Intensification of hot extremes in the United States

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[1] Governments are currently considering policies that will limit greenhouse gas concentrations, including negotiation of an international treaty to replace the expiring Kyoto Protocol. Existing mitigation targets have arisen primarily from political negotiations, and the ability of such policies to avoid dangerous impacts is still uncertain. Using a large suite of climate model experiments, we find that substantial intensification of hot extremes could occur within the next 3 decades, below the 2°C global warming target currently being considered by policy makers. We also find that the intensification of hot extremes is associated with a shift towards more anticyclonic atmospheric circulation during the warm season, along with warm-season drying over much of the U.S. The possibility that intensification of hot extremes could result from relatively small increases in greenhouse gas concentrations suggests that constraining global warming to 2°C may not be sufficient to avoid dangerous climate change. **Citation:** Diffenbaugh, N. S., and M. Ashfaq (2010), Intensification of hot extremes in the United States, *Geophys. Res. Lett.*, *37*, L15701, doi:10.1029/2010GL043888.

1. Introduction

[2] World governments are currently considering mitigation policies that will limit greenhouse gas (GHG) concentrations, including an international treaty to replace the expiring Kyoto Protocol [*United Nations Framework Convention on Climate Change* (*UNFCCC*), 2009]. Key questions include the level of GHG forcing that should be targeted and the urgency with which that target should be achieved, with considerable discussion oriented around trade-offs between avoiding policy-induced economic damage and GHG-induced climate damage [e.g., *Mastrandrea and Schneider*, 2004]. However, existing mitigation targets – such as the target of 2°C global warming above pre-industrial conditions set by world governments as part of the recent Copenhagen Accord [*UNFCCC*, 2009] – have arisen primarily from political negotiations. Although substantial scientific work has focused on the climate system response to varying GHG concentrations [*Mastrandrea and Schneider*, 2004; *Meehl et al.*, 2007b], there remains uncertainty as to whether "dangerous" climate change impacts could emerge below the target GHG envelope currently being considered by policy makers.

[3] Hot extremes, which are an important source of potential climate change impacts [e.g., *Battisti and Naylor*, 2009; *Poumadere et al.*, 2005; *Schlenker and Roberts*, 2009], can result from both large- and fine-scale climate processes. For instance, the 2003 European heat wave was associated with large-scale anticyclonic atmospheric anomalies [*Meehl and Tebaldi*, 2004], with local and regional land coupling both enhancing the large-scale circulation anomalies and accounting for more than half of the hot-day occurrence over much of the region [*Fischer et al.*, 2007b]. Likewise, the 20th-century Sahel drought has been attributed to a combination of large-scale ocean-atmosphere teleconnections and fine-scale land-atmosphere feedbacks [*Christensen et al.*, 2007]. Further, the response of hot extremes to high levels of GHG forcing appears sensitive to both large-scale atmospheric circulation and fine-scale surface-atmosphere interactions [*Diffenbaugh et al.*, 2005; *Meehl and Tebaldi*, 2004; *Seneviratne et al.*, 2006]. Quantification of the potential for near-term intensification of hot extremes therefore requires a climate modeling framework that can capture the uncertainties associated with both large- and fine-scale climate processes.

2. Methods

[4] We employ the RegCM3 nested climate model [*Pal et al.*, 2007], using the grid of *Diffenbaugh et al.* [2005], which covers the continental U.S. at 25-km horizontal resolution and 18 levels in the vertical. Our transient experiment includes five members simulating the period from 1950 to 2039 in the A1B emissions scenario [*Nackicenovic et al.*, 2000]. The first year (1950) is discarded to account for model equilibration. Each RegCM3 ensemble member uses the same parameterization options (as by *Diffenbaugh et al.* [2005]), with only the large-scale input varying between the members.

