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Supplement of

A multi-method framework for global real-time climate attribution

Daniel M. Gilford et al.

Correspondence to: Daniel M. Gilford (dgilford@climatecentral.org)

S1. Quantile Set

The set of quantiles used to construct quantile-scaling timeseries are
$q_i \in \{0.01, 0.04, 0.07, 0.11, 0.14, 0.18, 0.21, 0.24, 0.28, 0.31, 0.35, 0.38, 0.41, 0.45, 0.48, 0.52, 0.55, 0.59, 0.62, 0.65, 0.69, 0.72, 0.76, 0.79, 0.82, 0.86, 0.89, 0.93, 0.96, 0.99\}$

S2. Supplemental Tables

Table S1: List of CMIP5 Models and Experiments used in this study. All simulations are from ensemble "r1i1p1" and have N96 spatial resolution. Historical and RCP8.5 runs have temporal ranges of 1880–2005 and 2006–2100, respectively. Model forcing periods are defined by the period when the central year of the 31-year mean GMST anomaly (relative to 1850-1900) exceeds 1.07°C. Model natural periods are defined as the final 31 years in each natural simulation.

Model Name	Experiments	1.07°C Forcing Period
CCSM4	historical, historicalNat, rcp85	1985–2015
CESM1-CAM5	historical, historicalNat, rcp85	1999–2029
CSIRO-Mk3-6-0	historical, historicalNat, rcp85	2007–2037
CanESM2	historical, historicalNat, rcp85	1988–2018
GFDL-CM3	historical, historicalNat, rcp85	1998–2028
IPSL-CM5A-MR	historical, historicalNat, rcp85	1988–2018
MIROC-ESM	historical, historicalNat, rcp85	1995–2025
MIROC-ESM-CHEM	historical, historicalNat, rcp85	1994–2024
MRI-CGCM3	historical, historicalNat, rcp85	2014–2044
NorESM1-M	historical, historicalNat, rcp85	2004–2034
bcc-csm1-1	historical, historicalNat, rcp85	1987–2017
ACCESS1-0	historical, rcp85	1999–2029
ACCESS1-3	historical, rcp85	2003–2033
CESM1-BGC	historical, rcp85	1988–2018
CMCC-CESM	historical, rcp85	2010–2040
CMCC-CMS	historical, rcp85	2005–2035
CMCC-CM	historical, rcp85	2002–2032
EC-EARTH	historical, rcp85	1987–2017
IPSL-CM5B-LR	historical, rcp85	1992–2022
MIROC5	historical, rcp85	2003–2033
MPI-ESM-LR	historical, rcp85	1988–2018
MPI-ESM-MR	historical, rcp85	1989–2019
bcc-csm1-1-m	historical, rcp85	1985–2015
inmcm4	historical, rcp85	2011–2041

Table S2: The number of days ($N_{E,t}$) in a given average time period—an average month, season, year with total number of days (N_t)—expected to exceed a specific quantile (q_i).

Quantiles	N_t	$N_{E,t}$
$\boldsymbol{q_i = 0.90}$		
	30 (Month)	3.04
	91 (Season)	9.13
	365 (Year)	36.5
$\boldsymbol{q_i = 0.95}$		
	30 (Month)	1.52
	91 (Season)	4.56
	365 (Year)	18.3
$\boldsymbol{q_i = 0.975}$		
	30 (Month)	0.76
	91 (Season)	2.28
	365 (Year)	9.13
$\boldsymbol{q_i = 0.99}$		
	30 (Month)	0.30
	91 (Season)	0.91
	365 (Year)	3.64

S3. Supplemental Figures

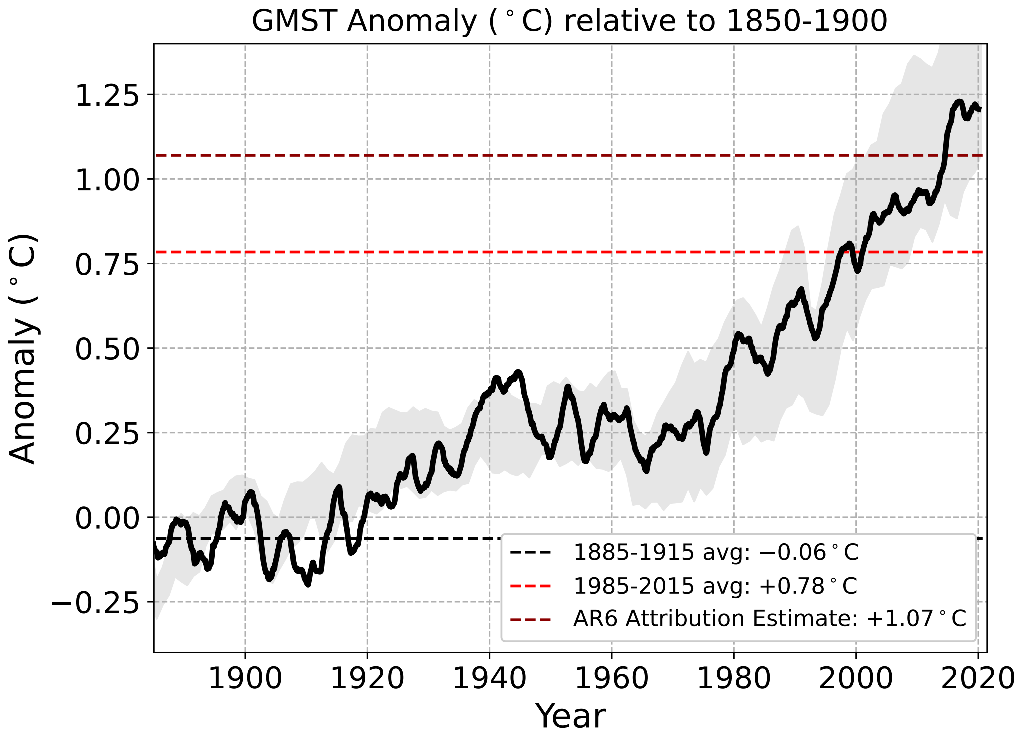

Figure S1: Global Mean Surface Temperature anomaly (in °C) relative to 1850–1900, from HadCRUT5 (black curve) and the 17th–83rd percentile of the CMIP5 ensemble (gray shading). The black dashed line shows the mean temperature anomaly over 1885–1915 representing the natural period in observational scaling analyses. The dashed bright red line shows the mean temperature anomaly over the climatology period, 1985–2015, which is shifted during observation-based scaling analyses. The dark red line shows the IPCC's AR6 best estimate of the total human-caused global surface temperature increase in 2010–2019 relative to 1850–1900.

