Temperature and humidity based projections of a rapid rise in global heat stress exposure during the 21st century

Supplemental material

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Daily maximum wet bulb temperature is estimated by calculating the wet bulb temperature at the time of highest air temperature. We compared this daily maximum to six-hourly wet bulb temperatures and found them to be similar (less than 0.1°C different) at the highest wet bulb temperatures (Supplementary Figure 1). The use of the NCEP Reanalysis II dataset for baseline wet bulb temperatures may introduce some bias, especially in data-sparse regions. We estimate this bias by comparing wet bulb temperatures calculated using the NCEP Reanalysis II to nearby station data in a variety of countries and regions (Supplementary Figure 2). We find that the NCEP bias is generally not statistically significant and also negative (meaning NCEP is too cool), indicating that the bias, when it is significant, will make our exposure projections more conservative. Given the unknown and possibly poor quality of station data in many regions, we choose not to bias-correct the NCEP-calculated wet bulb temperatures.

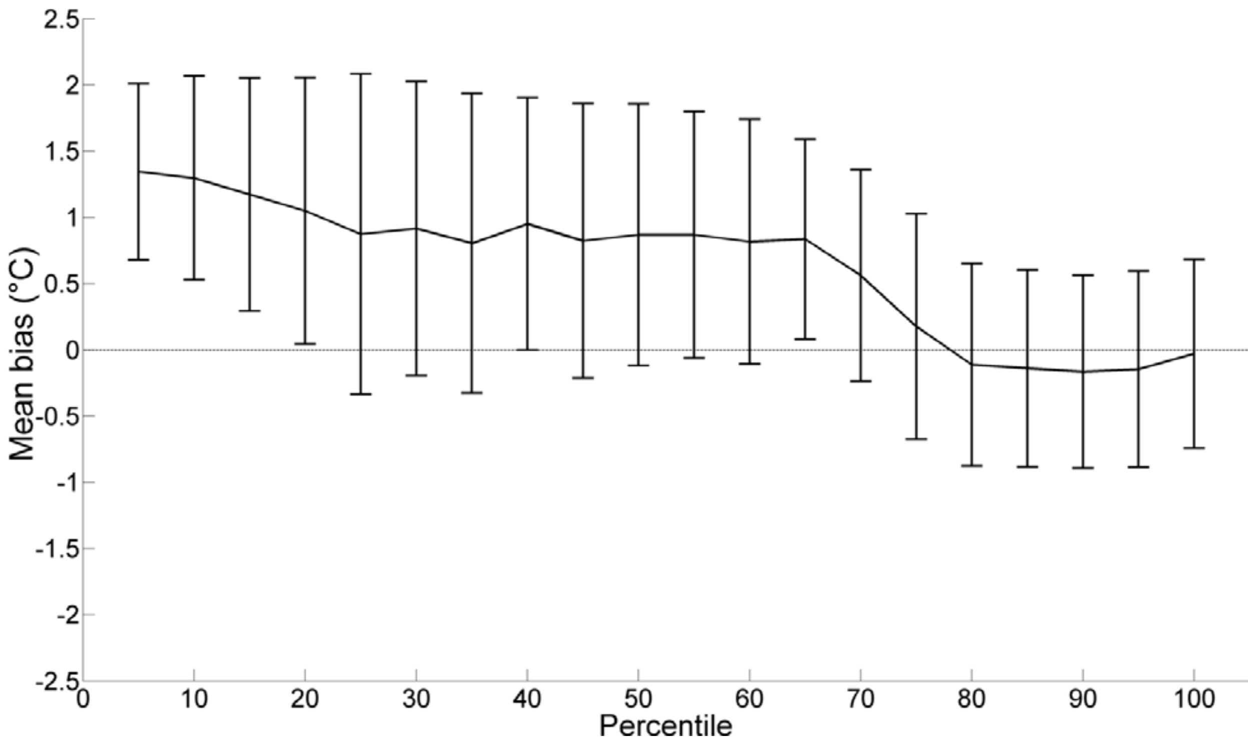
While wet bulb temperature increases are projected to be relatively consistent around the world, the driving changes in specific humidity and temperature vary between regions, as shown in Supplementary Figure 3.