[5] Large-scale boundary conditions are provided by the NCAR CCSM3 [*Collins et al.*, 2006]. We use five of the CCSM3 simulations archived as part of the CMIP3 intercomparison [*Meehl et al.*, 2007a]. (These CCSM3 ensemble members are identified by NCAR as c, e, bES, fES, and gES.) In order to generate the necessary sub-daily, 3-dimensional atmospheric variables, we re-run the atmospheric component (CAM3) from 1948 to 2039, using the original CCSM3-generated SSTs and sea ice as boundary conditions for the global atmosphere [see *Trapp et al.*, 2009]. These CAM3 simulations use the same resolution as in the original CCSM3 simulations (T85 spectral truncation with 26 levels in the vertical). We also analyze GCM output from the CMIP3 climate model archive [*Meehl et al.*, 2007a], selecting the

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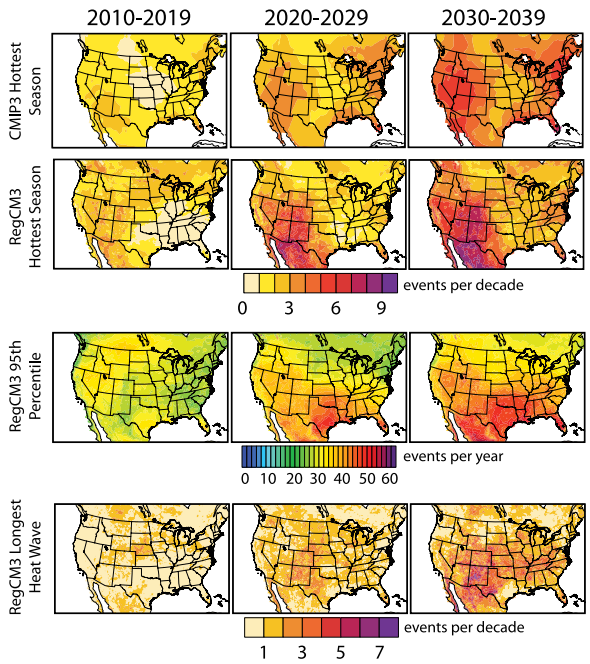

Figure 1. Projected changes in heat extremes in the coming decades. The top two rows show the decadal occurrence of the 1951–1999 hottest-season threshold in the CMIP3 and RegCM3 ensembles. The third and fourth rows show the decadal occurrence of the 95th -percentile daily maximum threshold (T95) and the historical hottest-heat-wave threshold for the RegCM3 ensemble.

output from "run 1" of each of the 22 GCMs that archived monthly surface air temperature results for the A1B scenario.

[6] We first calculate the hottest season of the 1951–1999 period at each grid point. Both the CMIP3 and RegCM3 ensembles are able to capture the observed magnitude and pattern of hottest-season and mean-summer temperature in the U.S. (Figure S1 of the auxiliary material).[1] The simulation of interannual variance of summer temperature is less accurate, with over-estimation of variance in the central U.S. (Figure S1). (*Walker and Diffenbaugh* [2009] diagnose the RegCM3 warm-season temperature biases over the U.S., including biases in the atmospheric circulation and moisture.) For each 21st century model realization, we calculate the number of exceedences of the hottest season of the respective 1951–1999 period. We then calculate the ensemble mean and standard deviation across the respective ensemble members.

[7] In addition, because of the availability of sub-daily output from the RegCM3 realizations, we are also able to calculate the occurrence of the annual-scale 95th -percentile daily maximum temperature (T95), and of the longest historical heat wave. For the former, which quantifies the frequency of exceedence of the present tail of the daily temperature distribution, we follow *Diffenbaugh et al.* [2005], using the 1980–1999 period as a baseline. In this approach, the T95 threshold at each grid point is calculated as the mean of the daily maximum temperature values from the 18th hottest day of each year in the baseline period. For the latter, we apply the heat wave duration index of *Frich et al.* [2002] to find the longest heat wave of the 1951–1999 period, along with the 21st century occurrence of heat waves that are at least as long as this historical maximum. As with the historical hottest season exceedence, we calculate the baseline and exceedence values at each grid point, and for each decade of the 2010–2039 period.