S4. Glossary

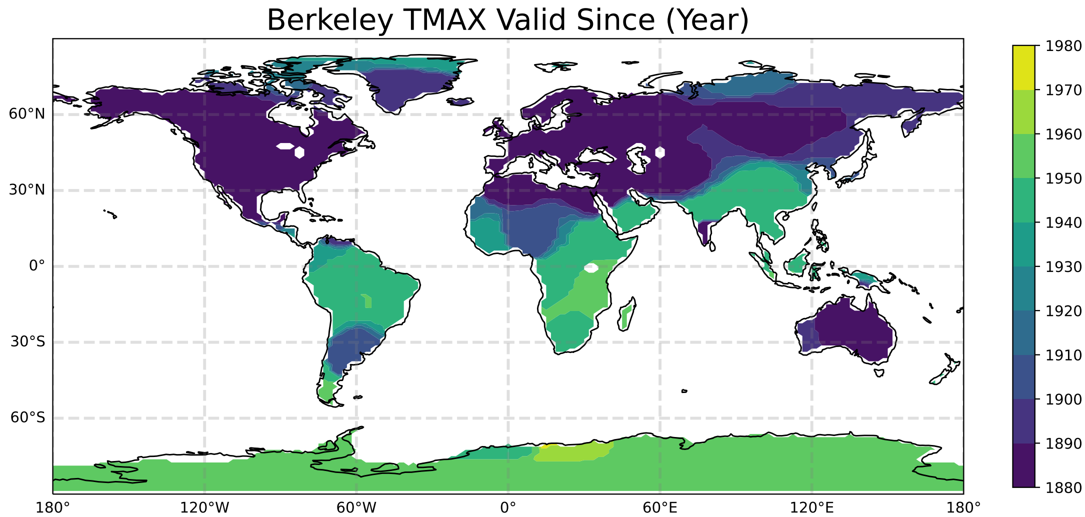

Figure S2: The year after which Berkeley land T_{max} data (drawn over 1880–2017 period) is maintained. Global land coverage north of 60°S is maintained since 1955.

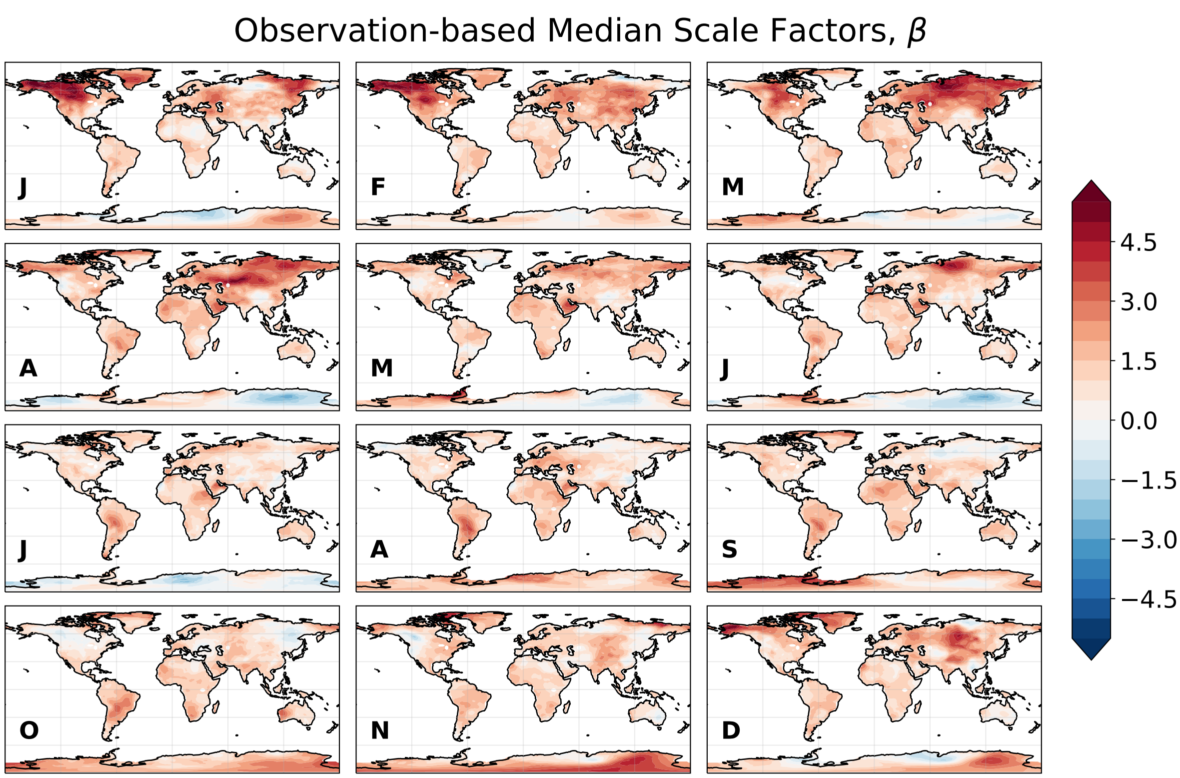

Figure S3: Observation-based median scale factors, β (units of °C T_{max} per °C GMST), for each month (January–December) found by regressing each monthly timeseries of T_{max} against smoothed GMST over all available years from 1880–2017.

