UCRL-JRNL-226477

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

# Climate change uncertainty for daily minimum and maximum temperatures: a model inter-comparison

D. Lobell, C. Bonfils, P. Duffy

December 1, 2006

Geophysical Research Letters

# Climate change uncertainty for daily minimum and maximum temperatures: a model inter-comparison

David B. Lobell[1], Céline Bonfils[2], and Phillip B. Duffy[1,2]

[1]Lawrence Livermore National Laboratory, Livermore, California
[2]University of California, Merced, California

Corresponding author: David Lobell
Lawrence Livermore National Laboratory
P.O. Box 808 L-103
Livermore, CA 94550
Tel: (925) 422-4148/ Fax: (925) 423-4908
Email: lobell2@llnl.gov

# Climate change uncertainty for daily minimum and maximum temperatures: a model inter-comparison

## Abstract

Several impacts of climate change may depend more on changes in mean daily minimum ($T_{min}$) or maximum ($T_{max}$) temperatures than daily averages. To evaluate uncertainties in these variables, we compared projections of $T_{min}$ and $T_{max}$ changes by 2046-2065 for 12 climate models under an A2 emission scenario. Average modeled changes in $T_{max}$ were slightly lower in most locations than $T_{min}$, consistent with historical trends exhibiting a reduction in diurnal temperature ranges. However, while average changes in $T_{min}$ and $T_{max}$ were similar, the inter-model variability of $T_{min}$ and $T_{max}$ projections exhibited substantial differences. For example, inter-model standard deviations of June-August $T_{max}$ changes were more than 50% greater than for $T_{min}$ throughout much of North America, Europe, and Asia. Model differences in cloud changes, which exert relatively greater influence on $T_{max}$ during summer and $T_{min}$ during winter, were identified as the main source of uncertainty disparities. These results highlight the importance of considering separately projections for $T_{max}$ and $T_{min}$ when assessing climate change impacts, even in cases where average projected changes are similar. In addition, impacts that are most sensitive to summertime $T_{min}$ or wintertime $T_{max}$ may be more predictable than suggested by analyses using only projections of daily average temperatures.

## 1. Introduction

Climate models are often characterized by their climate sensitivity, defined as the equilibrium change in globally averaged surface temperature that results from a doubling of atmospheric carbon dioxide ($CO_2$) levels [*Cubasch, et al.*, 2001]. The range or standard deviation of climate sensitivity among different models provides a common measure of uncertainty in the response of the climate system to atmospheric $CO_2$ increases. For example, a range of 1.5 – 4.5 ºC is commonly cited based on evaluation of 15+ models [*Cubasch, et al.*, 2001], with recent studies suggesting this range should be slightly higher [*Murphy, et al.*, 2004; *Stainforth, et al.*, 2005].

In addition to studies of average temperature responses, recent model inter-comparisons have focused on changes in extreme temperature events, such as frost days or heat waves [*Hegerl, et al.*, 2004; *Tebaldi, et al.*, in press]. This focus reflects the importance of both average temperatures and extreme events in determining climate change impacts [*Easterling, et al.*, 2000]. However, several societal and ecosystem impacts are more directly related to changes in mean daily minimum ($T_{min}$; i.e., nighttime) or maximum ($T_{max}$, i.e., daytime) temperatures than to average temperatures or extremes. For example, quantities such as growing degree days and accumulated chill hours, which are widely used in models to predict crop and pest development, are influenced differently by $T_{min}$ and $T_{max}$ [*McMaster and Wilhelm*, 1997; *Wilkens and Singh*, 2001]. In addition, changes in evapotranspiration and photosynthetic rates are likely to be more affected by $T_{max}$ than $T_{min}$ [*Dhakhwa and Campbell*, 1998].

Much of the uncertainty in climate sensitivity has been attributed to model differences in cloud behavior [*Soden and Held*, 2006; *Webb, et al.*, 2006]. Increased cloud cover, particularly of low clouds, leads to a greater fraction of reflected solar radiation and therefore cooling of $T_{max}$. In comparison, clouds have a relatively small net effect on $T_{min}$ [*Dai, et al.*, 1999].