Exposure to extreme wet bulb temperatures can be drastically reduced by following the RCP 4.5 scenario as opposed to RCP 8.5. Supplementary Figure 4 shows the projected exposure in person-days to wet bulb temperatures over 33°C, 34°C, and 35°C under both RCP 4.5 and RCP 8.5. Wet bulb temperatures higher than 32°C are relatively rare under RCP 4.5, and are confined to small geographical areas, mostly in India and the Amazon, whereas under RCP 8.5 they are projected to be widespread (Supplementary Figure 5). In addition, wet bulb temperatures of 34 - 35°C are unlikely to occur regularly under RCP 4.5, as shown in Supplementary Figure 6.

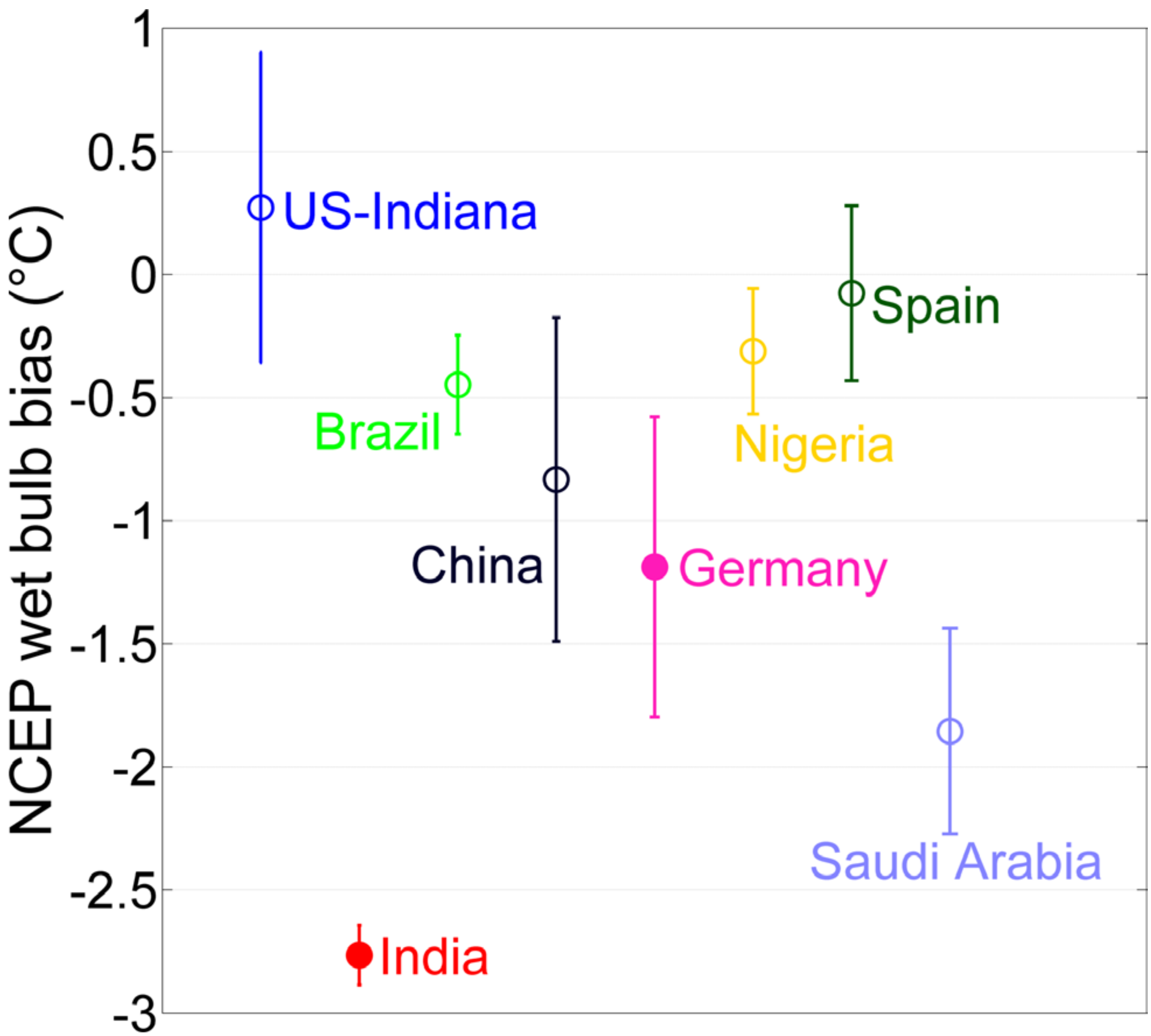
Five spatially explicit population scenarios were used in this study[2]. Each scenario makes different assumptions about economic, technological, and demographic change, which result in different global population growth and migration trajectories. Supplementary Figure 7 shows the decadal mean global population under each scenario.