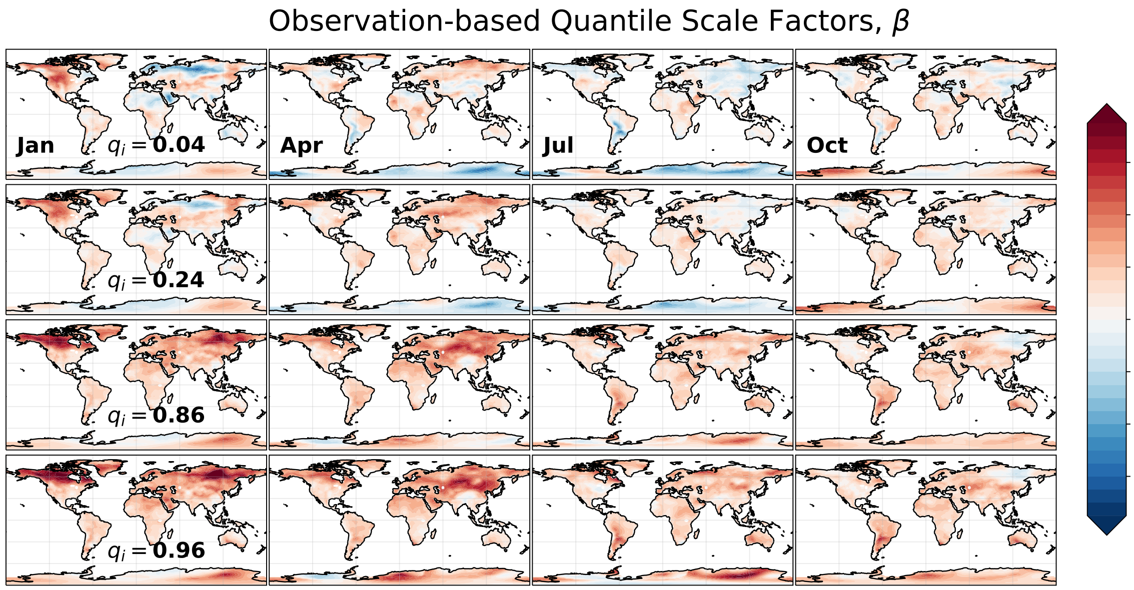

Figure S4: Observation-based quantile scale factors, β (units of °C T_{max} per °C GMST), for January, April, July and October (each column), and over four quantiles (0.04, 0.24, 0.76, 0.96; each row) found by regressing each monthly quantile timeseries of T_{max} against smoothed GMST over all available years from 1880-2017.

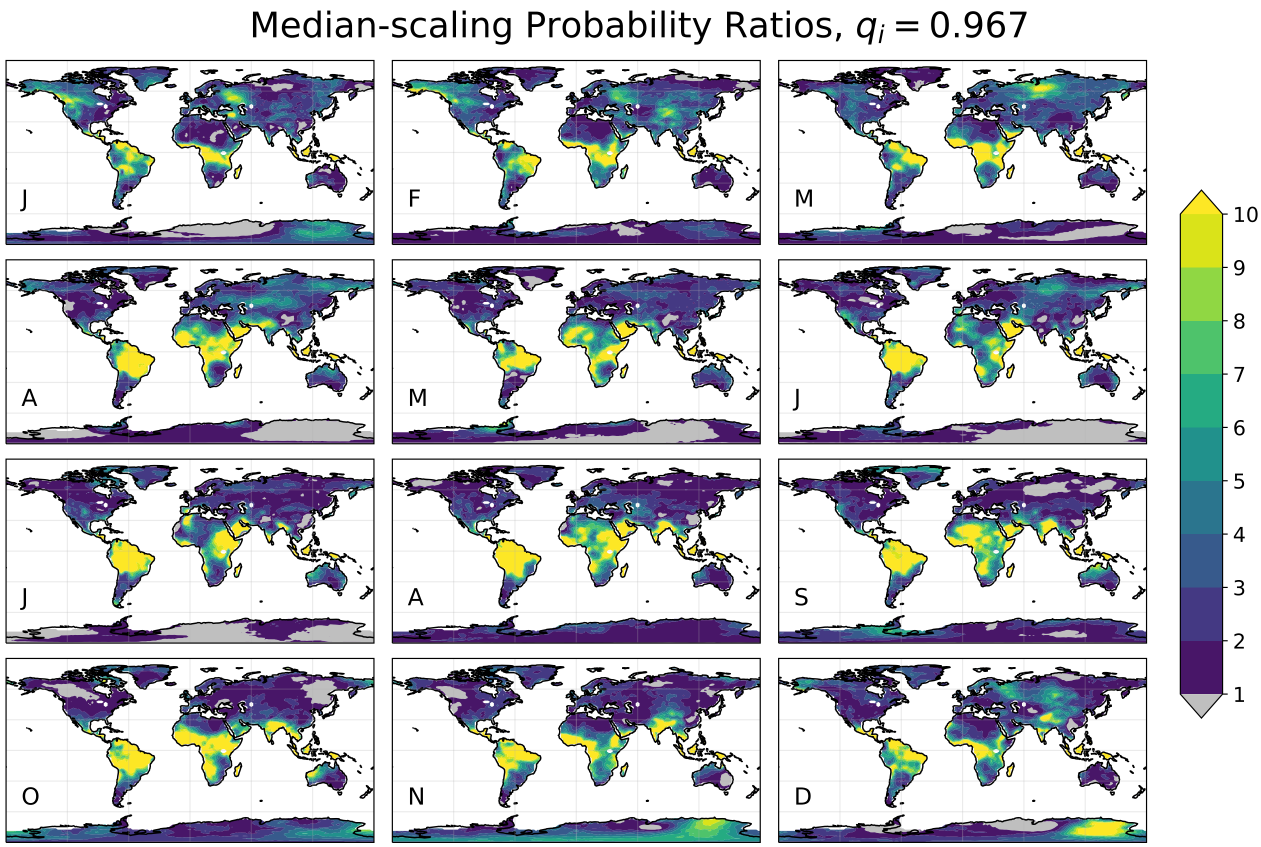

Figure S5: Probability ratios (unitless) from the observation-based median-scaling method, for each month (January–December) found by comparing mean daily exceedances of the 96.7$^{\mathrm{th}}$ percentile between median-scaled forced and natural distributions. Values below 2.0 are grayed out, and the colorbar saturates at each extent.