Given the important role of clouds in climate change uncertainty and the differential effect of clouds on day and night temperatures, a reasonable hypothesis is that inter-model differences in $T_{min}$ changes would be smaller than associated $T_{max}$ changes. Here we evaluate this hypothesis with daily $T_{min}$ and $T_{max}$ output for simulations from 12 general circulation models (GCMs) archived by the Program in Climate Model Diagnosis and Intercomparison (PCMDI; http://www-pcmdi.llnl.gov.) and used in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC.)

## 2. Models and Methods

Daily output of $T_{min}$ and $T_{max}$ used in this analysis were available for 12 models (Table 1). For each model, we computed average monthly and seasonal $T_{min}$, $T_{max}$, and average temperature ($T_{avg}$) for two available time slices: the 1961-1999 period in a simulation of 20th century climate (20c3m in the IPCC nomenclature), and the 2046-2065 period in a simulation of 21st century climate using an A2 emission scenario (sresa2 in the IPCC nomenclature). An ensemble average was computed for models that provided output from multiple realizations (Table 1). Differences between the two time slices were computed and then regridded for all models to a common 2° x 2° grid. For comparison with $T_{min}$ and $T_{max}$, monthly output for total cloud cover (clt) were processed in a similar manner. Below we focus on results for the June-August (JJA) and December-February (DJF) seasons.

## 3. Results and Discussion

For most locations, average changes in $T_{min}$ across all models were larger than associated changes in $T_{max}$ for both JJA and DJF (Figure 1a,d). Exceptions included the United States and Western Europe in JJA, and Mexico in DJF. These trends toward a reduction in the diurnal temperature range (DTR = $T_{max} – T_{min}$) are consistent with previous modeling results [*Dai, et al.*, 2001; *Stone and Weaver,* 2003], as well as observed 20th century trends [*Easterling, et al.*, 1997; *Vose, et al.*, 2005]. However, in most locations, with the exception of Europe where DTR increased, the average simulated changes in JJA DTR were small and not consistent across models (Figure 1b). DTR trends for DJF were consistently negative across models for high latitudes and parts of Africa and India, but were insignificant elsewhere (Figure 1e).

The inter-model standard deviations of $T_{min}$ changes, used here to quantify climate change uncertainty for a prescribed emission scenario, were significantly smaller than the standard deviation of $T_{max}$ in many locations. For example, throughout much of North America and Eurasia, $T_{max}$ changes for JJA were 50% or more variable between models than changes in $T_{min}$ (Figure 1 c). The large variability of projected $T_{max}$ changes relative to $T_{min}$ is similar to the observation by Alfaro et al. [2006] that the inter-annual standard deviation for JJA $T_{max}$ over central and western United States was 30% larger than for $T_{min}$.

Consistent with the hypothesis that projected $T_{max}$ changes are sensitive to cloud cover and downwelling radiation, the greatest disparity between $T_{max}$ and $T_{min}$ uncertainty was mainly observed during the local summer season (JJA in northern latitudes and DJF in southern latitudes) when downwelling solar radiation was greatest. To further evaluate the mechanism behind increased $T_{max}$ uncertainty, we computed the correlation across models between projected changes in $T_{min}$ or $T_{max}$ and total cloud cover (Figure 2). Modeled changes in $T_{max}$ were strongly and negatively correlated with changes in clt for most locations in JJA and in southern latitudes and U.S. in DJF, reflecting the cooling influence of increased clouds and reduced surface downwelling solar radiation on daytime temperature. Correlations between clt and $T_{min}$ were comparatively smaller, illustrating that uncertainty in cloud cover changes generally have less of an impact on $T_{min}$ than $T_{max}$.

However, in Northern Hemisphere boreal latitudes in DJF, $T_{min}$ and $T_{max}$ changes were positively correlated with cloud changes, and $T_{min}$ projections were more variable across models than $T_{max}$. This results from the small downwelling solar fluxes at high latitudes in DJF; the absolute sensitivity of these fluxes to cloud cover is therefore small as well. The insulating effect of clouds, which tends to warm surface temperatures by trapping infrared radiation, therefore becomes more important and gives rise to a positive relationship between cloud cover and temperature changes.