1. Fischer, E. M. & Knutti, R. Robust projections of combined humidity and temperature extremes. *Nat. Clim. Chang.* **3,** 126–130 (2012).

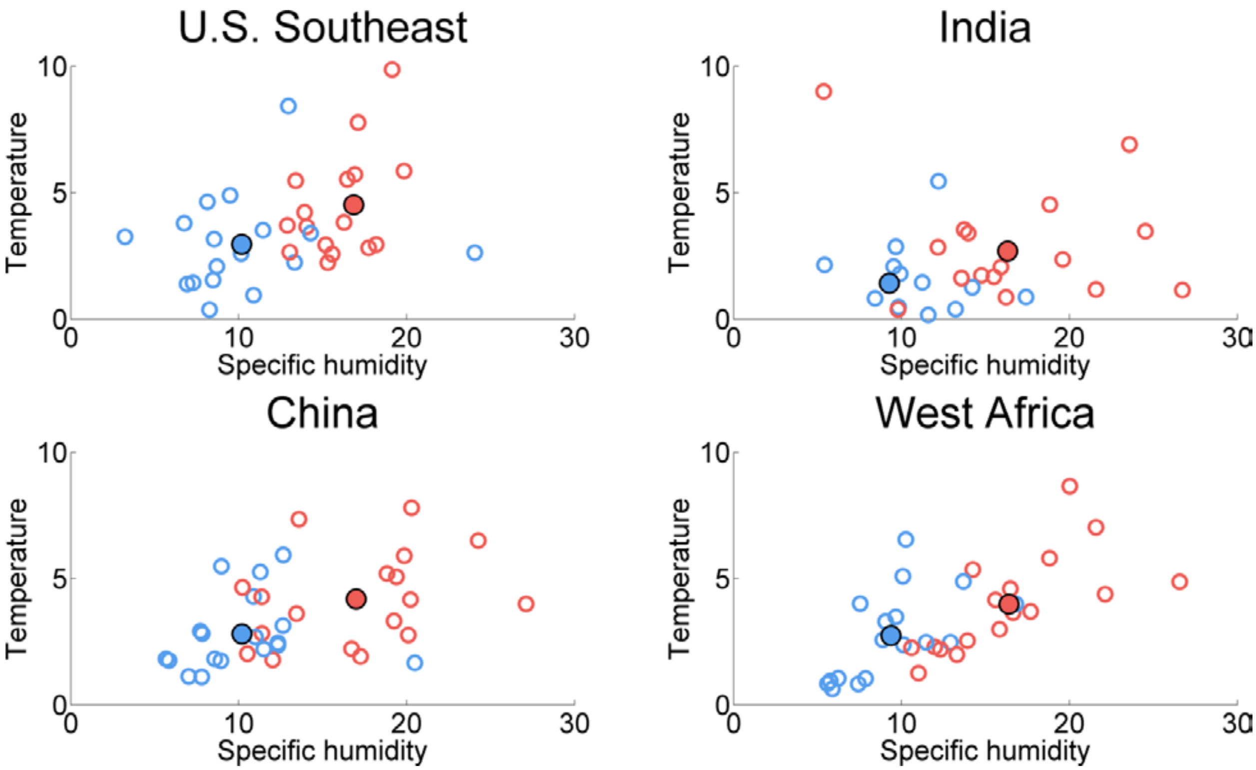
2. O'Neill, B. *et al.* A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Clim. Change* **122,** 387–400 (2014).