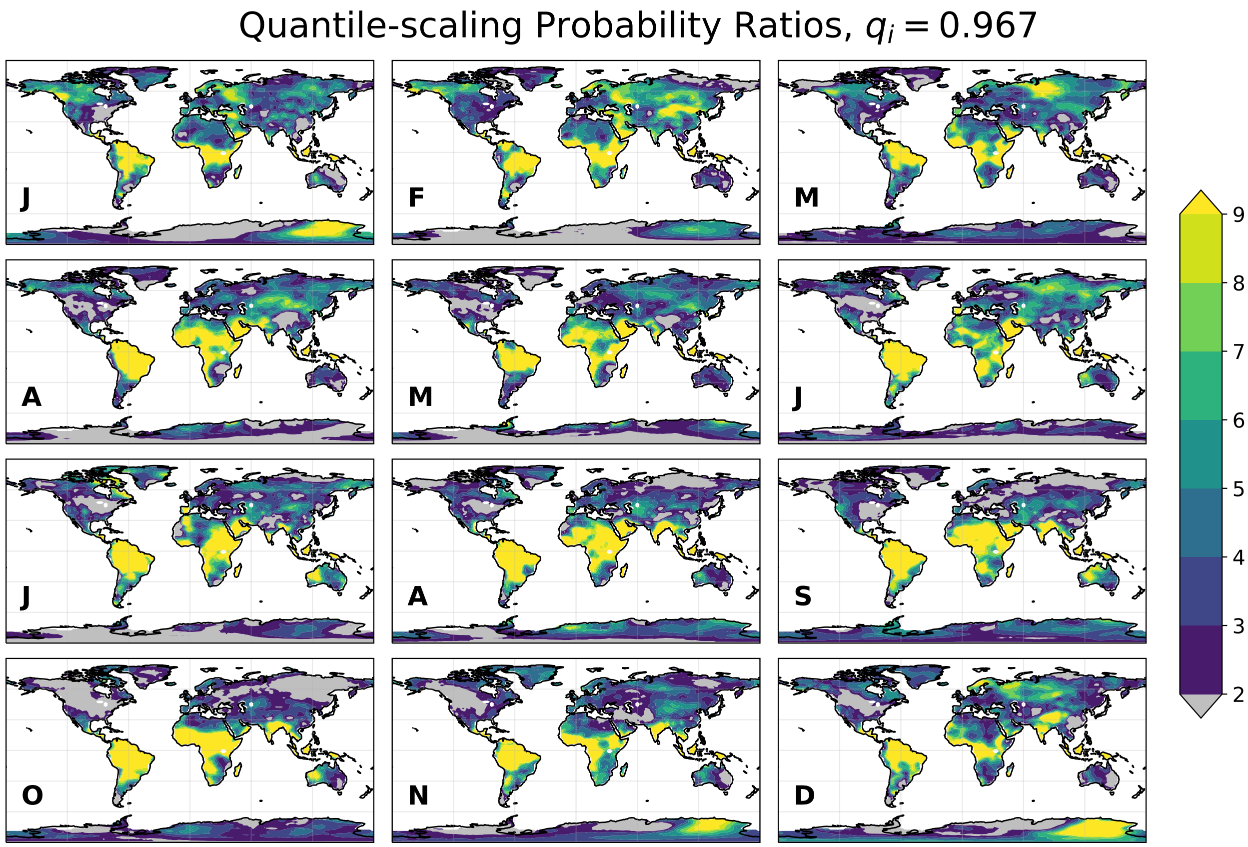

Figure S6: As in Fig. S5, but from the observation-based quantile-scaling method.

