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Summer aridity in the United States: Response to mid-Holocene changes in insolation and sea surface temperature

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[1] We examine the response of summer precipitation to mid-Holocene insolation forcing and insolation-induced changes in sea surface temperature. Using a high-resolution nested climate modeling system, we find that mid-Holocene insolation forcing results in drier-than-present conditions over the central continental United States (U.S.) and northern Rocky Mountains, as well as wetter-than-present conditions over the Atlantic seaboard and northwestern Great Plains. We find that changes in summer precipitation are dominated by changes in large-scale processes, with similar patterns of change in the global and nested models. We also find that insolation-induced changes in sea surface temperature do not change the basic pattern of precipitation response, primarily because the dynamical response is very similar with and without sea surface temperature changes. Notably, drier-than-present conditions over the central U.S. are associated with enhanced anticyclonic circulation aloft over the mid-continent and reduced low-level moisture content over the Gulf of Mexico and south-central U.S., while wetter-than-present conditions over the Atlantic seaboard are associated with enhanced low-level cyclonic circulation and elevated low-level moisture content. The simulated patterns of precipitation and soil moisture agree with proxy moisture records from most regions, indicating both that insolation was the strongest determinant of mid-Holocene summer aridity in the continental U.S. and that high-resolution nested climate modeling systems are able to capture the basic response of midlatitude warm-season aridity to changes in external climate forcing. **Citation:** Diffenbaugh, N. S., M. Ashfaq, B. Shuman, J. W. Williams, and P. J. Bartlein (2006), Summer aridity in the United States: Response to mid-Holocene changes in insolation and sea surface temperature, *Geophys. Res. Lett.*, *33*, L22712, doi:10.1029/2006GL028012.

1. Introduction

[2] Global climate differed from present during the mid-Holocene (approximately 8,000 to 3,000 years before present), with proxy records indicating substantial alterations of terrestrial moisture balance [e.g., *Kohfeld and Harrison*, 2000] and temperature [e.g., *Thompson et al.*, 1993], as well as ocean circulation [e.g., *Findlay and Giraudeau*, 2002] and variability [e.g., *Friddell et al.*, 2003]. The proxy record from the continental United States (U.S.) indicates drier-than-present conditions in the Pacific Northwest [*Mock and Brunelle-Daines*, 1999], the central U.S. (e.g., summary by *Harrison et al.* [2003], and the northeastern U.S. [e.g., *Shuman et al.*, 2004], along with wetter-than-present conditions in the southwestern U.S. [*Harrison et al.*, 2003; *Mock and Brunelle-Daines*, 1999] and the southeastern U.S. [e.g., *Shuman et al.*, 2002]. Proxy data also indicate that changes in summer precipitation played a major role in shaping mid-Holocene moisture balance in North America [e.g., *Bartlein et al.*, 1998; *Grimm*, 2001; *Mock and Brunelle-Daines*, 1999; *Thompson et al.*, 1993].

[3] Relative to the modern pre-industrial period, the primary difference in external climate forcing during the mid-Holocene was the seasonality and latitudinal distribution of insolation [*Kutzbach et al.*, 1998]. There is dynamical evidence that enhancement of the summer insolation maximum enhanced the Southwest summer monsoon [*Bartlein et al.*, 1998; *Harrison et al.*, 2003], and that this monsoon amplification suppressed summer precipitation in the central U.S. [*Harrison et al.*, 2003]. Additionally, modern climate analogues suggest that changes in summer large-scale circulation, including anticyclonic surface flow over the mid-continent and a stronger subtropical ridge aloft, explain the mid-Holocene pattern of effective moisture in the western U.S. [*Mock and Brunelle-Daines*, 1999]. Atmosphere-ocean feedbacks could also have played an important role in shaping mid-Holocene moisture balance in North America [e.g., *Harrison et al.*, 2003; *Shin et al.*, 2006], particularly given the critical role that sea surface temperature (SST) variability plays in regulating terrestrial aridity at present [e.g., *Schubert et al.*, 2004].