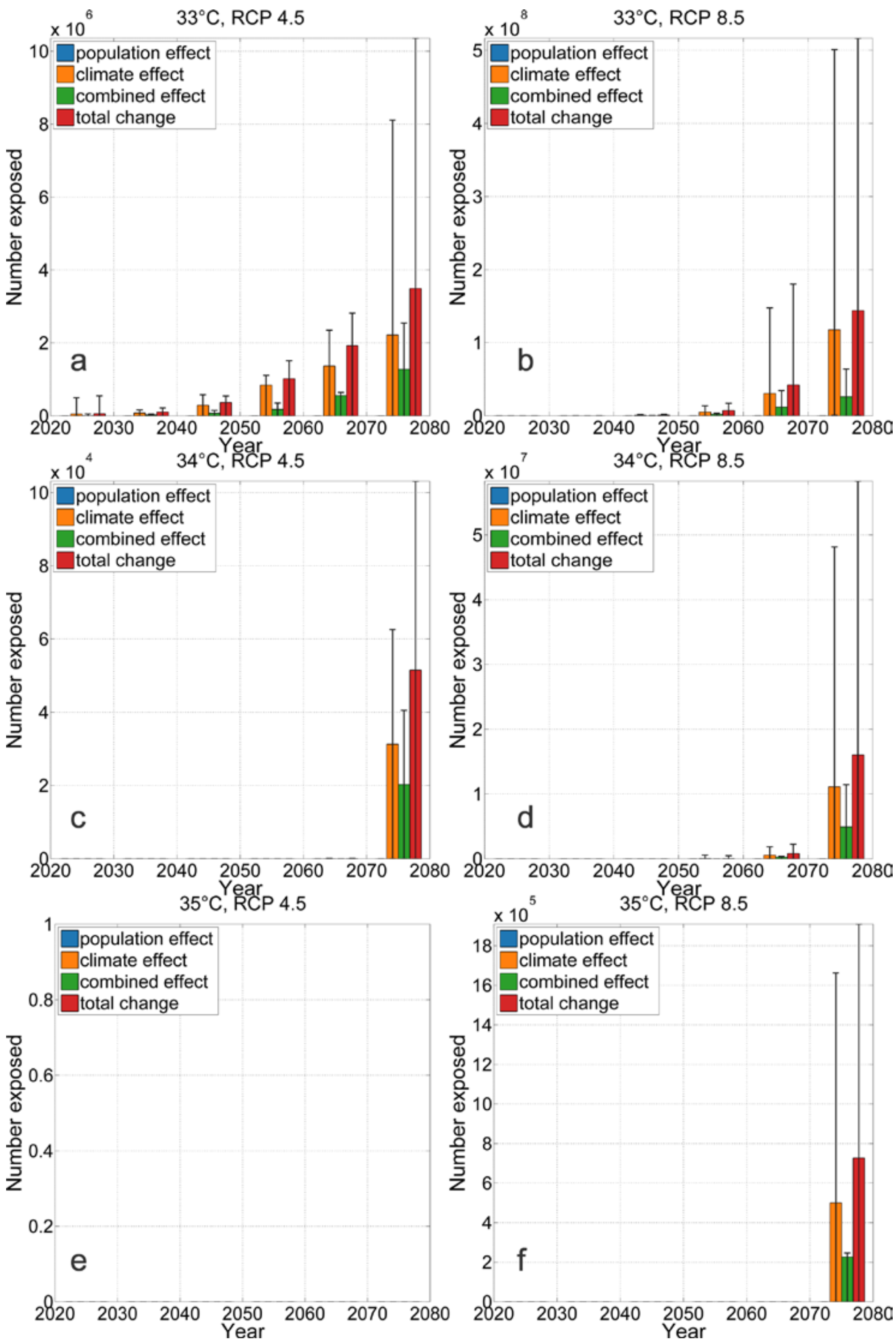
Supplementary Figure 1: Mean difference between the wet bulb temperature computed at the time of highest air temperature and the daily maximum wet bulb temperature computed using six-hourly data across the wet bulb temperature distribution for one GCM (BNU-ESM). At higher percentiles, the difference between the two methods becomes small (less than 0.1℃).Error bars show the standard deviation of the error across computed wet bulb temperatures in each percentile bin.



