Supporting Information

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SI Text

Reanalysis Data. The estimation of temperature extremes near the ground is difficult. Extreme values in instrumental data are susceptible to noise and bad data values and require very careful data quality control. Modest random and sampling errors can inflate extremes. We thus rely on reanalysis products, where forecast fields are used to identify and eliminate bad data values, and some degree of spatial consistency of results is enforced by the assimilation process. Such analyses are also spatially complete, which is not true of the raw observations.

Assimilation of near-surface observations has proven difficult. The new ERA-Interim dataset has improved on past efforts in a number of respects including the incorporation of many new data types using a 4DVAR approach, with finer model resolution and some bias correction to help harmonise different observation types (1). Nonetheless it is possible that extremes are underestimated in reanalysis datasets.

Due to the uncertainty associated with any data product, in addition to the ERA-Interim 2-meter data, we have examined data from the same ten years of the original NCEP reanalysis on the lowest analysis level (sigma $= 0.995$, approximately 50 meters above ground at sea level), shown in Fig. S1. We also examined 2-meter data from the NCEP-DOE reanalysis II, but these showed some apparently spurious features and agreed less well with either the other datasets or the CAM3 simulations. Regional details are somewhat dataset-specific, with NCEP data showing higher values in the eastern US than the Amazon, while the Amazon reaches the highest values globally in the ERA data. Fine geographic details would also vary from year to year. While the two datasets and models differ by a few °C regionally, and do not agree on which regions on Earth reach the highest T_W values, all show similar broad patterns and probability distributions of the variables.

Results shown in this article are not sensitive to the years shown, and in fact look quite similar (though slightly noisier) if any single year is used. Wet bulb temperatures are computed using a recently published method (2) employing a calculation of equivalent temperature to achieve an accuracy of better than 0.2 °C.

Model Description. In this study the Community Atmospheric Model, version 3.1 is used (3). This model is coupled to the standard Community Land Model (CLM), a slab ocean with fixed internal heat transport, and present day ice sheets. A suite of simulations at T42 spectral resolution, with the Eulerian dynamical core, spanning a range of $p\mathrm{CO}_2$ from 280 to 4480 ppmv, was performed in a well established approach (4). Solar constant, aerosols, non-CO_2 trace gas constituents and all other parameters were held at the default modern CAM values (3) in two of the simulations. In three other simulations, the solar constant was set at 1365 $\mathrm{W\,m^{-2}}$ and aerosol radiative effects were set to zero, and other trace gas concentrations were set to pre-Industrial conditions. Finally, one simulation used estimated conditions for the Eocene (Eocene geography, $p\mathrm{CO}_2$ of 2240 ppmv, no ice sheets).

These different configurations were used in order to assess the sensitivity of results to difficult-to-constrain parameters such as future solar constant and non-CO_2 greenhouse gas concentration. The results in Fig. 2 indicate that the scaling between global or tropical mean temperature and $T_{W\,\max}$ is robust to these details.

Heat Storage. Humans can endure negative cooling (heat storage) for brief periods by temporarily raising their core body temperature. In principle this allows survival of 35 °C wet bulb temperatures, but in practice this appears doubtful for any extended interval.

With 100 W of heat generation (a typical resting value), body mass of 75 kg, and specific heat of 3.5 $\mathrm{J\,g^{-1}\,K^{-1}}$, body temperature would increase by about one degree every 45 minutes. It would thus increase from a normal value of 37 °C to 42 °C—a value that begins to cause permanent tissue damage—in roughly four hours, leading to the tolerance times given in the main text.

Given standard values for human resting metabolic rate, mass, specific heat, and surface area, wet bulb temperatures of 37 °C would lead to irreversible heat trauma, associated with sustained core temperatures of 42 °C (, 5, 6, 7) within four to six hours of exposure. The presence of solar or infrared heating could shorten this time even if direct sunlight is avoided, especially if there are nearby solar-heated surfaces radiating at temperatures above ambient or scattered sunlight cannot be avoided.

Heat stress and water needs. When T_W approaches comfortable skin temperatures, the dissipation of heat becomes difficult due to increasing water requirements and decreasing gradients of heat available to drive the heat away from the body. Here we present a simple calculation to illustrate this. Much more extensive modeling of the human body may be found in other references cited in this article.

Excluding radiation, the sensible heat flux S may be written approximately as

$$S = k(T_{\mathrm{skin}} - T) \qquad \textbf{[S1]}$$

while the total (F, latent L plus sensible) flux is approximately

$$S + L = k(T_{\mathrm{skin}} - T_W) = F \qquad \textbf{[S2]}$$

for moderate temperature differences. Solving this gives

$$L = F\frac{T - T_W}{T_{\mathrm{skin}} - T_W} \qquad \textbf{[S3]}$$

$$k = \frac{F}{T_{\mathrm{skin}} - T_W} \qquad \textbf{[S4]}$$

Typically, T is a few degrees higher than T_W for the largest values of T_W (mean is 2.4 °C and 95% are within 5 °C, for $T_W >$ 26 °C in today's climate). So for example, if $T_{\mathrm{skin}} = 35$, $T = 38$ °C and $T_W = 34$ °C, we obtain $L = 4F$, which is over half a liter per hour for a resting person. This is much more than a resting person would perspire on a summer day now, but less than athletes can lose during competition. If we consider walking at a modest pace of 5 km/hr, or $F \sim 500$ W, then three litres of perspiration must be evaporated per hour, which exceeds what athletes typically consume even for short bursts but is physiologically possible. This illustrates how hard it would be to do any work as T_W approaches 35 °C. Note that these numbers ignore radiative heating.