In general, therefore, average changes in $T_{max}$ across all models were slightly smaller than changes in $T_{min}$ in both seasons, but the uncertainty for projected $T_{max}$ changes was significantly larger than $T_{min}$ uncertainty for most locations in both seasons (with the exception of northern high latitudes in DJF). The inter-model standard deviations of $T_{min}$ and $T_{max}$ were also compared with those of $T_{avg}$ (Figure 3), because projected changes in $T_{avg}$ are often more readily available than $T_{min}$ and $T_{max}$ [e.g., *Cubasch, et al.*, 2001]. Standard deviations of $T_{max}$ averaged ~20% higher than standard deviations for $T_{avg}$ in summer months, while uncertainty for $T_{min}$ was roughly 10% lower than for $T_{avg}$.

In DJF, $T_{min}$ uncertainty above 40º N was ~10% higher than $T_{avg}$ uncertainty, while $T_{max}$ uncertainty was slightly lower than $T_{avg}$. Interestingly, in some situations uncertainties for $T_{min}$ and $T_{max}$ were both larger than for $T_{avg}$ (0-20º S in JJA and 20-40º N in DJF). This result reflects the fact that modeled changes in $T_{max}$ and $T_{min}$ exhibited negative correlations in these regions, with the largest projected increases in $T_{max}$ tending to come from the same models with the smallest projected increases in $T_{min}$.

As mentioned above, agricultural impacts are one case where differences between $T_{min}$ and $T_{max}$ changes may be important, because many biological processes are differentially sensitive to daytime and nighttime conditions. Spatial averages for $T_{min}$, $T_{max}$, and $T_{avg}$ changes in major agricultural regions for JJA were computed to more directly assess uncertainties relevant to agriculture (Table 2). In contrast to the predominant global pattern, average changes in DTR were positive for several regions and significantly negative only in India, where all 12 models projected a DTR decrease with an average change of -0.5ºC.

Consistent with global patterns, uncertainty in $T_{max}$ was larger than for $T_{min}$ for most regions. For example, the inter-model range for $T_{max}$ changes was 1.1 ºC larger than $T_{min}$ in the U.S. Corn Belt and California, despite the fact that average changes in $T_{max}$ and $T_{min}$ were similar. Previous work has demonstrated that $T_{max}$ changes are more important than $T_{min}$ for U.S. maize yields, as water stress and development rates are both more sensitive to $T_{max}$ [*Dhakhwa, et al.*, 1997; *Dhakhwa and Campbell*, 1998; *Schlenker and Roberts*, 2006]. Studies of climate change impacts on U.S. agriculture may therefore underestimate uncertainties if using only projected changes in average temperatures. Uncertainties for $T_{min}$ and $T_{max}$ were more similar in regions such as Europe and China, and therefore use of $T_{avg}$ in these regions may be less problematic.

## 4. Conclusions

Analysis of simulated responses to increased greenhouse gases in 12 global climate models reveals that projected changes in $T_{min}$ are generally much more consistent across models than changes in $T_{max}$. This occurs because $T_{min}$ responses are less strongly influenced by cloud responses, which are a major source of climate sensitivity uncertainty. The 12 models considered in this study provided an inconsistent view of future changes in DTR for most regions. Only for northern high latitudes during winter months did models agree in projecting a negative DTR trend.

The results of this study indicate that changes in summertime daytime temperatures and associated impacts are currently less predictable than corresponding changes at nighttime. Studies that assess impacts of climate change using only projections of average temperatures therefore risk over- or under-estimation of uncertainties when considering processes that respond differently to day and night temperatures. Future work to evaluate the performance of each model in simulating past changes of $T_{min}$, $T_{max}$, and DTR would be useful for further constraining uncertainty in future projections [e.g., *Tebaldi, et al.*, 2004].

## Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48. DL was supported by a Lawrence Fellowship from LLNL. CB was supported by the State of California through the Public Interest Energy Research Program.

## References

Alfaro, E. J., et al. (2006), Prediction of summer maximum and minimum temperature over the central and western United States: The roles of soil moisture and sea surface temperature, *J. Clim.*, *19*, 1407-1421.

Cubasch, U., et al. (2001), Projections of Future Climate Change, in *Intergovernmental Panel on Climate Change Working Group 1, Climate Change 2001: The Scientific Basis*, edited, pp. 525-582, IPCC Working Group 1.

Dai, A., et al. (1999), Effects of Clouds, Soil Moisture, Precipitation, and Water Vapor on Diurnal Temperature Range, *J. Clim.*, *12*, 2451-2473.

Dai, A., et al. (2001), Climates of the twentieth and twenty-first centuries simulated by the NCAR climate system model, *J. Clim.*, *14*, 485-519.

Dhakhwa, G. B., and C. L. Campbell (1998), Potential effects of differential day-night warming in global climate change on crop production, *Clim Change*, *40*, 647-667.

Dhakhwa, G. B., et al. (1997), Maize growth: assessing the effects of global warming and CO2 fertilization with crop models, *Agric For Meteorol*, *87*, 253-272.

Easterling, D. R., et al. (1997), Maximum and minimum temperature trends for the globe, *Science*, *277*, 364-367.

Easterling, D. R., et al. (2000), Climate extremes: Observations, modeling, and impacts, *Science*, *289*, 2068-2074.

Hegerl, G. C., et al. (2004), Detectability of Anthropogenic Changes in Annual Temperature and Precipitation Extremes, *J. Clim.*, *17*, 3683-3700.

McMaster, G. S., and W. W. Wilhelm (1997), Growing degree-days: one equation, two interpretations, *Agric For Meteorol*, *87*, 291-300.

Murphy, J. M., et al. (2004), Quantification of modelling uncertainties in a large ensemble of climate change simulations, *Nature*, *430*, 768-772.

Schlenker, W., and M. J. Roberts (2006), Nonlinear Effects of Weather on Corn Yields, *Review of Agricultural Economics*, *28*, 391-398.

Soden, B. J., and I. M. Held (2006), An Assessment of Climate Feedbacks in Coupled Ocean-Atmosphere Models, *J. Climate*, *19*, 3354-3360.

Stainforth, D. A., et al. (2005), Uncertainty in predictions of the climate response to rising levels of greenhouse gases, *Nature*, *433*, 403-406.

Stone, D., and A. Weaver (2003), Factors contributing to diurnal temperature range trends in twentieth and twenty-first century simulations of the CCCma coupled model, *Climate Dynamics*, *20*, 435-445.

Tebaldi, C., et al. (in press), Going to the extremes An intercomparison of model-simulated historical and future changes in extreme events, *Clim Change*.

Tebaldi, C., et al. (2004), Regional probabilities of precipitation change: A Bayesian analysis of multimodel simulations, *Geophysical Research Letters*, *31*, L24213, doi:24210.21029/22004GL021276.

Vose, R. S., et al. (2005), Maximum and minimum temperature trends for the globe: An update through 2004, *Geophysical Research Letters*, *32*, L23822.

Webb, M. J., et al. (2006), On the contribution of local feedback mechanisms to the range of climate sensitivity in two GCM ensembles, *Climate Dynamics*, *27*, 17-38.

Wilkens, P., and U. Singh (2001), A code-level analysis for temperature effects in the CERES models, in *Modeling temperature response in wheat and maize*, edited by J. White, pp. 1-7, CIMMYT, El Batan, Mexico.

Figure Legends:

1) (a) Ratio of average projected changes in $T_{max}$ for 12 climate models to projected changes in $T_{min}$ for June-August season. (b) Mean projected change in JJA DTR divided by inter-model standard deviation. Values below -2 or above +2 are statistically significant (c) Ratio of inter-model standard deviation of $T_{max}$ changes to standard deviation of $T_{min}$ changes for June-August season. (d)-(f) same as (a)-(c) except for December-February season. All changes correspond to the difference between 2046-2065 averages in an A2 simulation and 1961-1999 averages in a 20th century simulation.