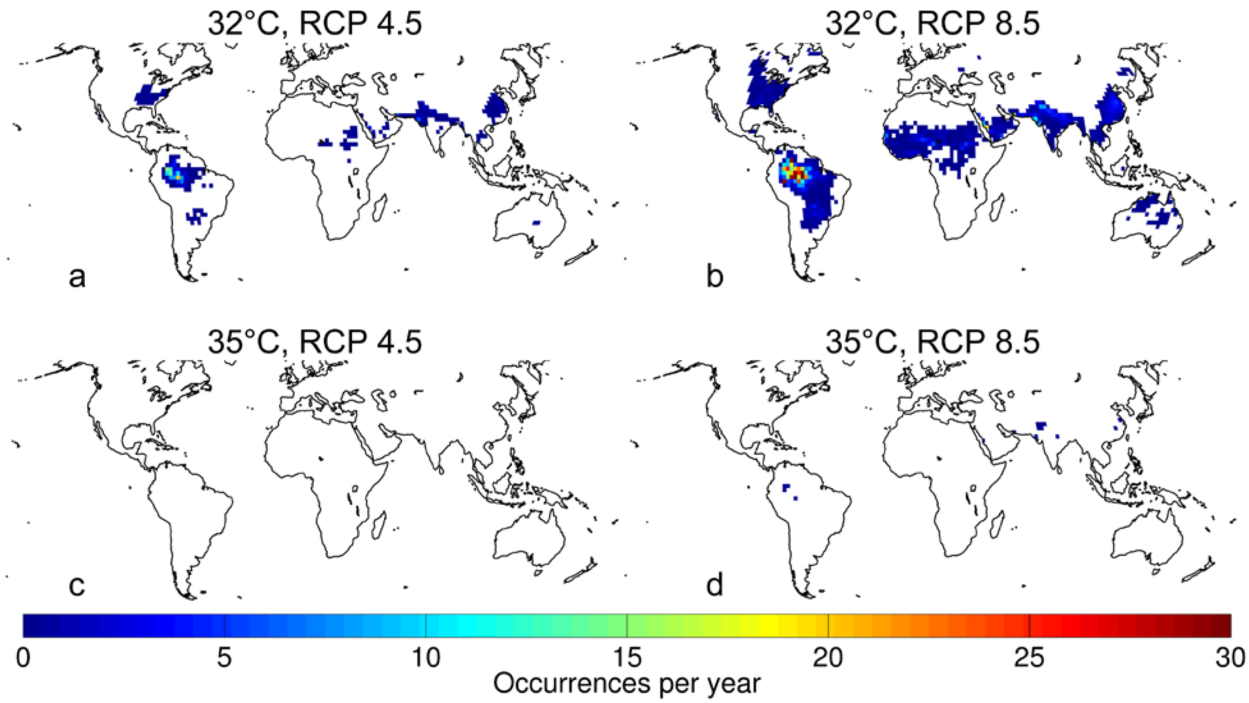
Supplementary Figure 2: Mean bias in daily maximum wet bulb temperature between regionally-aggregated weather station data and the NCEP Reanalysis II. All available weather station records between 2010 and 2017 were used, and bias was calculated for each NCEP grid cell using the stations geographically contained within the grid cell region. Error bars show the mean difference in the standard deviation bias across daily wet bulb temperatures from each NCEP II grid cell and all corresponding stations, averaged across all grid cells in the specified country between each station's time series and that for the corresponding NCEP grid cell. Filled markers indicate a statistically significant mean bias (Student t-test, 95th percentile).



