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Changes in extreme, cold-season synoptic precipitation events under global warming

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Abstract
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1. Introduction

[2] Changes in extreme precipitation can have strong impact on human and natural systems and thus are an important aspect of global warming [e.g., *Field et al.*, 2007; *Kundzewicz et al.*, 2007]. Global climate models produce increased extreme precipitation under greenhouse-warming scenarios [*Wehner*, 2005; *Kharin et al.*, 2007]. Because verification of projections decades into the future is not possible at this time, other means of attaining confidence in such projections are needed. Understanding the physical basis for increases in extreme precipitation is one means for increasing confidence in projections. Confidence in projected changes in extremes also increases when the physical mechanisms producing extremes in models are consistent with observed behavior. Physical consistency of simulations with observed behavior is necessary, though not sufficient, evidence for accurate projection.

[3] Here, we assess model simulations of extreme cold season precipitation linked to synoptic weather patterns. Specifically, we examine extreme daily precipitation events in the central United States that cover several observation sites or several grid points in a regional climate model (RCM). We term these widespread extreme events. By restricting our analysis to such widespread events, we are assuming that the hydroclimate dynamics producing the events are resolvable by the RCM, so that the model should replicate observed behavior. Thus, we compare simulations of contemporary climate with observations and assesses whether or not the simulated widespread extreme events have the same physical basis as observed events. We also examine similar events in a future scenario, assessing the physical basis for changes between contemporary and projected climates.

2. Observations, Simulations and Analysis Methods

2.1. Observations

[4] Observed daily precipitation comes from cooperative climate-observing-network data archived by the U.S. National Climatic Data Center. *Eischeid et al.* [2000] and *Clark and Hay* [2004] extracted the observations used here and provided quality control assessments. We use data for the 1980s, but to mesh with other analyses we are performing, we required all stations used here to report for the period 1950–1999 with no more than 7.5% missing or questionable data. We assumed that continuity of record over a 50-year period implied reliability and thus an acceptable quality level in the data. Our analysis focused on an Upper Mississippi basin (UMS) region (Figure 1), for which 476 stations met our reliability criterion.

[5] We also evaluate the synoptic circulation associated with observed extreme precipitation as our basis for understanding the environment conducive to the extremes. For this part of the analysis, we use 500 hPa geopotential heights from the reanalysis [*Kanamitsu et al.*, 2002] produced by the National Centers for Environmental Prediction (NCEP) and the U.S. Department of Energy.

2.2. Simulations

[6] Model output used here came from contemporary and future-scenario periods simulated by the Second-Generation Regional Climate Model (RegCM2) [*Giorgi et al.*, 1993a, 1993b]. Simulations used the continental U.S. domain shown in Figure 1, with 50-km grid spacing. For this domain, the model had 316 grid points in the UMS region (Figure 1). Reanalysis or global climate model (GCM) output provided initial and lateral boundary conditions. The model computed precipitation using the *Grell* [1993] convection parameterization and a simplified version [*Giorgi and Shields*, 1999] of the *Hsie et al.* [1984] explicit moisture scheme. *Pan et al.* [2001] and *Gutowski et al.* [2007] provide further details of the model configuration.

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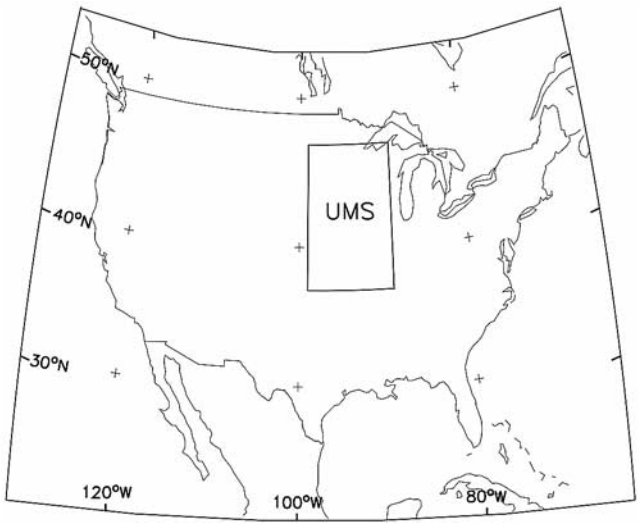

Figure 1. Simulation domain and the location of the Upper Mississippi analysis box.