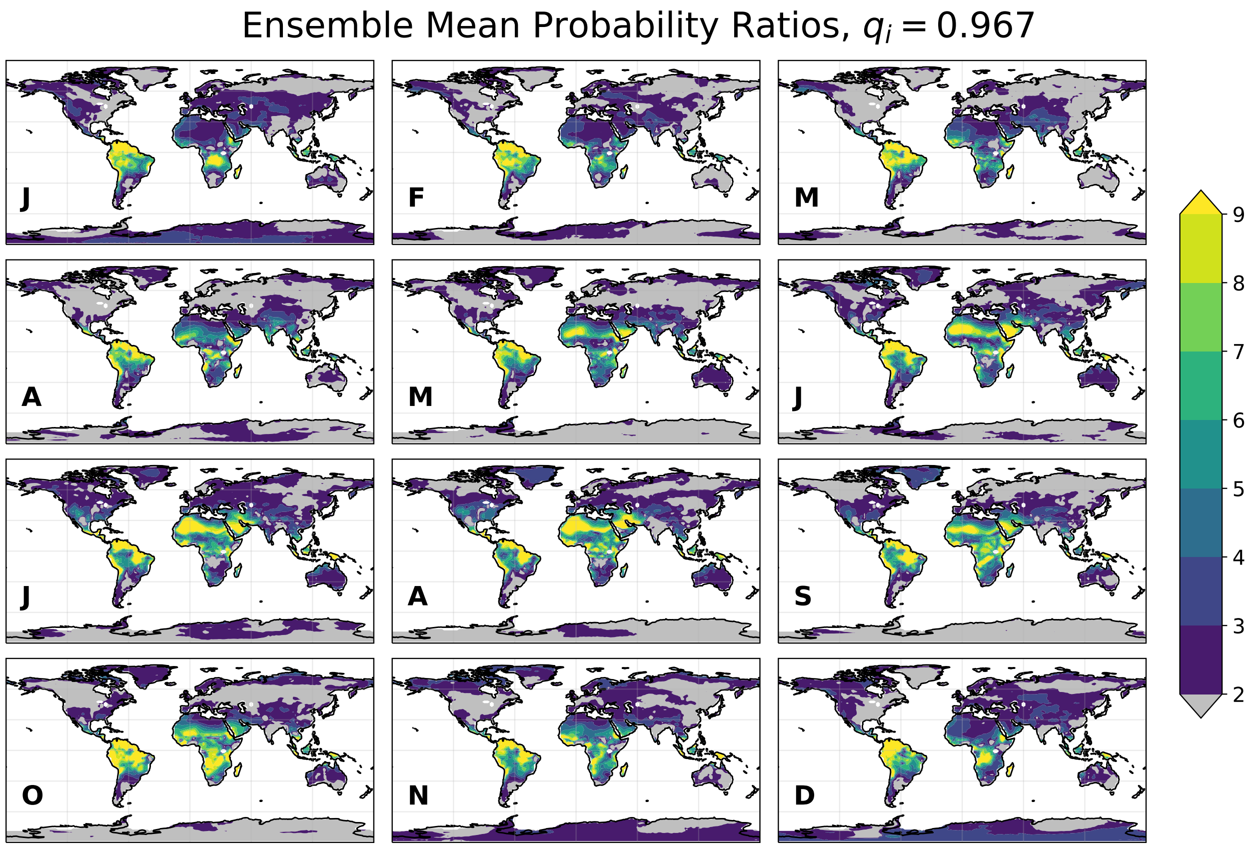

Figure S7: CMIP5 ensemble multi-model mean probability ratios (unitless) from the model-based method, for each month (January–December) calculated by taking the ensemble average of daily exceedances of the 96.7$^{\text{th}}$ percentile between each individual forced model divided by the daily exceedances of the pooled natural distribution (over a 31-year period). Values below 2.0 are grayed out, and the colorbar saturates at each extent.

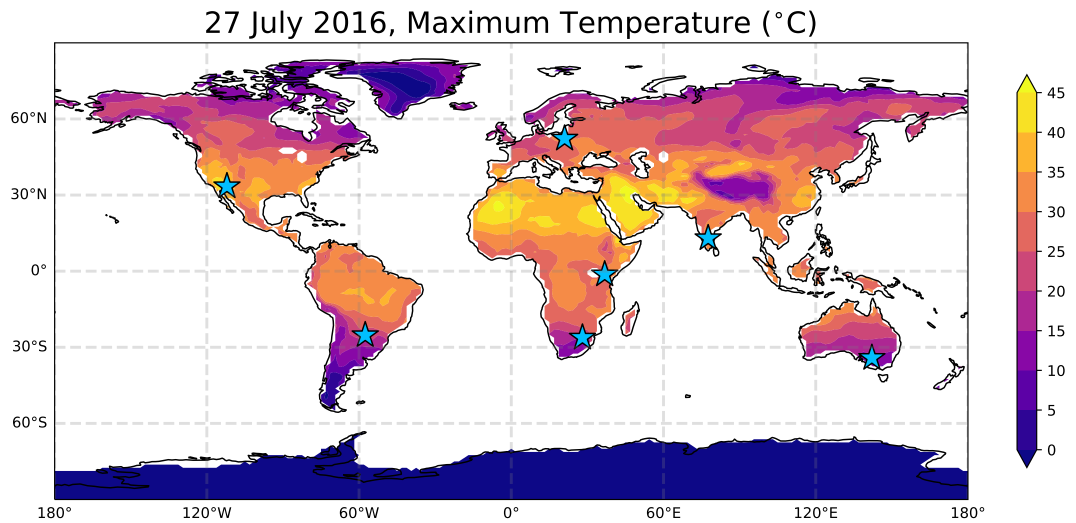

Figure S8: Maximum temperatures (°C) on 27 July 2016 from Berkeley-Earth observations. Blue stars indicate example locations around the world where attribution estimates are analyzed (Table 1), as discussed in section 3.2.

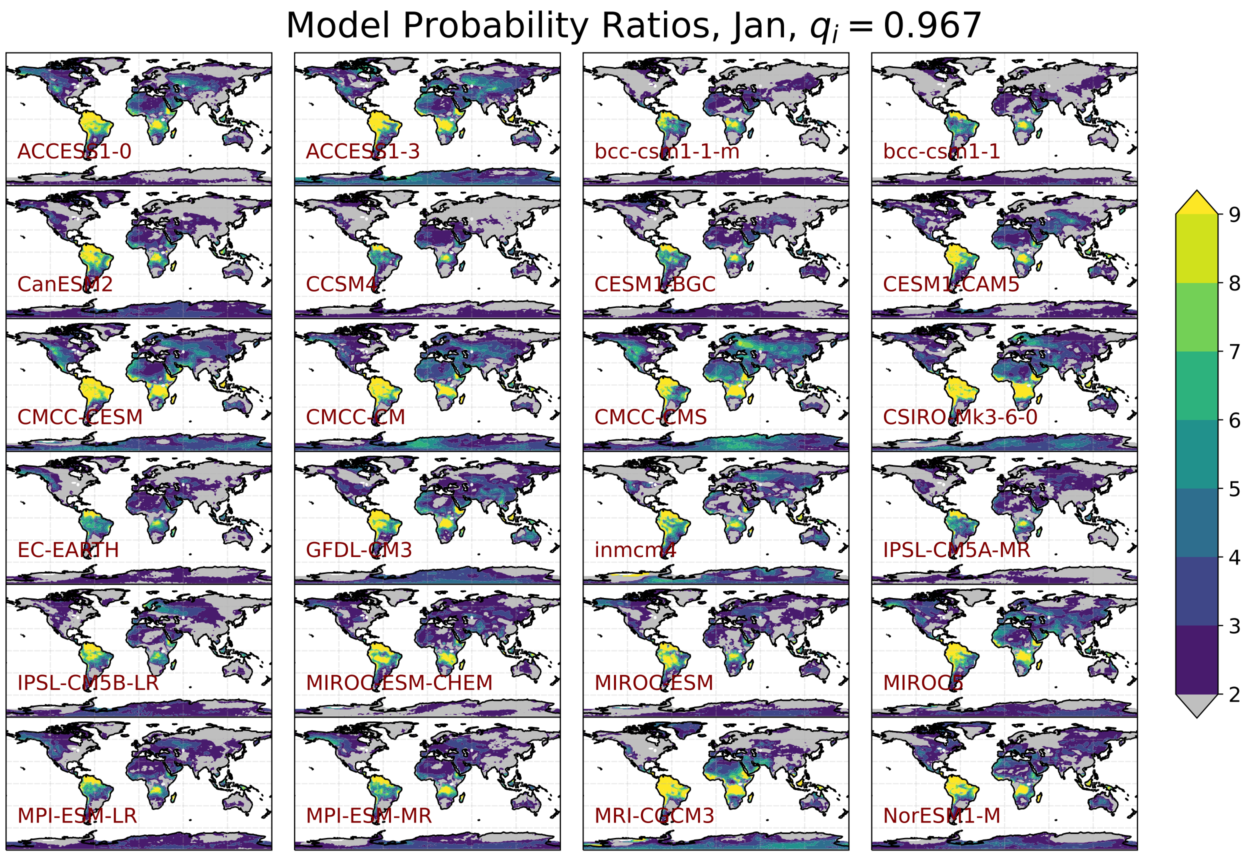

Figure S9: January probability ratios (unitless) from each individual CMIP5 model using the model-based method, calculated from daily exceedances of the 96.7$^{\text{th}}$ percentile between each individual forced model divided by the daily exceedances of the pooled natural distribution (over a 31-year period). Values below 2.0 are grayed out, and the colorbar saturates at each extent.