[4] Dynamical investigations of mid-Holocene aridity in the continental U.S. have focused on large-scale processes [e.g., *Bartlein et al.*, 1998; *Harrison et al.*, 2003; *Shin et al.*, 2006]. Although considerable attention has been paid to the potential role that complex topography, land cover, and coastal interfaces could play in shaping the response of precipitation to elevated greenhouse gas concentrations [e.g., *Diffenbaugh et al.*, 2005], the influence of fine-scale processes on the response of precipitation to insolation variability remains unconstrained. Thus, we use a high-resolution nested climate modeling system to test the relative roles of large- and fine-scale processes in shaping

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the response of summer aridity to mid-Holocene insolation forcing and insolation-induced changes in SST.

2. Models and Methods

2.1. Nested Climate Modeling System

[5] We employ the Abdus Salam ICTP regional climate model (RegCM3) [*Pal et al.*, 2006] and the NCAR Community Climate System Model (CCSM3) [*Collins et al.*, 2006]. RegCM3 is a 3-dimensional, primitive equation, sigma-coordinate, high-resolution nested regional climate model (RCM). Our RegCM3 grid and physics parameter values follow those of *Pal et al.* [2000]. The grid covers the continental U.S. and surrounding areas with a horizontal resolution of 55.589 km. There are 18 levels in the vertical.

[6] CCSM3 is a general circulation model (GCM) with fully coupled atmosphere, ocean, land, and sea ice components. Lateral atmospheric boundary conditions for the RegCM3 integrations are supplied at 6-hourly time resolution by CAM3, the atmosphere component of CCSM3. CAM3 is run at T42 resolution with 26 levels in the vertical. SSTs for the RegCM3 integrations are supplied at monthly time resolution by POP, the ocean component of CCSM3, with POP SSTs interpolated to a 1-degree geographical grid.

2.2. Experimental Design

[7] We use 3 climate model cases: *Control*, *Insolation*, and *Insolation* + *SST* (Table 1). *Control* uses 0 ka insolation and 0 ka SSTs, and serves as the control simulation. *Insolation* tests the climate response to mid-Holocene (6 ka) insolation forcing of the atmosphere without insolation-induced changes in SSTs. *Insolation* + *SST* tests the climate response to 6 ka insolation with insolation-induced changes in SSTs. For all cases, mean monthly 1-degree SST data are taken from years 131 through 163 of the 0 ka or 6 ka CCSM3 integration of [*Otto-Bliesner et al.*, 2006]. Those 1-degree SST data are interpolated to the T42 CAM3 grid and used as fixed SSTs in CAM3 to create 6-hourly large-scale atmospheric boundary conditions in equilibrium with each of the SST prescriptions. The 1-degree SST data are also interpolated to a 1-degree geographical grid and used as the SST boundary conditions in the respective RegCM3 integrations.

[8] Atmospheric greenhouse gas concentrations follow [*Otto-Bliesner et al.*, 2006]. Atmospheric CO_2 and N_2O concentrations are set to 280 ppmv and 270 ppbv, respectively, in all climate model integrations. Atmospheric CH_4 concentrations are set to 650 ppbv in integrations with 6 ka insolation, and to 760 ppbv in integrations with 0 ka insolation. In order to allow for model equilibration, the first 2 years of each CAM3 integration and the first year of each RegCM3 integration are discarded, leaving 30 years of each model integration available for data analysis. Because these are continuous model integrations, changes in summer climate incorporate changes in climate dynamics during all parts of the annual cycle.