2) Inter-model correlation of projected changes in total cloud cover and changes in (a) minimum temperatures and (b) maximum temperatures for June-August season. (c)-(d) same as (a)-(b) except for December-February season.

3) Zonal means of standard deviation for minimum and maximum temperature changes, expressed as a fraction of the standard deviation for average temperature changes, for (a) June-August and (b) December-February.

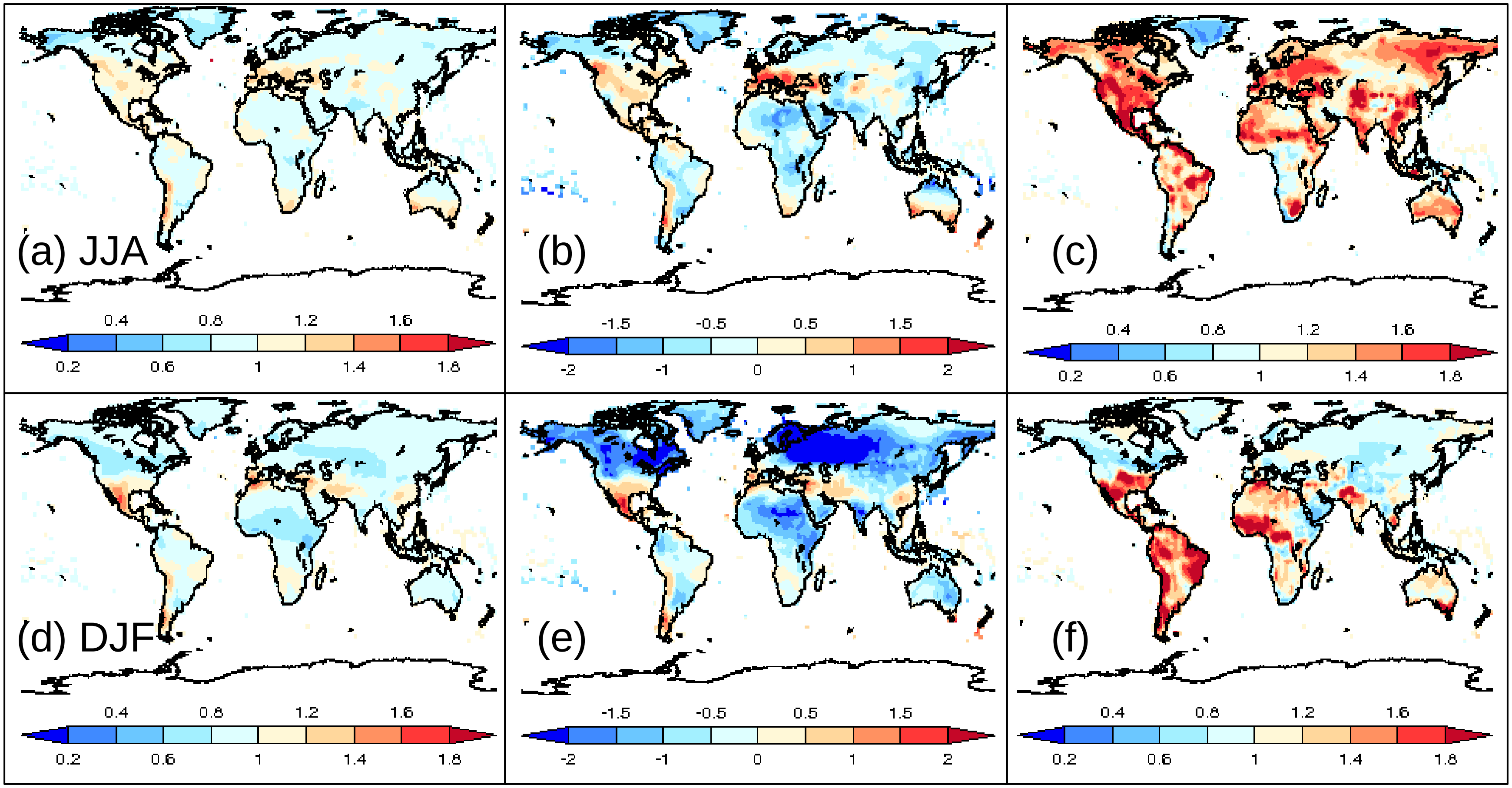
Table 1. Climate models whose output was used in this study. See PCMDI web site (http://www-pcmdi.llnl.gov) for more details on individual models.