3. Results

[8] We find that the exceedence of the historical hottest-season threshold increases over the next three decades in the A1B scenario (Figure 1). The intensification of hot extremes emerges quickly in the RegCM3 simulations, with 3 to 4 exceedences per decade over large areas of the U.S. in the 2010–2019 period (Figure 1) (with an intra-ensemble standard deviation (S.D.) of 2 to 3 exceedences per decade over most of the U.S. (Figure S2)). This emergence intensifies in the 2020–2029 period, with up to 8 exceedences per decade over the western U.S. (S.D. of 3 to 4), and up to 4 exceedences per decade over much of the eastern U.S (S.D. of 2 to 3). Further, in the 2030–2039 period, most areas of Utah, Colorado, Arizona and New Mexico experience at least 7 exceedences per decade (S.D. of 3 to 4), and much of the rest of the U.S. experiences at least 4 exceedences per decade (S.D. of 2 to 5 over most areas). The summer warming in the RegCM3 ensemble is not uniform, with greater increases in the mean in the eastern U.S. than the western U.S. (Figure S3), along with increased variance in the northcentral U.S., increased skewness in the southwestern and southeastern U.S., and decreased kurtosis throughout most of the continental U.S. (Figure S3). The intensification of hottest-season exceedence is similar in the CMIP3 ensemble (compared with the RegCM3 ensemble), including up to 6 exceedences per decade over the western and northeastern U.S. in the 2030–2039 period, and up to 8 exceedences per decade over parts of the southeastern U.S. (with S.D. of 4 over most of the western and eastern U.S., and 3 over most of the central U.S.). However, the intensification of seasonal hot extremes emerges more quickly and strongly in the RegCM3 ensemble, particularly over the western U.S., where the higher-resolution topographic boundary condition leads to a more accurate representation of extreme seasonal temperature values (Figure S1).

[9] The annual occurrence of the T95 threshold exceeds 30 days per year over much of the U.S. during the 2020–2029 period (Figure 1) (S.D. of 2 to 12 (Figure S2)), with peak occurrence of up to 52 days per year over Texas and Florida (S.D. of 10 to 24). T95 occurrence exceeds 38 days per year over much of the U.S. in the 2030–2039 period (S.D. of 4 to 16), with the area exceeding 46 days per year expanding to include most of the southern Great Plains and much of the Gulf Coast region (S.D. of 10 to 24). Likewise, the area experiencing at least one exceedence of the historical heat wave threshold per decade covers most of the U.S. in the 2020–2029 period, including up to 5 exceedences per decade over areas of the western and central U.S. (Figure 1) (S.D. of 1 to 5 over most of the U.S. (Figure S2)). Occurrence of the longest historical heat wave further intensifies in the 2030–2039 period, including greater than 5 occurrences per decade over much of the western U.S., and

[1]Auxiliary materials are available in the HTML. doi:10.1029/2010GL043888.

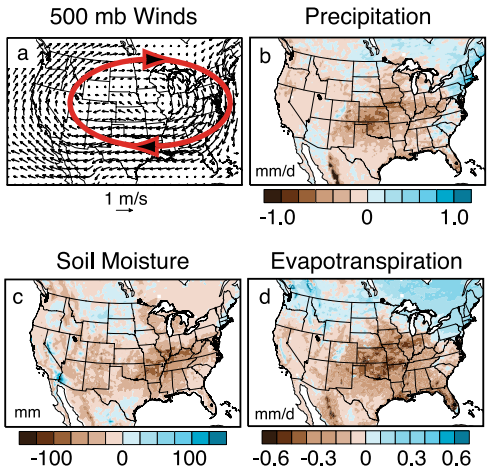

Figure 2. Changes in summer (a) 500 mb winds, (b) precipitation, (c) total soil moisture, and (d) evapotranspiration in the RegCM3 ensemble. Changes are calculated as 2030–2039 minus 1980–1999 for June-July-August. The ellipse and large arrows in Figure 2a are added for emphasis.

greater than 3 exceedences per decade over much of the eastern U.S. (S.D. of 3 to 7 over most of the U.S.).