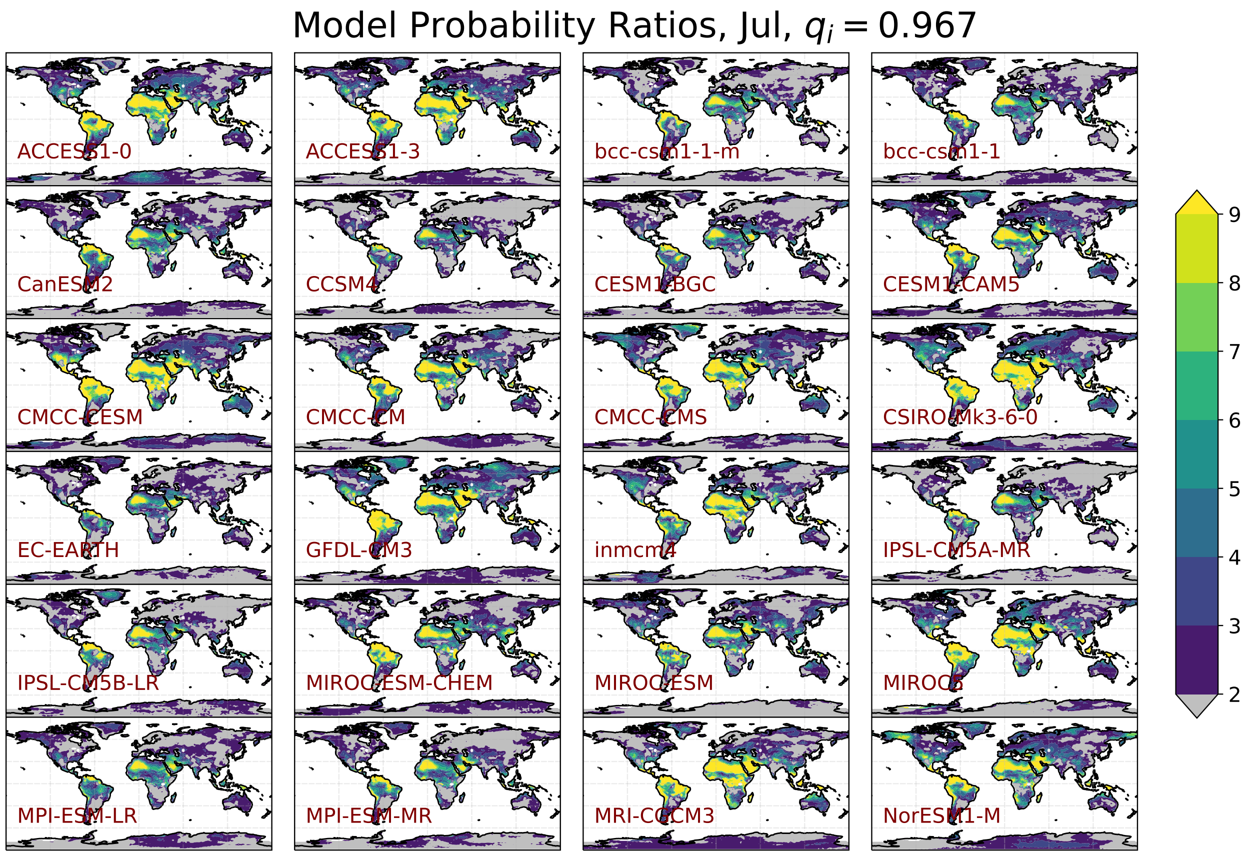

Figure S10: July probability ratios (unitless) from each individual CMIP5 model using the model-based method, calculated from daily exceedances of the 96.7$^{\text{th}}$ percentile between each individual forced model divided by the daily exceedances of the pooled natural distribution (over a 31-year period). Values below 2.0 are grayed out, and the colorbar saturates at each extent.