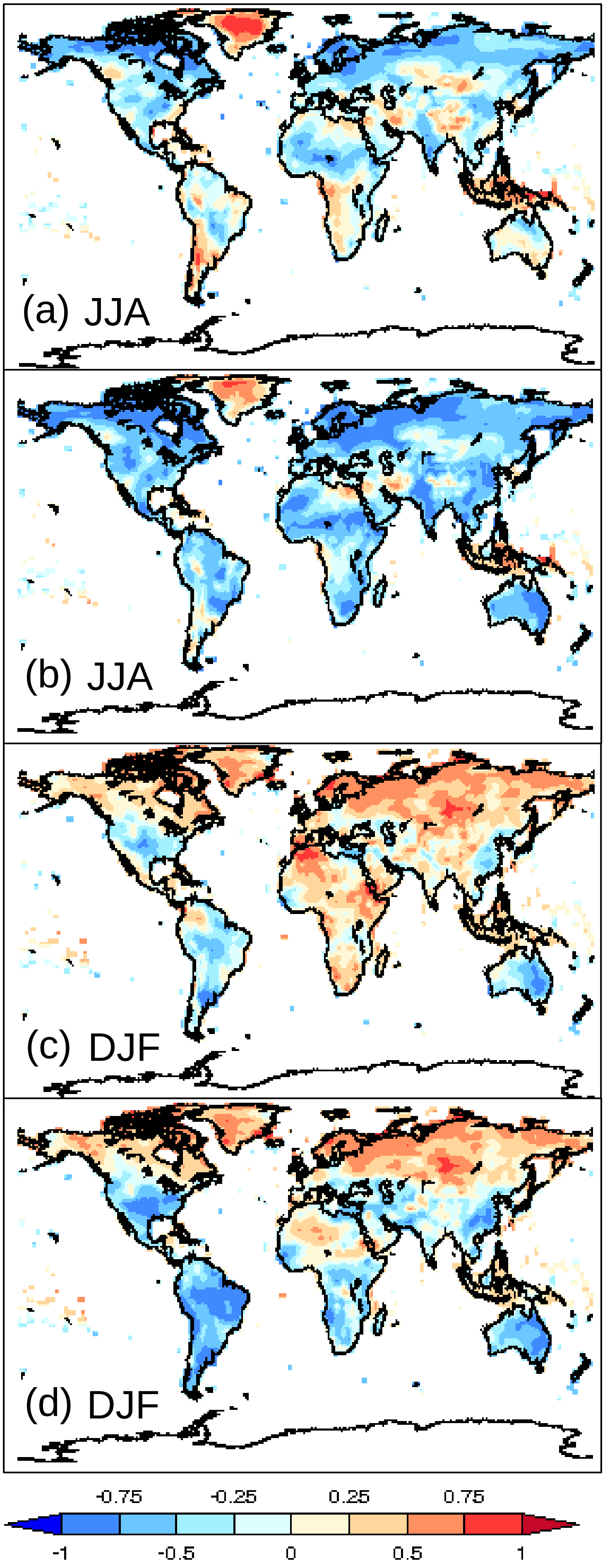
| Model Designation | Resolution | Originating group(s) | # runs* |
|---|---|---|---|
| GFDL-CM2.0 | 2.0 × 2.5° | GFDL, USA | 1, 1 |
| GFDL-CM2.1 | 2.0 × 2.5° | GFDL, USA | 1, 1 |
| GISS-ER | 4.0 × 5.0° | GISS, USA | 1, 1 |
| MIROC3.2(medres) | T42 | CCSR/NIES/FRCGC, Japan | 3, 3 |
| MIUB/ECHO-G | T30 | MIUB/METRI/MD Germ./Korea | 3, 3 |
| MRI-CGCM2.3.2 | T42 | MRI, Japan | 5, 5 |
| BCCR-BCM2.0 | T63 | BCCR, Norway | 1, 1 |
| CCCma-CGCM3.1(T47) | T47 | CCCma, Canada | 5, 3 |
| CNRM-CM3 | T63 | CNRM, France | 1, 1 |
| CSIRO-Mk3.0 | T63 | CSIRO, Australia | 3, 1 |
| ECHAM5/MPI-OM | T63 | MPI, Germany | 2, 1 |
| bigIPSL-CM4 | 2.5 × 3.75° | IPSL, France | 2, 1 |