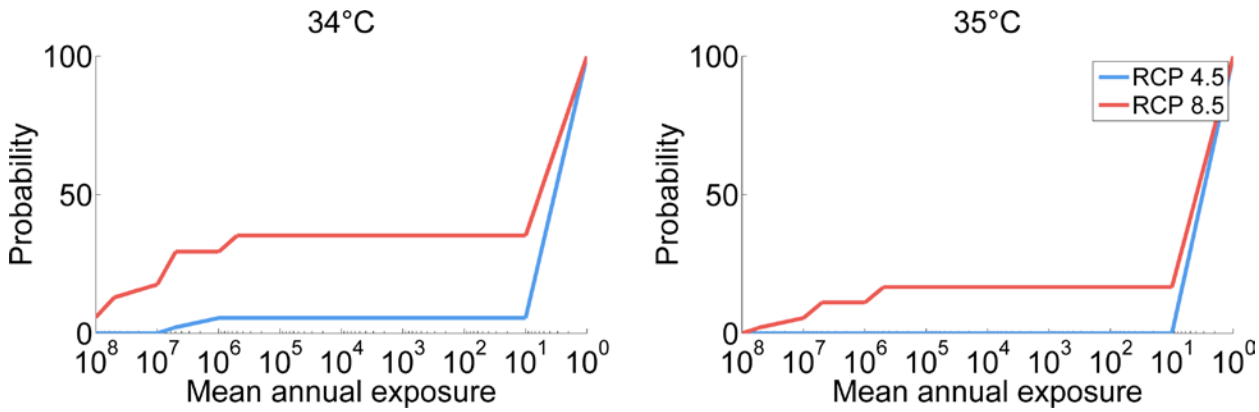
Supplementary Figure 3: Projected change in air temperature (°C) and specific humidity (percent) on the 100 highest wet bulb days in 2060-2080 relative to 1985-2005 for each GCM (un-filled circles) and the multi-GCM mean (filled circles) for RCP 4.5 (blue) and RCP 8.5 (red). Both temperature and specific humidity changes are relatively consistent in the four regions despite differences in geography and synoptic patterns during heat stress events.