Table 1. Climate Model Cases

	Insolation, ka	SST, ka	CO_2, ppm	CH_4, ppb	N_2O, ppb
Control	0	0	280	760	270
Insolation	6	0	280	650	270
Insolation + SST	6	6	280	650	270

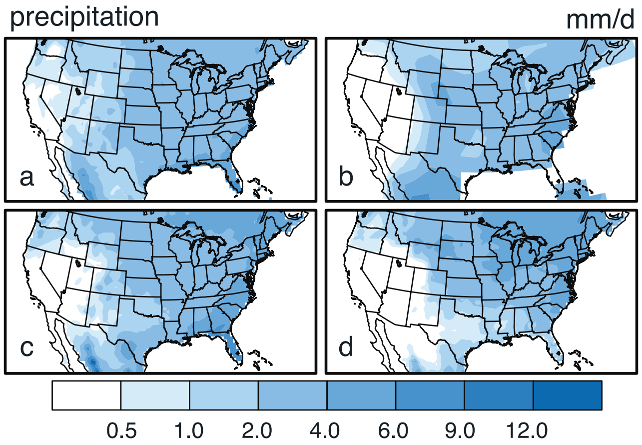

Figure 1. 1983–1999 summer (JJA) precipitation. (a) Observed values from the Climate Research Unit [*New et al.*, 2000]. (b) Values calculated by CAM3 with observed sea surface temperatures. (c) Values calculated by RegCM3 driven by the NCEP/NCAR reanalysis product [*Kalnay et al.*, 1996]. (d) Values calculated by RegCM3 driven by CAM3 with observed sea surface temperatures.

3. Results

3.1. Performance of the Nested Climate Modeling System

[9] In order to test the performance of RegCM3 against the instrumental record, we conduct two "validation" simulations covering the period 1983 through 1999. In the first, RegCM3 is driven by NCEP/NCAR reanalysis data (NNRP2) [*Kalnay et al.*, 1996]. In the second, RegCM3 is driven by CAM3 output, with the NNRP2 SSTs prescribed in both CAM3 and RegCM3. In either case, RegCM3 is able to capture the seasonal distributions of temperature (Figure S1 of the auxiliary material[1]) and precipitation (Figures 1 and S2) over the continental U.S. The key temperature biases in the NNRP2-RegCM3 configuration are a summer warm bias over the south-central U.S. and a spring cold bias over the Rocky Mountains (Figure S1). These biases are stronger and more seasonally persistent in the CAM3-RegCM3 configuration. The primary precipitation biases in both configurations are an autumn and winter dry bias over the southeastern U.S., a spring, summer and autumn wet bias over southeastern Canada and the Upper Midwest, and a winter wet bias over the Rocky Mountains (Figures 1 and S2). The CAM3-RegCM3 enhancement of the winter wet bias over the Rocky Mountains likely contributes to the CAM3-RegCM3 enhancement of the seasonal cold bias over those same areas, with excess snow persisting later in the year and artificially cooling the surface through enhancement of surface albedo. Additionally, the CAM3-RegCM3 configuration exhibits a number of biases that are not seen in the NNRP2-RegCM3 configuration, including a spring and summer dry bias over the

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GL028012.

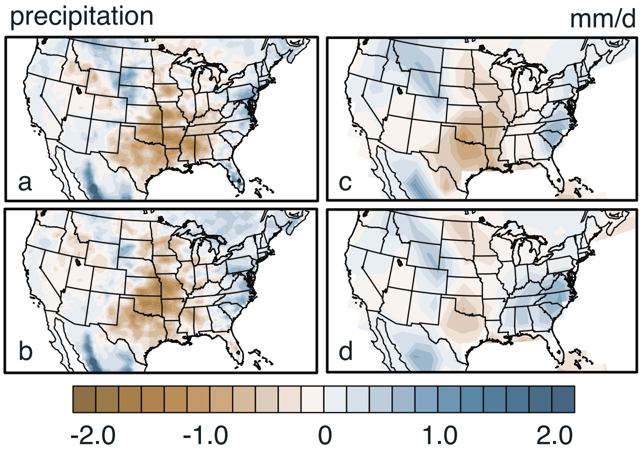

Figure 2. Change in summer (JJA) precipitation. (a) Response to changes in insolation and sea surface temperatures (*Insolation* + *SST* minus *Control*) calculated in the RegCM3 simulations. (b) Response to changes in insolation only (*Insolation* minus *Control*) calculated in the RegCM3 simulations. (c) Response to changes in insolation and sea surface temperatures (*Insolation* + *SST* minus *Control*) calculated in the CAM3 simulations. (d) Response to changes in insolation only (*Insolation* minus *Control*) calculated in the CAM3 simulations.

southeastern U.S., a summer dry bias over northern Mexico, and a summer wet bias over the Great Plains (Figures 1 and S2).

