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

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

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4 **Abstract**

5 Several impacts of climate change may depend more on changes in mean daily
6 minimum (T_{\min}) or maximum (T_{\max}) temperatures than daily averages. To evaluate
7 uncertainties in these variables, we compared projections of T_{\min} and T_{\max} changes by
8 2046-2065 for 12 climate models under an A2 emission scenario. Average modeled
9 changes in T_{\max} were slightly lower in most locations than T_{\min} , consistent with historical
10 trends exhibiting a reduction in diurnal temperature ranges. However, while average
11 changes in T_{\min} and T_{\max} were similar, the inter-model variability of T_{\min} and T_{\max}
12 projections exhibited substantial differences. For example, inter-model standard
13 deviations of June-August T_{\max} changes were more than 50% greater than for T_{\min}
14 throughout much of North America, Europe, and Asia. Model differences in cloud
15 changes, which exert relatively greater influence on T_{\max} during summer and T_{\min} during
16 winter, were identified as the main source of uncertainty disparities. These results
17 highlight the importance of considering separately projections for T_{\max} and T_{\min} when
18 assessing climate change impacts, even in cases where average projected changes are
19 similar. In addition, impacts that are most sensitive to summertime T_{\min} or wintertime
20 T_{\max} may be more predictable than suggested by analyses using only projections of daily
21 average temperatures.

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1 **1. Introduction**

2 Climate models are often characterized by their climate sensitivity, defined as the
3 equilibrium change in globally averaged surface temperature that results from a doubling
4 of atmospheric carbon dioxide (CO₂) levels [*Cubasch, et al., 2001*]. The range or
5 standard deviation of climate sensitivity among different models provides a common
6 measure of uncertainty in the response of the climate system to atmospheric CO₂
7 increases. For example, a range of 1.5 – 4.5 °C is commonly cited based on evaluation of
8 15+ models [*Cubasch, et al., 2001*], with recent studies suggesting this range should be
9 slightly higher [*Murphy, et al., 2004; Stainforth, et al., 2005*].

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

22 Much of the uncertainty in climate sensitivity has been attributed to model
23 differences in cloud behavior [*Soden and Held, 2006; Webb, et al., 2006*]. Increased

1 cloud cover, particularly of low clouds, leads to a greater fraction of reflected solar
2 radiation and therefore cooling of T_{\max} . In comparison, clouds have a relatively small net
3 effect on T_{\min} [Dai, *et al.*, 1999].

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

11

12 **2. Models and Methods**

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

1

2 **3. Results and Discussion**

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

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

21 Consistent with the hypothesis that projected T_{\max} changes are sensitive to cloud
22 cover and downwelling radiation, the greatest disparity between T_{\max} and T_{\min} uncertainty
23 was mainly observed during the local summer season (JJA in northern latitudes and DJF

1 in southern latitudes) when downwelling solar radiation was greatest. To further evaluate
2 the mechanism behind increased T_{\max} uncertainty, we computed the correlation across
3 models between projected changes in T_{\min} or T_{\max} and total cloud cover (Figure 2).
4 Modeled changes in T_{\max} were strongly and negatively correlated with changes in clt for
5 most locations in JJA and in southern latitudes and U.S. in DJF, reflecting the cooling
6 influence of increased clouds and reduced surface downwelling solar radiation on
7 daytime temperature. Correlations between clt and T_{\min} were comparatively smaller,
8 illustrating that uncertainty in cloud cover changes generally have less of an impact on
9 T_{\min} than T_{\max} .

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

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

1 deviations for T_{avg} in summer months, while uncertainty for T_{min} was roughly 10% lower
2 than for T_{avg} .

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

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

17 Consistent with global patterns, uncertainty in T_{max} was larger than for T_{min} for
18 most regions. For example, the inter-model range for T_{max} changes was 1.1 °C larger than
19 T_{min} in the U.S. Corn Belt and California, despite the fact that average changes in T_{max}
20 and T_{min} were similar. Previous work has demonstrated that T_{max} changes are more
21 important than T_{min} for U.S. maize yields, as water stress and development rates are both
22 more sensitive to T_{max} [Dhakhwa, *et al.*, 1997; Dhakhwa and Campbell, 1998; Schlenker
23 and Roberts, 2006]. Studies of climate change impacts on U.S. agriculture may therefore

1 underestimate uncertainties if using only projected changes in average temperatures.
2 Uncertainties for T_{\min} and T_{\max} were more similar in regions such as Europe and China,
3 and therefore use of T_{avg} in these regions may be less problematic.

4

5 **4. Conclusions**

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

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

21

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1 Figure Legends:

2

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

10

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

14

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

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1 Table 1. Climate models whose output was used in this study. See PCMDI web site
 2 (<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

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

5

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.

Description	Region		ΔT_{\min}					ΔT_{\max}					ΔT_{avg}				
	Latitude (°N)	Longitude (°E)	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