[7] The reanalysis simulation used the reanalysis produced by NCEP and the National Center for Atmospheric Research [*Kalnay et al.*, 1996] for lateral boundary conditions, supplemented by observations of surface temperatures in the Gulf of California and the North American Great Lakes. The simulations spanned October 1978 to December 1988. GCM-driven simulations used output from the Hadley Centre Climate Model, Version 2 (HadCM2) [*Johns et al.*, 1997]. The HadCM2 contemporary-climate simulation had effective greenhouse gases corresponding roughly to the 1990s. The HadCM2 scenario-climate simulation assumed a 1% per year increase of effective greenhouse-gas concentrations after 1990. The period for the scenario-climate was the decade 2040–2049 [*Pan et al.*, 2001]. Here, we refer to the contemporary and future RCM climates driven by HadCM2 as the control and scenario simulations, respectively, and the climate change is the scenario minus control difference. To reduce influences of spin-up and because of storage problems, we used only the final 8 years of the NCEP-driven simulation and the final 9 years of the GCM-driven runs. Analysis of observations covered the same 8-year period as the NCEP-driven run, 1981–1988. Further details of this simulation suite are given by *Pan et al.* [2001].

[8] Updated versions exist for the RCM, the GCM and the reanalysis boundary conditions used here. However, we have studied a variety of hydroclimate issues using this simulation suite, such as downscaling for simulating surface hydrology [*Wilby et al.*, 2000; *Hay et al.*, 2002; *Jha et al.*, 2004], extreme precipitation events [*Kunkel et al.*, 2002], a seasonal precipitation deficit in GCM and RCM simulations [*Gutowski et al.*, 2004], and a possible constraint on precipitation intensity changes [*Gutowski et al.*, 2007]. We thus have substantial understanding of the behavior of this well-analyzed suite, which aids our diagnosis. The physical basis for our results here also suggests that they are not strongly dependent on the specific models used.

2.3. Analyses

[9] We extracted extreme events using the precipitation-versus-intensity analysis presented by *Gutowski et al.* [2007]. A precipitation event in the analysis was a nonzero daily amount at one observing site or one model grid box in the UMS region (Figure 1). We pooled all such events from the observations and, separately, for each RCM simulation. In each case, we extracted events exceeding the 99.95th percentile as the extreme daily events analyzed here. We thus consider highly extreme precipitation in this analysis [cf. *Groisman et al.*, 2005]. From these events, we then found widespread extremes by searching for multiple extreme events occurring on the same day. We focused on the cold half of the year, October–March, under the assumption that synoptic dynamics are more likely to play a role in extreme widespread events during this part of the year compared to the warm half, when smaller scale convective events may be more important. For synoptic events, the model should resolve the relevant circulation, which it may not be able to do as well for convection-dominated events.

3. Widespread Extreme Precipitation

[10] The model reproduces well the observed average precipitation for the UMS region during October–March (Table 1). In addition, *Gutowski et al.* [2007] show that the NCEP-driven simulation for the UMS region during October–March produces intensities that agree fairly well with observations out to about the 95th percentile. The GCM-driven control simulation averages 13% more precipitation than observations, but the GCM driving does not seriously distort the precipitation frequency versus intensity distribution [*Gutowski et al.*, 2007].

[11] For higher percentiles, the model's precipitation intensity is much weaker than observed (Table 1). The difference is due to difficulties climate models have in simulating the intensity of extreme events as strongly as observed [e.g., *Gutowski et al.*, 2003, 2007], which is at least partly a consequence of relatively coarse resolution versus the dynamics directly producing intense condensation. The scenario-simulation threshold increases by about the same amount (17%) over the control simulation as the climate change for average precipitation.