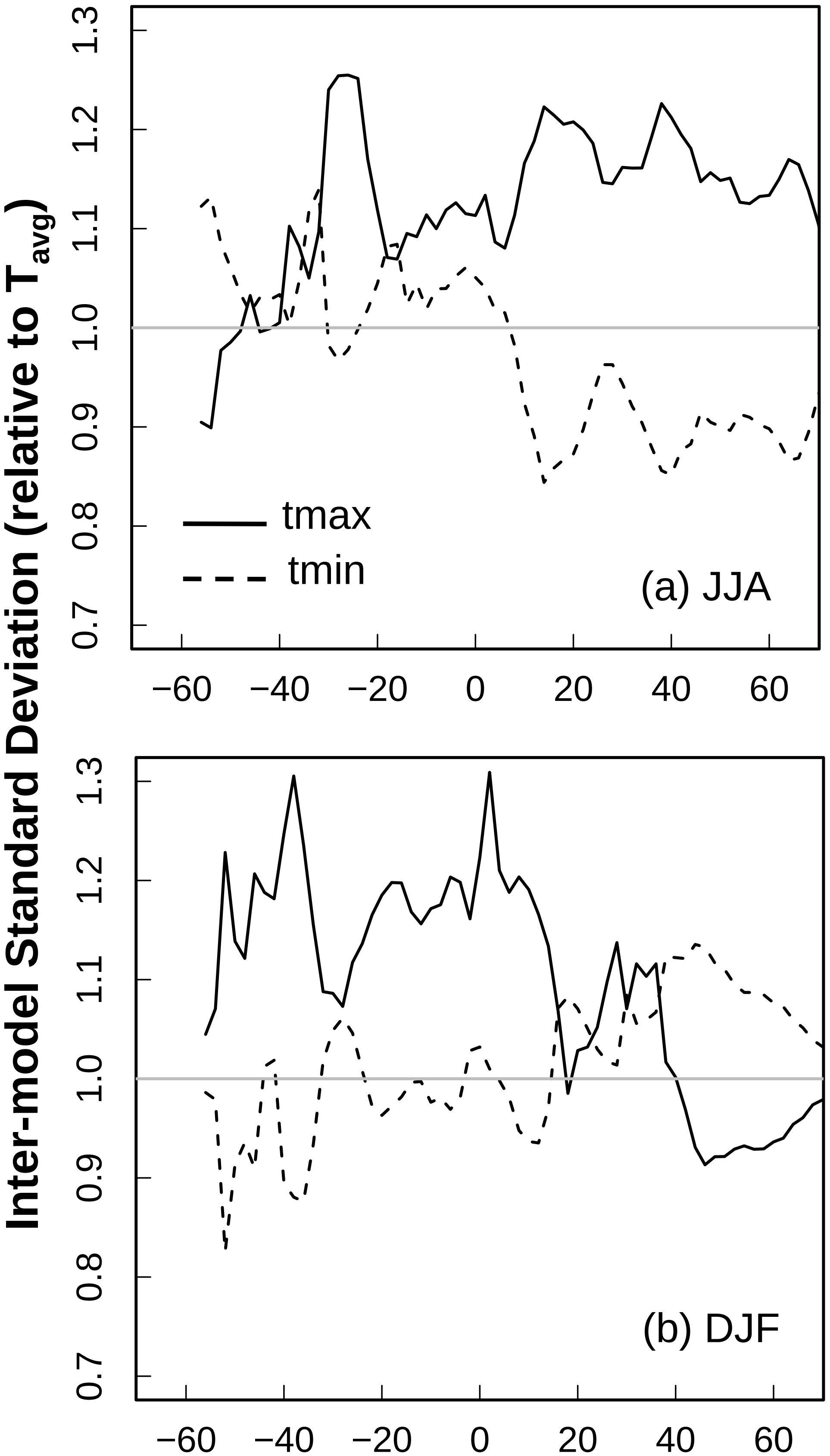
*number of realizations used for the 20th century (before comma) and A2 scenario (after comma) simulations

