions. Dashed lines show best linear 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 $T_{W(\text{Max})}$ 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 $T_{W(\text{Max})} = 35$ °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 $T_{W(\text{max})}$ 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 $T_{W\max} > 35^\circ\text{C}$ represents a well-defined reference point where devastating impacts on society seem assured even with adaptation efforts. This reference point contrasts 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.

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- Sokolov AP, et al. (2009) Probabilistic forecast for 21st century climate based on uncertainties in emissions (without policy) and climate parameters. *J Climate* 22:5175–5204.
- Roe GH, Baker MB (2007) Why is climate sensitivity so unpredictable?. *Science* 318:629–632.
- Knutti R, Hegerl GC (2008) The equilibrium sensitivity of the earth's temperature to radiation changes. *Nat Geosci* 1:735–742.
- Meinshausen M, et al. (2009) Greenhouse-gas emission targets for limiting global warming to 2 degrees c. *Nature* 458:1158–U96.
- Montenegro A, Brovkin V, Eby M, Archer D, Weaver AJ (2007) Long term fate of anthropogenic carbon. *Geophys. Res. Lett.* 34:L19707.
- Friedlingstein P, et al. (2006) Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison. *J Climate* 19:3337–3353.
- Williams JW, Jackson ST, Kutzbach JE (2007) Projected distributions of novel and disappearing climates by 2100 AD. *Proc Natl Acad Sci USA* 104:5738–5742.
- Ise T, Dunn AL, Wofsy SC, Moorcroft PR (2008) High sensitivity of peat decomposition to climate change through water-table feedback. *Nat Geosci* 1:763–766.
- Weitzman ML (2009) On modeling and interpreting the economics of catastrophic climate change. *Rev Econ Stat* 91:1–19.
- Alley RB, et al. (2003) Abrupt climate change. *Science* 299:2005–2010.
- Kovats RS, Hajat S (2008) Heat stress and public health: A critical review. *Annu Rev Publ Health* 29:41–55.
- Borden KA, Cutter SL (2008) Spatial patterns of natural hazards mortality in the United States. *Int J Health Geogr* 7 Art. No. 64.
- Karl TR, et al. (1993) A new perspective on recent global warming-asymmetric trends of daily maximum and minimum temperatures. *B Am Meteorol Soc* 74:1007–1023.
- Kjellstrom T, Kovats RS, Lloyd SJ, Hold T, Tol RSJ (2008) The direct impact of climate change on regional labour productivity. (ESRI). Working paper 260 27 pp.
- Delworth TL, Mahlman JD, Knutson TR (1999) Changes in heat index associated with CO₂-induced global warming. *Climatic Change* 43:369–386.
- Diffenbaugh NS, Giorgi F, Pal JS (2008) Climate change hotspots in the United States. *Geophys Res Lett* 35:L16709.
- McNab BK (2002) *The Physiological Ecology of Vertebrates: A View from Energetics* (Cornell Univ Press, Ithaca, NY) p 525.
- Pandolf KB, Goldman RF (1978) Convergence of skin and rectal temperatures as a criterion for heat tolerance. *Aviat Space Environ Med* 49:1095–1101.
- Bynum GD, et al. (1978) Induced hyperthermia in sedated humans and the concept of critical thermal maximum. *Am J Physiol Regulatory Integrative Comp Physiol* 235:228–236.
- Bouchama A, et al. (2005) Inflammatory, hemostatic, and clinical changes in a baboon experimental model for heatstroke. *J Appl Physiol* 98:697–705.
- Mehnert P, et al. (2000) Prediction of the average skin temperature in warm and hot environments. *Eur J Appl Physiol* 82:52–60.
- Emanuel KA, Neelin JD, Bretherton CS (1994) On large-scale circulations in convecting atmospheres. *Q J Roy Meteor Soc* 120:1111–1143.
- Battisti DS, Naylor RL (2009) Historical warnings of future food insecurity with unprecedented seasonal heat. *Science* 323:240–244.
- Willett KM, Gillett NP, Jones PD, Thorne PW (2007) Attribution of observed surface humidity changes to human influence. *Nature* 449:710–U6.
- Pauluis O, Czaja A, Korty R (2008) The global atmospheric circulation on moist isentropes. *Science* 321:1075–1078.
- Zachos JC, Pagani M, Sloan L, Thomas E, Billups K (2001) Trends, rhythms, and aberrations in global climate 65 ma to present. *Science* 292:686–93.
- Pearson PN, et al. (2007) Stable warm tropical climate through the Eocene epoch. *Geology* 35:211–214.
- Head JJ, et al. (2009) Giant boid snake from the Palaeocene neotropics reveals hotter past equatorial temperatures. *Nature* 457:715–U4.
- Smith FA, et al. (2004) Similarity of mammalian body size across the taxonomic hierarchy and across space and time. *Am Nat* 163:672–691.
- Alroy J, Koch PL, Zachos JC (2000) Global climate change and North American mammalian evolution. *Paleobiology* 26:259–288.
- Alroy J (1998) Cope's rule and the dynamics of body mass evolution in North American fossil mammals. *Science* 280:731–734.
- Gingerich P (2006) Environment and evolution through the paleocene-eocene thermal maximum. *Trends Ecol Evol* 21:246–253.
- Hope C (2006) The marginal impact of CO₂ from PAGE2002: An integrated assessment model incorporating the IPCC's five reasons for concern. *Integ Assessment J* 6:19–56.
- Nordhaus W, Boyer J (2000) *Warming the World: Economics Models of Global Warming* (MIT Press, Cambridge, MA).