[10] Of these, the summer dry bias over the southeastern U.S. and the summer wet bias over the Great Plains are also seen in the CAM3 simulation (Figure 1b), implying that they may be introduced by the large-scale features supplied to RegCM3 by CAM3. The same cannot be said for the CAM3-RegCM3 dry bias over northern Mexico, which is absent in the CAM3 simulation. Further, the summer wet bias over the northeast of the domain is absent in the CAM3 simulation but present in the NNRP2-RegCM3 configuration, implying that it is introduced by the RegCM3 physics. Finally, CAM3-RegCM3 enhancement of the NNRP2-RegCM3 summer warm bias over the south-central U.S. (Figure S1) could contribute to the CAM3-RegCM3 dry bias over those areas, creating excessively warm and dry conditions not seen in either the NNRP2-RegCM3 configuration or in the CAM3 simulation.

3.2. Simulated Mid-Holocene Climate Changes

[11] Changes in summer (June–July–August) precipitation are very similar between the two experimental prescriptions (Figure 2). Summer precipitation anomalies (mid-Holocene minus control) are negative over the central U.S., with differences of up to −2 mm/d stretching from southern Texas through the upper Midwest. Summer precipitation anomalies are also negative over the northern Rocky Mountains in both mid-Holocene experiments (up to −1.2 mm/d). Additionally, summer precipitation anomalies are positive over the Atlantic coast region (up to 1.6 mm/d) and northern Mexico (up to 9.5 mm/d) in both mid-Holocene experiments. Anomalies are also positive over the northwestern Great Plains (up to 1.6 mm/d), with larger changes in the *Insolation* + *SST* experiment (Figure 1a) than in the *Insolation* experiment (Figure 1b). For both experiments, the pattern of summer precipitation change is very similar between the RegCM3 and CAM3 integrations (Figures 1c and 1d). However, the RegCM3 simulations do show negative precipitation anomalies in the interior and northwestern U.S. for both experiments, in contrast to the generally positive anomalies simulated by the coarser-resolution CAM3 (Figure 2).

[12] Changes in low-level atmospheric moisture content and circulation are also very similar between the mid-Holocene experiments (Figure 3). For instance, both experiments show negative anomalies in 850 mb mixing ratio of up to −0.0007 kg/kg off of the southern Pacific coast, and over the Gulf of Mexico and south-central U.S. Similarly, both experiments show positive anomalies in 850 mb mixing ratio (up to 0.0015 kg/kg) over much of the continent, including peaks over northern Mexico, the northwestern Great Plains, and the Atlantic coast. Also at 850 mb, both mid-Holocene experiments show enhanced cyclonic circulation over the Atlantic coast, enhanced anticyclonic circulation over the upper Midwest, northern Great Plains and Pacific Northwest, and enhanced poleward flow over the south-central U.S. Further, both mid-Holocene experiments show similar changes aloft (Figures 3c and 3d). Peak positive anomalies in 500 mb mixing ratio (up to 0.0008 kg/kg) occur over the southwestern U.S. and northern Mexico, with smaller positive differences over most other continental areas. Negative anomalies in 500 mb mixing ratio occur off of the northern Pacific and southern Atlantic coasts, with the SST experiment showing more spatially extensive negative differences over land than the insolation-only experiment. Both mid-Holocene experiments also show enhanced anticyclonic circulation at 500 mb over most of the continental U.S., with the