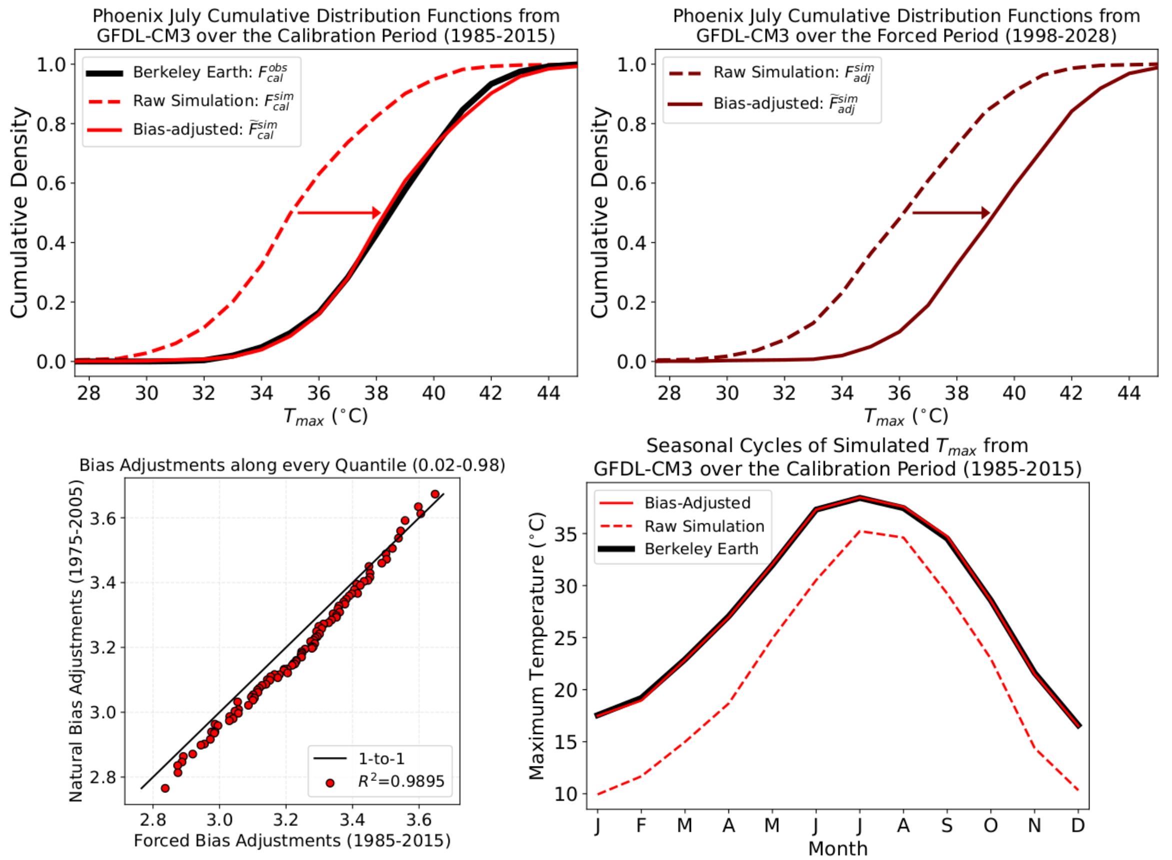

Figure S11: Bias-adjustment analyses near Phoenix, AZ, USA (see Appendix A). Upper left panel: Empirical cumulative distribution functions of maximum temperature over the calibration period (1985–2015) from Berkeley-Earth observations (black curve), the raw GFDL-CM3 simulation (dashed red curve), and the GFDL-CM3 simulation after bias adjustment (solid red curve). Upper right panel: Empirical cumulative distribution functions of maximum temperature over the forced period (1998–2028) of the GFDL-CM3 model from the raw simulation (dashed maroon curve), and after bias adjustment (solid maroon curve). Lower left panel: Scatter plot of GFDL-CM3 model bias adjustments (in °C, and over each distribution quantile from 0.02 to 0.98) applied to the historical+projected simulation (over the calibration period 1985–2015) and the natural simulation (over the last 31-years period in the run, 1975–2005). Bias-adjustment mappings are strongly correlated. Lower right panel: Mean seasonal cycles (averaged over 1985–2015) of observed (black curve) and GFDL-CM3 simulated maximum temperatures before (dashed red curve) and after bias adjustment (solid red curve).

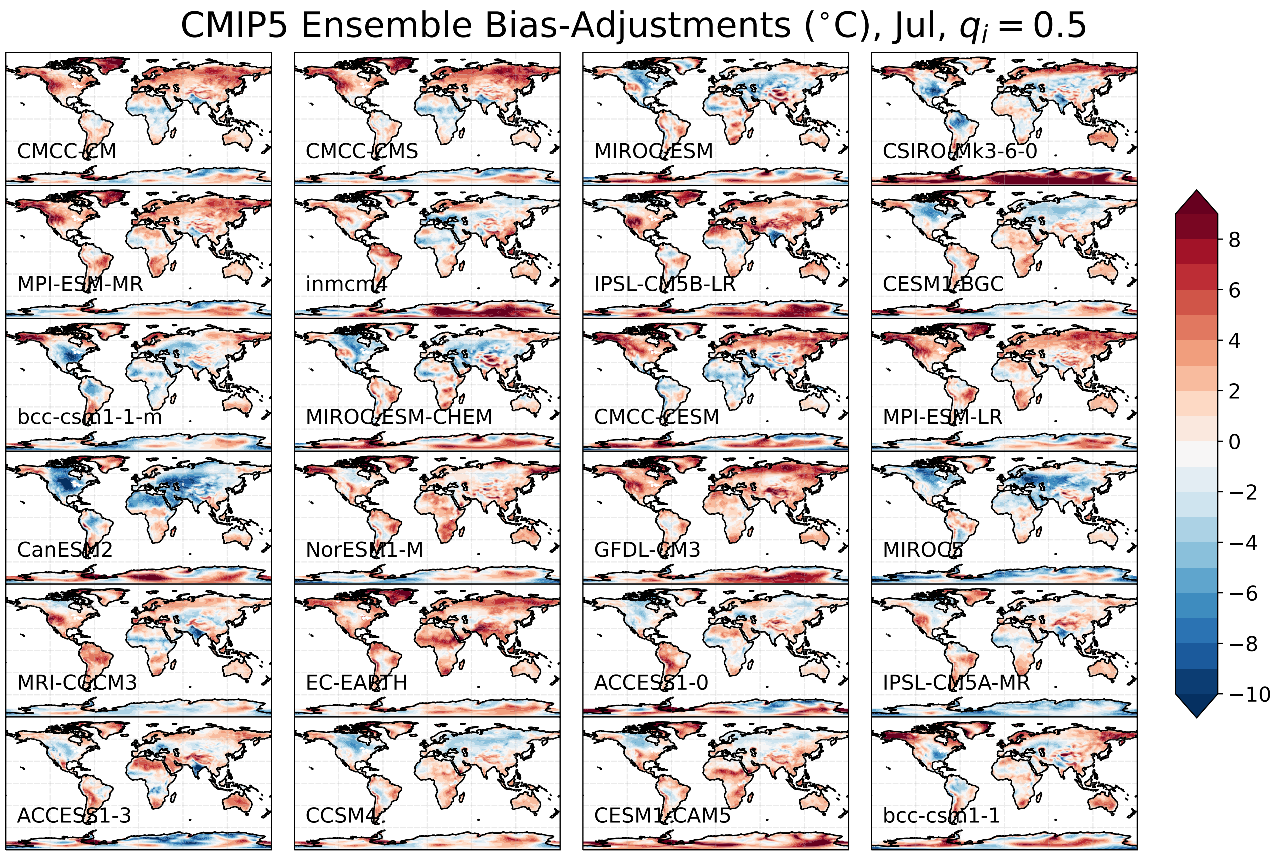

Figure S12: Bias-adjustment magnitudes (°C) in July from each individual CMIP5 model, evaluated at the median of each simulated distribution over the models' 31-year forced periods (cf. Supporting Table S1). The colorbar saturates at each extent.