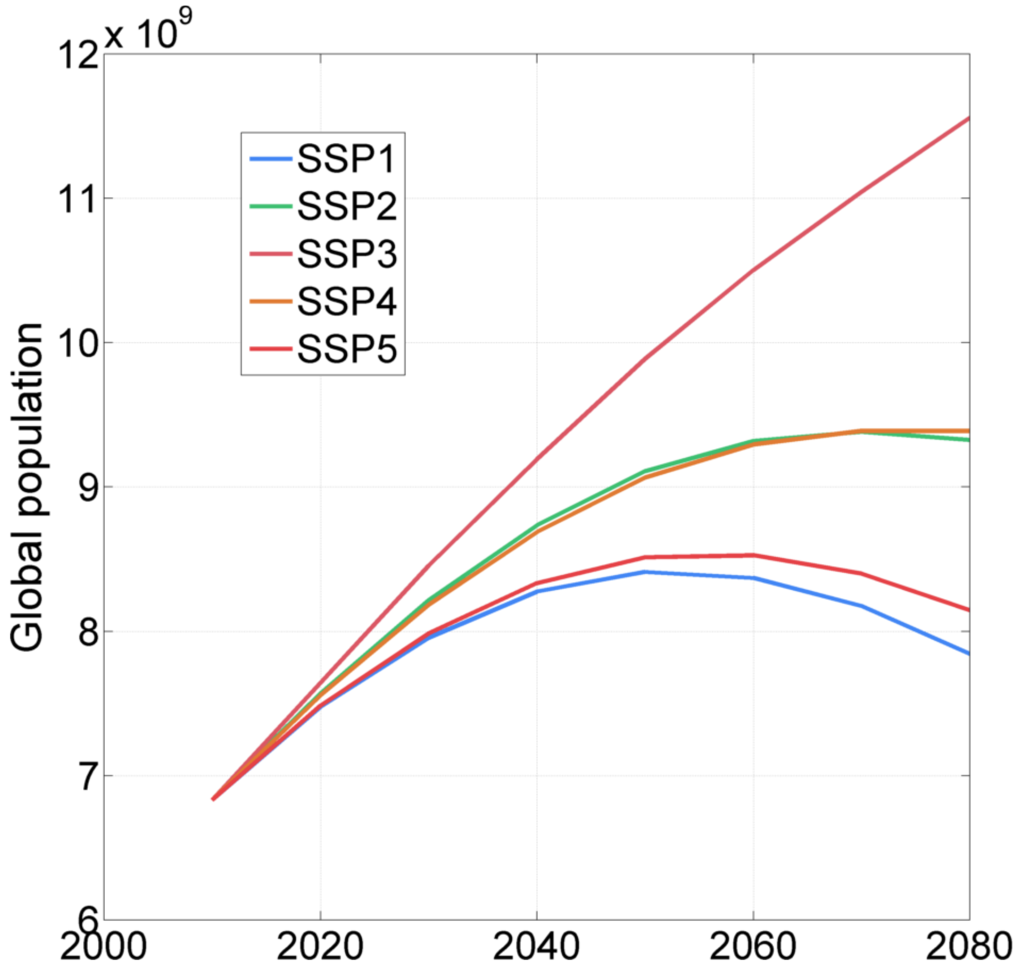
Supplemental Figure 4: Projected global annual mean exposure in person-days to wet bulb temperatures above 33°C (a-b), 34°C (c-d) and 35°C (e-f) under RCP 4.5 (left panels) and RCP 8.5 (right panels). Note the large differences in the y-axis scale between RCP 4.5 and RCP 8.5 plots; following the lower emissions scenario results in drastically lower exposure to the highest wet bulb temperatures. Error bars show the 10th – 90th percentile range across GCMs and SSPs.



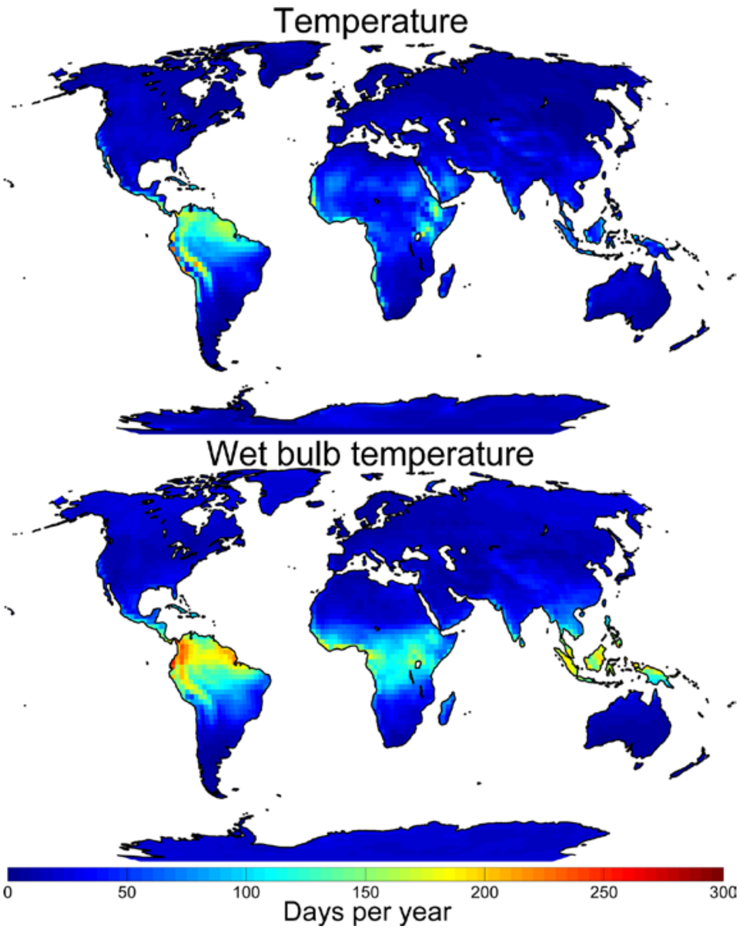
Supplementary Figure 5: Multi-GCM mean number of days in 2070 – 2080 with wet bulb temperatures above 32°C (top row) and 35°C (bottom row). Left panels show results under RCP 4.5 and right panels under RCP 8.5. Wet bulb temperatures above 35°C are limited to small geographic areas, even under RCP 8.5, but some of these regions – in particular northeastern India and eastern China – are densely populated. RCP 4.5 completely avoids wet bulb temperatures of 35°C through 2080.