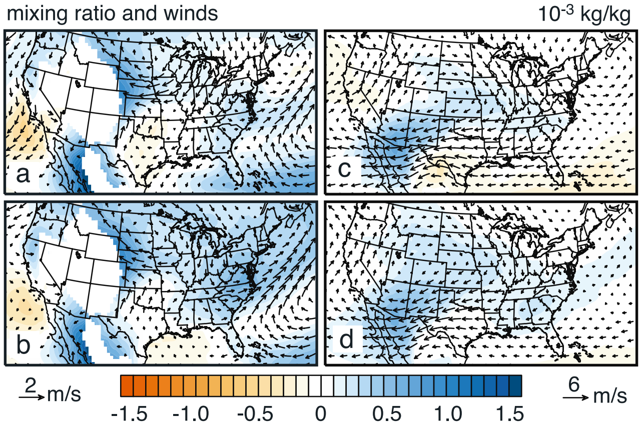

Figure 3. Change in atmospheric dynamics. (a) Response of 850 mb mixing ratio and winds to changes in insolation and sea surface temperatures (*Insolation* + *SST* minus *Control*) calculated in the RegCM3 simulations. (b) Response of 850 mb mixing ratio and winds to changes in insolation only (*Insolation* minus *Control*) calculated in the RegCM3 simulations. (c) Response of 500 mb mixing ratio and winds to changes in insolation and sea surface temperatures (*Insolation* + *SST* minus *Control*) calculated in the RegCM3 simulations. (d) Response of 500 mb mixing ratio and winds to changes in insolation only (*Insolation* minus *Control*) calculated in the RegCM3 simulations.

exception of enhanced cyclonic circulation over northern New England and the coastal Pacific Northwest.

4. Discussion

[13] The similarity in the results of the two experiments (*Insolation* and *Insolation + SST*) implies that mid-Holocene insolation forcing dominates the response of summer precipitation over the continental U.S. This uniformity in the response of summer precipitation ultimately results from uniformity in the dynamical response. For instance, positive low-level moisture anomalies occur over northern Mexico, the northwestern Great Plains, and the Atlantic coast region in both of the mid-Holocene experiments (Figure 3). At present, summer precipitation over these areas is dominated by convective processes. Greater low-level moisture, coupled with greater summer surface temperature (not shown), will serve to increase convective available potential energy (CAPE). Additionally, increases in CAPE over the Atlantic coast region are augmented by enhanced low-level cyclonic circulation in both of the experiments, further amplifying conditions for convection by increasing atmospheric instability. Likewise, positive anomalies in low-level moisture over northern Mexico are associated with positive anomalies in atmospheric moisture content aloft.

[14] As with these positive changes in precipitation, uniform changes in summer climate dynamics lead to uniform negative changes in precipitation. For example, in both experiments, negative precipitation anomalies over the upper Midwest are associated with enhanced anticyclonic circulation aloft (Figure 3), which leads to increases in descending, stable air, and clearer, dryer conditions. Additionally, while both mid-Holocene experiments show enhanced poleward low-level flow over the south-central U.S., this change is coupled with negative differences in low-level moisture content over the south-central U.S. and the Gulf of Mexico (Figure 3). Likewise, negative anomalies in summer soil moisture closely follow negative anomalies in summer precipitation over the central U.S. in both experiments (Figure S3).

[15] Comparison of the RCM and GCM results reveals that incorporation of fine-scale processes in the climate modeling system does not alter the basic large-scale pattern of precipitation response (Figure 2), implying that insolation-induced changes in summer precipitation are dictated primarily by large-scale processes. Although the magnitude of summer precipitation change is larger in the RCM experiments than in the respective GCM experiments in many areas, the effects of fine-scale processes in shaping this RCM-enhancement cannot be distinguished from the effects of systematic RCM bias. For instance, negative summer precipitation anomalies over the south-central U.S. could be enhanced in the RCM experiments by the summer warm and dry biases in the RCM (Figures S1 and S2). Similarly, positive summer precipitation anomalies over the northeastern U.S. could be enhanced by the summer wet biases in the RCM (Figure 1).