[12] Extreme precipitation can occur simultaneously at several UMS observing stations or several model grid points. We extract for further analysis days for which at least 10 model grid points or observation sites have extreme precipitation, defining these to be widespread extreme events. For the simulations, the upper 0.05% of all precipitation events includes about 230 daily events in each simulation, spread among all grid points over the analysis period. Of these, 50–70% (depending on the simulation)

Table 1. Average Precipitation and Precipitation Rate for the 99.95th Percentile for the Cold Half of the Year in Observations and Model Simulations Driven by the NCEP Reanalysis or GCM Control and Scenario Climates

SOURCE	Average (mm/d)	99.95% (mm/d)
Observations	1.61	120.0
NCEP-driven	1.66	42.2
Control	1.82	43.2
Scenario	2.14	50.3

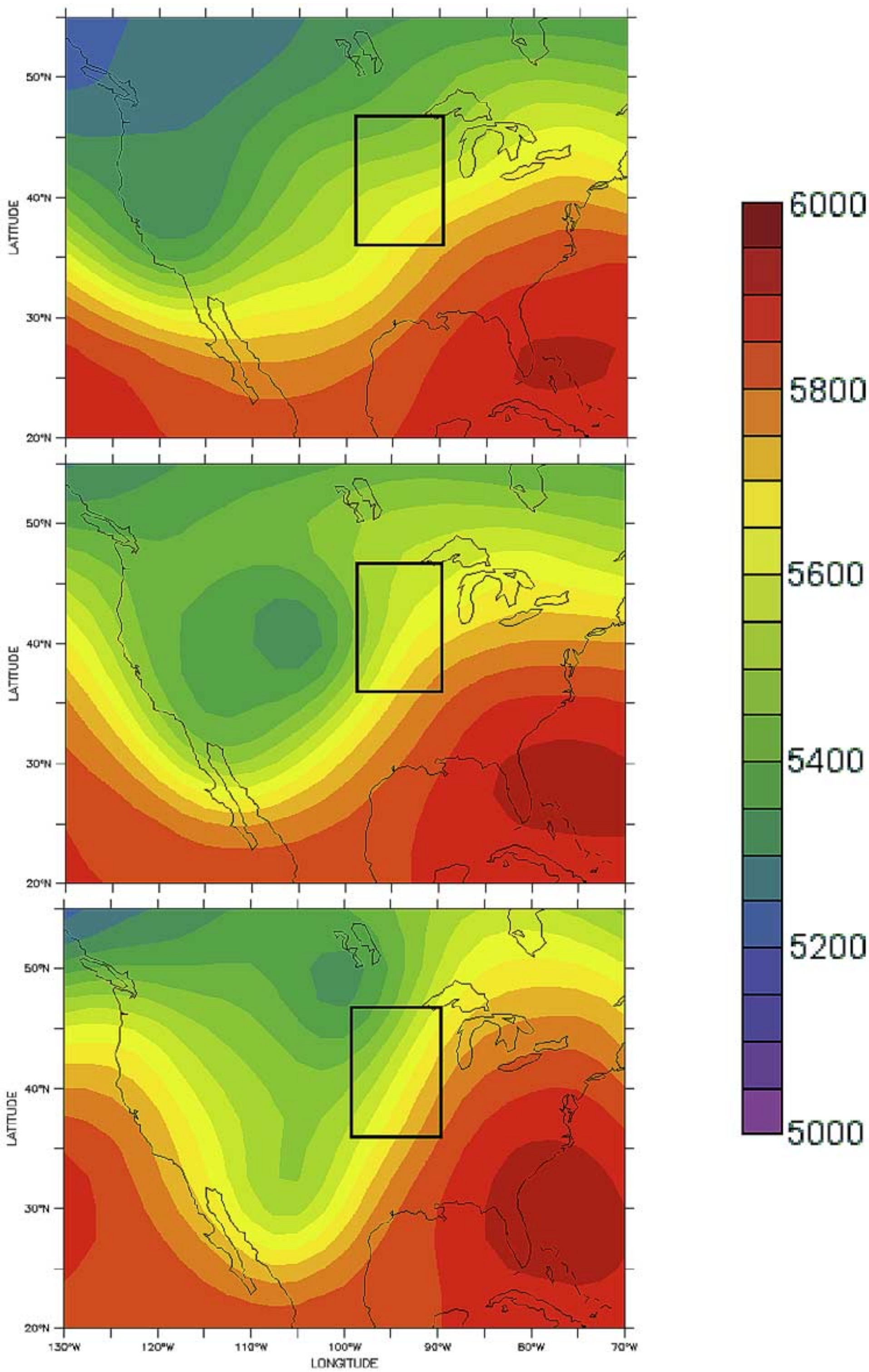

Figure 2. Example of 500 hPa geopotential heights at 00 UTC during an observed widespread extreme precipitation event in the Upper Mississippi region (boxes) for (top) 1 day before the event (1 Dec 1982), (middle) the day of the event (2 Dec 1982) and (bottom) 1 day after the event (3 Dec 1982). The contours are every 50 meters.

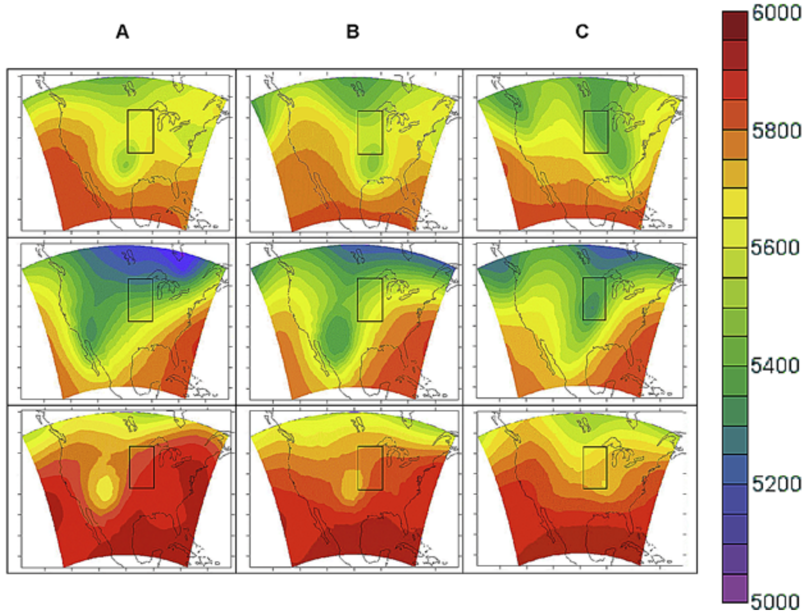

Figure 3. Examples of 500 hPa geopotential heights at 00 UTC during simulated widespread extreme precipitation events in the Upper Mississippi region (boxes) (a) for 1 day before the event, (b) the day of the event and (c) 1 day after the event. Examples are from (top) the NCEP-driven run, (middle) the GCM-driven control run and (bottom) the GCM-driven scenario run. The contours are every 50 meters.

occur in widespread events, as we define them. There are 6 days with such widespread events in the observed UMS precipitation, whereas the simulations have 7 (NCEP-driven), 8 (control) and 5 (scenario) days with widespread events, so that the events examined here occur on average every 1–2 years.

[13] The difference in threshold levels between observations and simulations might suggest that simulations offer little insight into the changes in extreme daily precipitation. However, the surface saturation humidity in the region increases by approximately 17% from the control to scenario simulations due to a warming of 2.5°C. Extreme precipitation should increase by about the same amount in a warming climate [*Trenberth et al.*, 2003], so the 17% increase in threshold precipitation intensity agrees with theoretical expectations, even though the actual amount for the current climate is less than observed.