4. Discussion

[10] The intensification of hot extremes in the RegCM3 ensemble is associated with warm-season drying over much of the U.S. (Figure 2). By the 2030–2039 period, a summer anticyclonic circulation anomaly develops aloft (at 500 mb) over most of the continental U.S. Associated with this anticyclonic anomaly are decreases (2030–2039 minus 1980–1999) in precipitation (exceeding −1.0 mm/day), total soil moisture (exceeding −125 mm), and evapotranspiration (exceeding −0.6 mm/day). Although the ensemble-mean large-scale circulation anomalies are very similar between the driving CAM3 and nested RegCM3 ensembles in the autumn, winter and spring, the summer anticyclonic anomaly is more widespread in RegCM3 than CAM3 (Figure S4).

[11] We find that the coupling of changes in summer temperature, precipitation and soil moisture is robust across the model realizations. For the 2030–2039 period, all five RegCM3 members exhibit a negative correlation between changes in summer total soil moisture and changes in summer temperature, and a positive correlation between changes in summer total soil moisture and changes in summer precipitation (Figure 3). (The ensemble mean correlation is −0.35 for change in temperature and 0.37 for change in precipitation.) We also find that all five RegCM3 members exhibit a decrease in summer total soil moisture across the domain. (The ensemble mean fractional change in total soil moisture is −0.02.) For the CMIP3 ensemble, we find that 89% of the realizations show a negative (positive) correlation between changes in summer soil moisture and changes in summer temperature (precipitation). (The ensemble mean correlation is −0.28 for change in temperature and 0.30 for change in precipitation.) We also find that 78% of the GCM realizations show a decrease in summer total soil moisture across the domain for the 2030–2039 period. (The ensemble mean fractional change in total soil moisture is −0.03.)

[12] Surface drying associated with anticyclonic circulation anomalies is thought to have amplified severe hot and dry events such as the 1988 event in the U.S. [*Chen and Newman*, 1998] and the 2003 event in Europe [*Fischer et al.*, 2007b], and has been identified as a key regulator of changes in climate variability in response to elevated GHG forcing [*Seneviratne et al.*, 2006]. The fact that most of the GCM realizations simulate soil-moisture/temperature/precipitation relationships of the same sign as the RegCM3 ensemble suggests that the coupling is likely to be robust over the U.S., a result that supports previous work [e.g., *Fischer et al.*, 2007a; *Lorenz et al.*, 2010; *Seneviratne et al.*, 2006]. However, although we have identified correlations between changes in temperature, precipitation, and soil moisture that are robust across a large suite of climate model experiments, it is not clear from the analysis of these experiments alone whether the surface drying is the cause of the intensified hot extremes. For instance, the decreases in soil moisture could be a product of decreases in precipitation (Figure 2) and/or increases in net surface radiation (Figure S5) associated with the changes in large-scale circulation (Figure 2). Targeted experiments that physically isolate moisture fluxes, radiation fluxes, and atmospheric circulation (as by *Seneviratne et al.* [2006]) are necessary in order to fully determine causation.