Further difficulties would arise due to the difficulty of evaporating this much water, even if it could be consumed and perspired. If we compare $T_W = 24$ °C and $T_{\mathrm{skin}} = 32$ °C (a typical warm summer day), with $T_W = 34$ °C and $T_{\mathrm{skin}} = 35$ °C in a hot climate, we see from Eq. **S4** above that k must be roughly an order of magnitude higher in the hot climate than in today's to achieve the same F. This would require, for instance, increasing the wind speed from 5 m/s to 40 m/s or some equivalent change.

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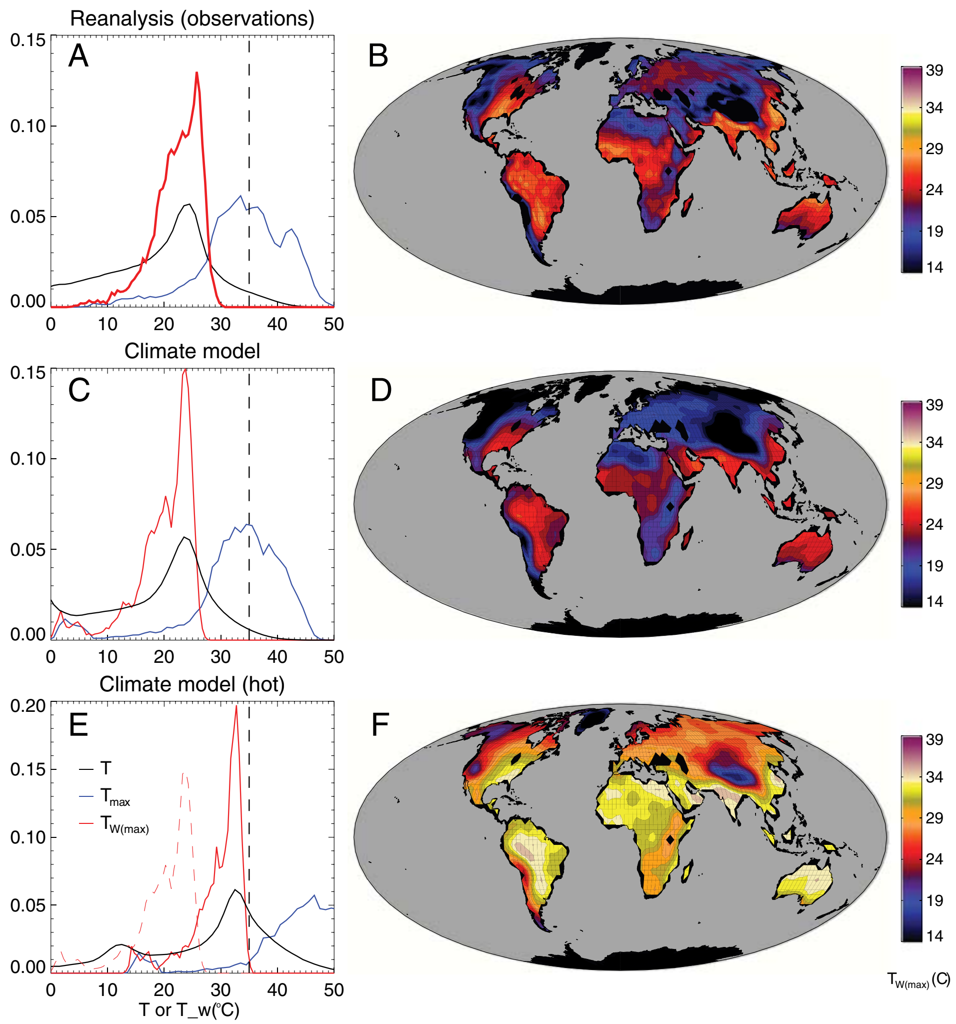

Fig. S1. As in Fig. 1, but observations (*A* and *B*) are from the sigma = 0.995 level (roughly 50 meters above ground) of the NCEP-NCAR reanalysis. Model calculations (*C–F*) are taken from the sigma = 0.9925 level of the GCM (roughly 75 meters above ground) for comparison. Accounting for bias in the GCM and the difference in levels, the $T_{W(\mathrm{max})}$ values for the "hot" simulation roughly correspond to those expected at 50 meters with 7–8 °C of global-mean warming.