4. Synoptic Conditions

[14] We diagnosed synoptic conditions associated with these events by examining 500 hPa geopotential heights at 00 UTC for the day of the event as well as the day before and the day after. The 500 hPa circulation for nearly all of these widespread extreme events has a cut-off low or deep trough over the center of the United States (e.g., Figures 2 and 3). Typically the cut-off low or deep trough is present at about the same location the day before, so that it is slow moving or even stationary. These features indicate that the flow is equivalent barotropic, so that during this period the lower level circulation is transporting substantial moisture from the Gulf of Mexico into the center of the U.S. The circulation pattern often continues the day after the widespread extreme precipitation event, but for only about two-thirds of the events examined here. The key synoptic transport process to the event appears to be persistent flow from the Gulf of Mexico that allows the Upper Mississippi River Basin to import substantial moisture for its extreme event.

[15] An important feature of the results in Figures 2 and 3 is that the observed and simulated events all have the same synoptic behavior. Thus, even though the model has difficulty in simulating the intensity of extreme precipitation, it reproduces the observed 500 hPa circulation associated with the observed widespread extreme events. This suggests that the model can still be used to assess the processes producing extreme precipitation, even if the precipitation amount itself is less extreme than observed. In other words, we can place more confidence in the quality of the circulation simulation associated with extreme behavior than in the resulting precipitation amount.

[16] Figure 3 also shows that the 500 hPa circulation associated with these extreme events is essentially the same in the NCEP-driven, control and scenario simulations. According to the RCM used here, the circulation pattern and wind speeds for widespread extreme daily precipitation

Table 2. Monthly Occurrence of Widespread Extreme Events in Observations and Model Simulations Driven by the NCEP Reanalysis or GCM Control and Scenario Climates

SOURCE	Oct	Nov	Dec	Jan	Feb	Mar
Observations	5	2	2		2	
NCEP-driven	2	1	1	1		2
Control	2	2	3	1		1
Scenario	3	1				1

in the UMS cold season do not change with climate change. Instead, the warmer climate allows more atmospheric moisture, which can and, in these cases, does lead to more precipitation in the widespread extreme events.

[17] We have also tabulated the monthly occurrence of the extreme events examined here (Table 2). In the observations and in each simulation, most of the events occur in the first half of the cold season. This feature is consistent with the circulation pattern producing the extremes: the waters of the Gulf of Mexico are warmer on average during September–December than January–March, so they can potentially evaporate more moisture into the atmosphere for transport into the central U.S. Thus, the model responds to the physical environment in the same way as the observations. In addition, the Gulf of Mexico warms by about 2°C between the control and scenario climates, suggesting a 14% increase in moisture in its overlying atmosphere and a corresponding increase in moisture transport to the central U.S., which is roughly the same as the increase in extreme precipitation. However, the 10 of 11 observed events extend over two days, whereas only 2 of the 20 simulated events occur as a two-day event. The simulated extremes do not last as long as the observed extremes.

5. Conclusions

[18] The regional climate model examined here, RegCM2, reproduces the observed synoptic conditions associated with widespread extreme daily precipitation during the cold half of the year for our Upper Mississippi River Basin box. This circulation behavior occurs even though the simulated extreme precipitation amount is low compared to the observed precipitation for the same percentile range. The result suggests that circulation analyses may give more robust indication of the occurrence and change in extreme precipitation events, which is consistent with findings by others that precipitation downscaled from circulation changes in multiple GCMs can provide a more consistent projection of precipitation change than the GCMs' precipitation [e.g., *Hewitson and Crane*, 2006].

[19] The model's scenario climate has the same synoptic conditions for widespread extreme precipitation as its contemporary climate. This suggests that there are no shifts in circulation regime for the extremes examined here. Rather a more important factor is the amount of moisture the atmosphere can contain, which is greater in a warmer climate. Moreover, the increase in the extreme precipitation threshold examined here is consistent with expectations based on changes in saturation humidity from the temperature increase. This suggests that one can estimate how such events will change in a future climate. Thus, a simple extrapolation based on the consistency of circulation patterns and a 2.5°C warming suggests that the 95.95% threshold for such events will be about 140 mm/d in the warmer climate, an increase of 20 mm/d.

[20] These results are from one RCM driven by one GCM. Although the behavior examined is physically plausible, confirmation from other models is needed. The emerging results from the North American Regional Climate Change Assessment Program (2008, http://narccap.ucar.edu) should provide such an opportunity.

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