[13] The spread within the CMIP3 ensemble (in which multiple GCMs are included) is greater than the spread within the RegCM3 ensemble (in which only one GCM-RCM combination is included) (Figures S2 and 3). Earlier work using an RCM nested within an atmosphere-only GCM suggests that some of the spread in our nested

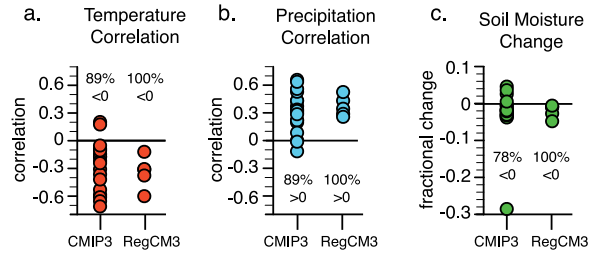

Figure 3. Simulated relationships between summer temperature, precipitation, and soil moisture in the RegCM3 and CMIP3 ensembles. (a) Correlation between the change in summer temperature and the change in summer soil moisture for the 2030–2039 period. (b) Correlation between the change in summer precipitation and the change in summer soil moisture for the 2030–2039 period. (c) Change in summer soil moisture for the 2030–2039 period. Each circle represents one model realization. We first calculate the change in mean summer temperature, precipitation and soil moisture for the 2030–2039 period (relative to the 1980–1999 period, with the change in total soil moisture calculated as a fraction of the 1980–1999 summer mean). We then calculate the correlation between the change in temperature (precipitation) and the change in soil moisture across the land grid points that encompass the RegCM3 domain. The CMIP3 ensemble uses "run 1" from the 18 CMIP3 GCMs archiving total soil moisture.

ensemble could be generated by internal atmospheric variability [*Dutton and Barron*, 2000]. The fact that our high-resolution ensemble is nested within an ensemble of coupled AOGCM experiments further enhances the effects of internal variability on the ensemble simulation. This atmosphere-ocean internal variability dominates the near-term "uncertainty" in the CMIP3 ensemble [*Hawkins and Sutton*, 2009]. However, by the mid-century, structural uncertainty from different model formulations is greater than that from internal variability [*Hawkins and Sutton*, 2009], suggesting that multiple GCM-RCM combinations could yield greater spread than is seen in our nested simulations.

[14] Our results suggest that near-term increases in GHG forcing could result in warm-season drying and intensification of hot extremes throughout much of the U.S. Indeed, all of the individual RegCM3 ensemble members exhibit at least 6 hottest-season occurrences in the 2030–2039 period over much of the western U.S. (Figure S6). However, the members vary in the level of hot event intensification in the eastern U.S., with three of the members showing substantial intensification in the 2030–2039 period, and two of the members showing very little intensification (Figure S6). (For reference, the RegCM3 f-member shows the greatest summer warming over the continental U.S. in the 2030–2039 period, while the g-member shows the least.) The variation seen within the physically-uniform RegCM3 ensemble (Figures S2, S3, and 3) suggests a strong influence of internal variability on decadal-scale changes in regional- and local-scale hot extremes.

5. Conclusions

[15] Because of the known sensitivity of natural and human systems, intensification of hot extremes could carry substantial impacts. At the end of the 2030–2039 period, the expected global mean temperature change relative to the late 20th century ranges from 1.0 to 1.7°C in the CMIP3 A1B scenario [*Meehl et al.*, 2007b], and from 1.1 to 1.3°C in the CCSM3 ensemble [*Meehl et al.*, 2006]. Given the IPCC calculation of approximately 0.8°C of global warming from the mid-19th century to the late 20th century [*Trenberth et al.*, 2007], the CMIP3 ensemble warming above pre-industrial conditions is approximately 1.8 to 2.5°C by the year 2040, while the CCSM3 ensemble is approximately 1.9 to 2.1°C. Further, given that global warming is likely to continue for decades after stabilization of GHG concentrations [*Meehl*, 2005], and that the late-21st century warming in the A1B scenario ranges from 2.25 to 4.25°C above the late 20th century [*Meehl et al.*, 2007b], the response to a given GHG stabilization target is likely to be greater than to the equivalent concentrations within the transient trajectory tested here. Although accurate decadal-scale climate prediction represents a significant challenge [e.g., *Meehl et al.*, 2009], the intensification of hot extremes reported here suggests that constraining global warming to 2°C above pre-industrial conditions may not be sufficient to avoid dangerous climate change.

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