Table 2. Statistics of projected changes in June-August average daily minimum, maximum, and average temperatures over selected agricultural regions. Values are for 2046-2065 under an A2 emission scenario compared to 1961-1999. Statistics refer to mean, standard deviation, minimum, and maximum values, and range across the 12 climate models in Table 1.

| Region | | | $\Delta$ $T_{min}$ | | | | | $\Delta$ $T_{max}$ | | | | | $\Delta$ $T_{avg}$ | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Description | Latitude (ºN) | Longitude (ºE) | mean | s.d. | min | max | range | mean | s.d. | min | max | range | mean | s.d. | min | max | range |
| U.S. Corn Belt | 38-48 | -100 – -80 | 3.0 | 0.7 | 2.1 | 4.5 | 2.4 | 3.2 | 1.0 | 2.1 | 5.6 | 3.5 | 3.1 | 0.8 | 2.2 | 5.1 | 2.9 |
| Europe | 45-55 | -5 – 25 | 2.0 | 0.4 | 1.5 | 2.9 | 1.4 | 2.3 | 0.5 | 1.4 | 3.0 | 1.6 | 2.2 | 0.5 | 1.4 | 2.9 | 1.5 |
| India | 22-32 | 68 – 88 | 2.4 | 0.5 | 1.3 | 3.3 | 2.0 | 1.9 | 0.7 | 0.7 | 3.1 | 2.4 | 2.1 | 0.6 | 1.2 | 3.2 | 2.0 |
| Eastern China | 20-50 | 108 – 128 | 2.1 | 0.4 | 1.4 | 2.8 | 1.3 | 2.0 | 0.4 | 1.3 | 2.6 | 1.3 | 2.0 | 0.4 | 1.4 | 2.7 | 1.3 |
| California | 35-40 | -123 – -119 | 2.5 | 0.4 | 1.5 | 2.9 | 1.4 | 2.4 | 0.7 | 0.8 | 3.3 | 2.5 | 2.4 | 0.6 | 1.2 | 3.0 | 1.9 |


(a) JJA
0.4 0.8 1.2 1.6
0.2 0.6 1 1.4 1.8
(b)
-1.5 -0.5 0.5 1.5
-2 -1 0 1 2
(c)
0.4 0.8 1.2 1.6
0.2 0.6 1 1.4 1.8
(d) DJF
0.4 0.8 1.2 1.6
0.2 0.6 1 1.4 1.8
(e)
-1.5 -0.5 0.5 1.5
-2 -1 0 1 2
(f)
0.4 0.8 1.2 1.6
0.2 0.6 1 1.4 1.8


(a) JJA
(b) JJA
(c) DJF
(d) DJF
-0.75
-0.25
0.25
0.75
-1
-0.5
0
0.5
1


Inter-model Standard Deviation (relative to $T_{avg}$)
1.3
1.2
1.1
1.0
0.9
0.8
0.7
tmax
tmin
(a) JJA
−60
−40
−20
0
20
40
60
1.3
1.2
1.1
1.0
0.9
0.8
0.7
(b) DJF
−60
−40
−20
0
20
40
60
Latitude