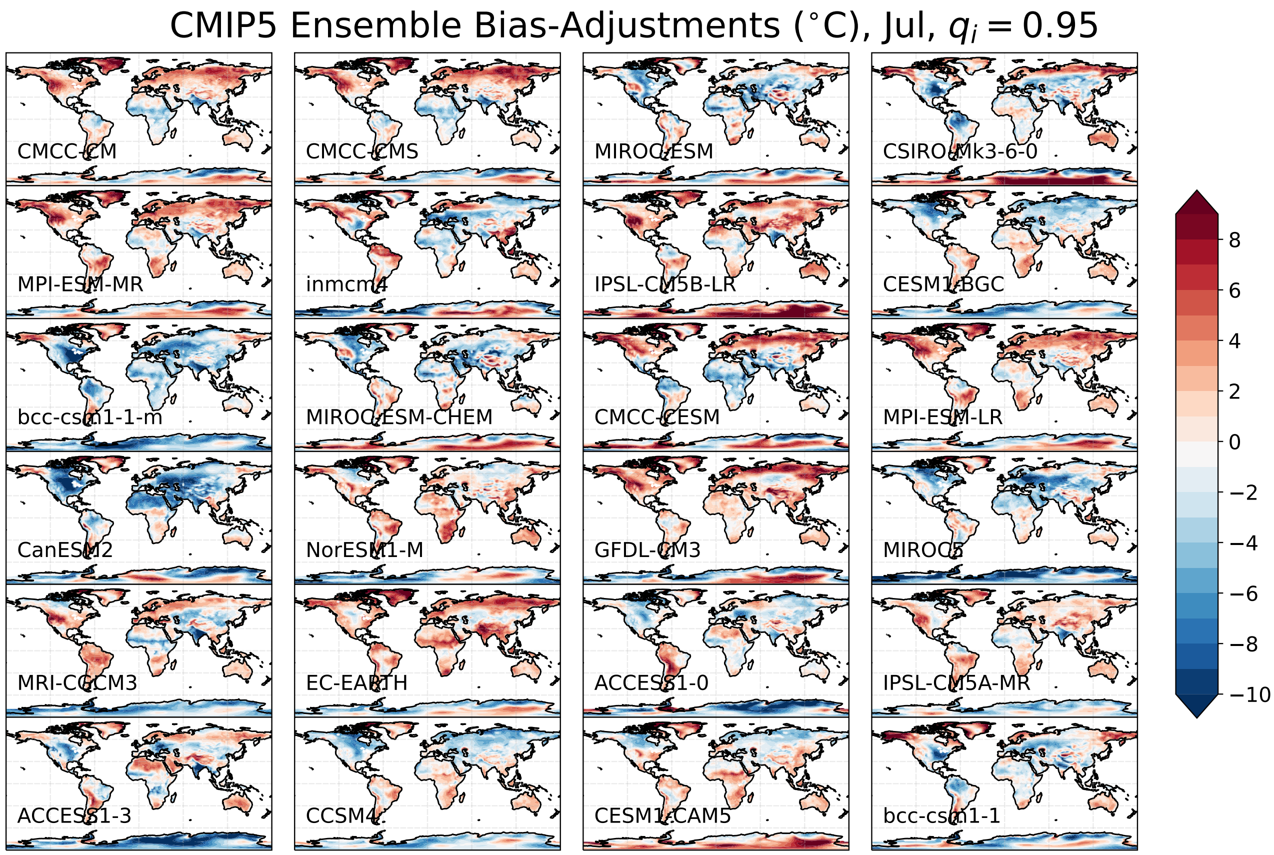

Figure S13: As in Fig. S12, but evaluated at the 95^{th} percentile.

Table S3: **Glossary**—Definitions of key terms.

Term	Meaning
Absolute temperature threshold	The absolute temperature associated with the critical quantile, calculated from a particular distribution; in this study we define the threshold from the climatological distribution
Adjustment period	The time period over which the bias-adjustment method is applied to recover a simulated distribution informed by an observed distribution
Climatology or climatological distribution	A 31-year reliably-observed distribution of the state variable that may be translated into either a forced or counterfactual distribution, through the state variable's relationship with GMST (Appendix B); in this study the climatology is defined by the period 1985–2015
Calibration period	A time interval used to train the bias-adjustment method on the relationship mapping between detrended observed and simulated distributions
Counterfactual distribution	A 31-year distribution of the state variable representative of the climate during a period assumed to have not been significantly influenced by human activity
Critical quantile	The quantile at which the expected number of daily exceedances or subceedances is 1; it is derived directly from the quantile definition and depends on the number of days in the sample being analyzed (i.e. the time scale context)
Forced distribution	A 31-year distribution of the state variable representative of the climate contemporary to the events/days that are being assessed for attribution; it is assumed to have been influenced by human-driven climate change
Hazard-based approach	Framing attribution as an estimate of how the probability of event occurrence or exceedance responds to human-caused climate change
Pre-industrial reference period	The climatological period 1850–1900, representing approximate "pre-industrial" temperature levels as defined by the IPCC (SR15 report, FAQ1.2); GMST anomalies in this study are calculated relative to the 1850–1900 mean

Table S3 *(continued)*

Term	Meaning
Probability ratio (PR)	The ratio of forced and counterfactual distribution exceedance probabilities, defined by the fraction of each distribution exceeding a prescribed absolute temperature
State variable	An observable and modelable physical Earth-system quantity such as temperature, precipitation, humidity, sea level, etc.; our framework is designed to flexibly adapt, enabling attribution estimation (and uncertainty quantification) across a wide range of state variables found by integrating over all values of the conditional distribution
Threshold	The temperature or quantile above which we integrate the CDF to calculate probability of exceedance