[16] Although the RCM and GCM simulations are similar at the large scale, there are notable smaller scale differences between them. Over the northern Rocky Mountains and adjacent northern Great Plains, the enhanced topographic variability in the RCM could enhance the contrast between negative summer precipitation anomalies at high elevations and positive summer precipitation anomalies at lower elevations (Figure 2), although the RCM does exhibit a slight summer dry bias over the northern Rocky Mountains (Figure 1). A similar topographically consistent contrast in anomalies exists between the northern Rocky Mountains and the northern Great Basin.

[17] Both simulations appear broadly consistent with paleoclimate proxy data. Like the simulations, multiple paleoclimate records show evidence of dry conditions in the mid-continent of North America during the mid-Holocene [e.g., *Harrison et al.*, 2003]. Numerous pollen and pack-rat midden data also show evidence of summer-wet conditions in the southwestern U.S. during the mid-Holocene [*Harrison et al.*, 2003; *Mock and Brunelle-Daines*, 1999; *Thompson et al.*, 1993]. Although simulated precipitation differences are small in the Southwest, simulated total soil moisture changes are strongly positive. Southwestern lake records, which also track hydrologic moisture balance, are equivocal [*Mock and Brunelle-Daines*, 1999; *Weng and Jackson*, 1999], and the extent to which those records reflect warm-season precipitation versus cold-season snowpack requires further study.

[18] In the northern Great Plains, lake-level and dune data [e.g., *Digerfeldt et al.*, 1992; *Forman et al.*, 2001] indicate a dry mid-Holocene, which is also evident in the experiment without changes in SST (Figure 1c). However, high but fluctuating abundances of *Ambrosia* pollen may indicate wet but variable summers in the Great Plains [*Grimm*, 2001]. In the northeastern U.S., moisture reconstructions indicate drier-than-present conditions during the mid-Holocene [e.g., *Shuman et al.*, 2004]. However, the dry conditions likely derived from low winter precipitation levels, as isotopic data and hydrologic model simulations indicate that summers may have been wetter than today [*Shuman and Donnelly*, 2006; *Shuman et al.*, 2006]. If so, the data from the northeastern U.S. match precipitation and soil moisture changes in both of the experiments (Figures S3a and S3b). In the Pacific Northwest, pollen-based precipitation reconstructions indicate dry conditions during the mid-Holocene [*Mock and Brunelle-Daines*, 1999]. This pattern is seen in the interior of the Pacific Northwest in both experiments.

5. Conclusions

[19] We find that the basic pattern of summer precipitation response to mid-Holocene insolation forcing is largely similar with and without insolation-induced changes in SST. Additionally, we find that this pattern is dictated primarily by changes in large-scale processes. While the basic pattern of simulated summer moisture agrees with that inferred from the mid-Holocene proxy record, it is notable that in some localities the experiment without changes in SST shows greater agreement with the proxy record than the experiment with the more complete ocean treatment. This raises the possibility that the ocean dynamics calculated by the coupled GCM are not entirely correct. Experiments using both uncoupled (as in the work by *Shin et al.* [2006] and coupled techniques with a suite of GCMs will

help to further distinguish the relative sensitivities to insolation variations and insolation-induced changes in SST.

[20] Additionally, we have not considered the role of climate-vegetation feedbacks in the summer precipitation response. Such feedbacks have been shown to be potentially important for mid-Holocene regional climate [e.g., *Diffenbaugh and Sloan*, 2002; *Kutzbach et al.*, 1996]. However, the role that fine-scale vegetation feedbacks may have played in shaping the net response of North American aridity to mid-Holocene insolation forcing, particularly through changes in soil moisture and convective triggering, has not yet been explored. Further, actual convective processes operate over spatial scales considerably finer than those resolved here. Complete quantification of the relative contributions of climate system forcings and feedbacks to past changes in warm-season precipitation ultimately requires application of convection permitting dynamical models over integration lengths that are sufficient to also capture more slowly-varying ocean, land, and ecosystem processes.

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