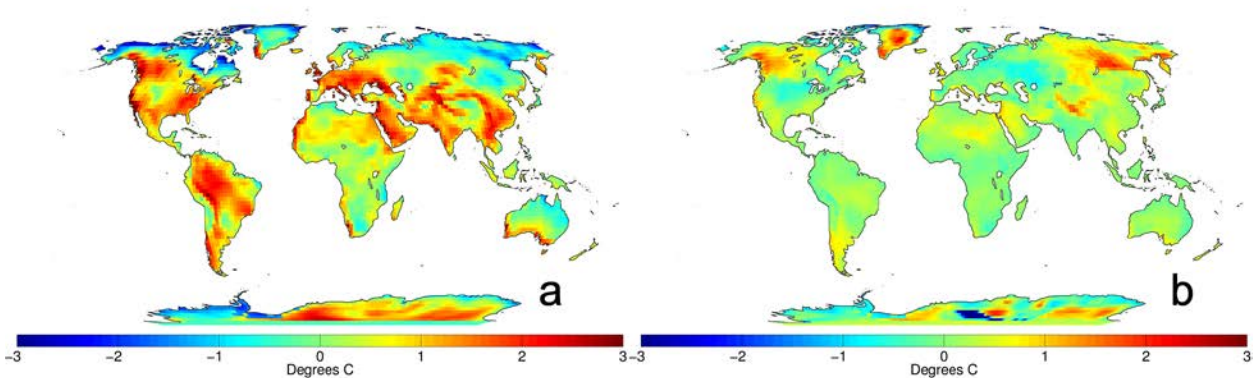
Supplementary Figure 6: Probability of mean annual exposure in person-days to 34°C and 35°C under RCP 4.5 (blue) and RCP 8.5 (red) in 2070-2080. Following the RCP 4.5 emissions scenario substantially reduces the probability of large exposures to 34°C and mostly eliminates exposure to 35°C. Probabilities calculated as the percentage of 90 runs (18 GCMs and five SSPs for each emissions scenario) which result in a given level of exposure.



Supplementary Figure 7: Projected global population through 2080 under the five shared socioeconomic pathway (SSP) scenarios.



Supplementary Figure 8: Multi-GCM mean number of days per year in 2060 – 2080 that exceed the historical annual maximum temperature under RCP 4.5. Numbers are lower than under RCP 8.5, but geographical patterns are similar.



Supplementary Figure 9: (a): Multi-GCM mean difference between the projected change in annual maximum temperature and mean daily maximum temperature in 2070 – 2080 under RCP 8.5. (b) Same as (a) but for wet bulb temperature.