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Atlantic and Pacific SST influences on Medieval drought in North America simulated by the Community Atmospheric Model

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[1] Severe drought is arguably one of the greatest recurring natural disasters that strikes North America. A synthesis of multiproxy data shows that North America was in the grip of a severe centennial-scale drought during medieval times (800–1300 AD). In this study, the Community Atmospheric Model (CAM) is used to investigate the role of sea surface temperature (SST) anomalies from the North Atlantic and the tropical Pacific Ocean on this megadrought. These anomalies are obtained from proxy reconstructions of SST. Four model experiments with prescribed SST anomalies in the tropical Pacific and/or North Atlantic Ocean were made. The CAM results captured the major dry features that occurred during medieval times in North America. The cold tropical Pacific alone can simulate essentially the drought intensity, while the warm North Atlantic alone can simulate the drought areal extent. The two working together can explain the severity and longevity of the drought. During the spring season, the cool tropical Pacific, or the warm North Atlantic, or both, results in less moisture transport to the High Plains, with a 15–40% decrease in rainfall. The importance of the Atlantic Ocean on medieval drought in North America suggests that attention should be paid not only to the tropical Pacific Ocean but also to the North Atlantic Ocean in understanding the North America drought variability and predictability, both at present and during the past. This is especially true because the Pacific Ocean SST anomalies in medieval times as recorded by proxy data are somewhat controversial, while the North Atlantic anomalies seem more certain.

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1. Introduction

[2] Drought is a costly natural disaster in the United States (U.S.). During 1980–2005, drought and drought-related economic losses accounted for nearly 29% (compare to 51% of the tropical storm and hurricanes) of the total losses caused by natural disasters in the U.S. (http://www1.ncdc.noaa.gov/pub/data/papers/200686ams1.2nlfree.pdf). Much of the U.S. was in the grip of severe drought during the 1930s, 1950s, and more recently during the period of 1998–2005. Northern Mexico and large portions of the Canadian Prairie provinces also suffered from severe drought during those periods. The severity and durations of those historic droughts, as bad as they may have been, are dwarfed when compared to so-called "megadroughts" that affected North America over the past 2000 years [*Woodhouse and Overpeck*, 1998]. One of these megadroughts occurred during medieval times (approximately 800–1300 AD). This episode has been recorded in tree rings [e.g., *Cook et al.*, 2004, 2007; *Herweijer et al.*, 2006, 2007; *Meko et al.*, 2001], terrestrial eolian deposits and alluvial stratigraphic evidence [e.g., *Daniels and Knox*, 2005; *Forman et al.*, 2001, 2005; *Mason et al.*, 2004; *Miao et al.*, 2007; *Sridhar et al.*, 2006], and lake sediment chemical and salinity reconstructions [e.g., *Hodell et al.*, 2005; *Laird et al.*, 1996, 2003; *Woodhouse and Overpeck*, 1998]. This persistent drought in medieval times may have contributed to Native Americans in the western U.S. abandoning their homes and migrating to areas with a more reliable water supply [*Benson et al.*, 2007a, 2007b].

[3] Some evidence also suggests that the atmospheric circulation in medieval times underwent pronounced changes and was different from the modern conditions. *Laird et al.* [2003] argued that the changes in shape and location of the jet stream and associated storm tracks caused a shift of moisture regimes from wet to dry in early medieval times, at least in the upper Great Plains and Canadian Prairie. By analyzing sand mobility and sand dune orientation in central Nebraska, *Sridhar et al.* [2006] identified a historically unprecedented shift in the spring and summer surface winds over the Great Plains. This shift replaced moist southerly flow with stronger southwesterly flow. Those changes in wind direction suggested a possible eastward shift in the mean position of the dry line [*Sridhar et al.*, 2006] and possible northward displacement of the

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surface heat low in the Rocky Mountains [*Tang and Reiter*, 1984].

[4] The dry/wet fluctuations experienced across much of the U.S. in the past few decades are thought to be closely related to sea surface temperature (SST) variations in the tropical Pacific [*Hu and Feng*, 2001a; *Ting and Wang*, 1997; *Trenberth and Guillemot*, 1996]. The major North American droughts of the instrumental record during the 1850s–1860s, 1870s, 1890s, 1930s, and 1998–2005 have been shown to coincide with cool SST anomalies in the tropic Pacific [*Cole et al.*, 2002; *Cook et al.*, 2004; *Herweijer et al.*, 2006; *Hoerling and Kumar*, 2003; *Schubert et al.*, 2004; *Seager et al.*, 2005]. A fossil coral from the tropical Pacific Ocean and marine sediment cores from the southeastern Pacific suggest that the eastern tropical Pacific Ocean was cooler in medieval times than modern values [*Cobb et al.*, 2003; *Rein et al.*, 2004]. Other studies show that the timing of the onset and end of the medieval drought in North America was consistent with transitions into and out of a cool condition in the tropical Pacific [*Cook et al.*, 2004, 2007; *Graham et al.*, 2007; *Herweijer et al.*, 2006, 2007; *Kennett and Kennett*, 2000].

[5] Within the past decade, a growing body of evidence demonstrates a close relationship between North American drought and multidecadal variations of SST in the North Atlantic Ocean, i.e., the Atlantic Multidecadal Oscillation (AMO) [*Kerr*, 2000]. *Enfield et al.* [2001] found that when the North Atlantic Ocean is warm (AMO warm phase), most of the U.S. receives less than normal precipitation; this includes the Midwest droughts of the 1930s and 1950s. *Rogers and Coleman* [2003] found that the AMO warm (cold) phase is linked statistically to low (high) streamflow in the Mississippi Valley. *McCabe et al.* [2004] show that the AMO can significantly influence drought variations in the Midwest and the western U.S., explaining about 28% of the variance in drought frequency over the contiguous U.S. They further noted that long-term predictability of drought may reside in the multidecadal behavior of the AMO. The AMO impacts the number of hurricanes generated in the Caribbean Sea as well as hurricane landfalls in the southeastern U.S. [*Goldenberg et al.*, 2001] and also the low level jet that transports moisture from the Gulf of Mexico into the central U.S. [*Wang et al.*, 2006]. The impact of the AMO on North American drought has also been simulated by climate models [*Knight et al.*, 2006; *Sutton and Hodson*, 2005, 2007]. Multiple proxy data suggest that the North Atlantic in Medieval times was warmer than the modern average [*Black et al.*, 2004; *Dahl-Jensen et al.*, 1998; *deMenocal et al.*, 2000; *Jiang et al.*, 2005; *Keigwin*, 1996]. The warm North Atlantic, therefore, could also have contributed to the medieval drought in North America. A similar hypothesis has also been proposed by *Benson et al.* [2007b] and *Seager et al.* [2007].

[6] *McCabe et al.* [2004] showed that both the Pacific Ocean and the North Atlantic Ocean modulated drought frequency on multidecadal timescales in North America. *Enfield et al.* [2001] and *Rogers and Coleman* [2003] found that the AMO can modulate the impact of the tropical Pacific SST on the rainfall variability in the U.S. The interactions between the North Atlantic and tropical Pacific Oceans on drought variability in North America revealed in recent years raises the following questions: (1) What was the role of Atlantic Ocean SST on the medieval drought in North America?; (2) If the North Atlantic and tropical Pacific Oceans both affected drought during medieval times, what are the relative roles of each ocean?; and (3) Could Atlantic and Pacific Ocean SST during medieval times have induced the circulation and wind direction changes revealed by sand dune activity in the central Great Plains [*Sridhar et al.*, 2006]? Those questions, and related issues, are addressed in this study using both proxy data and climate model simulations.

[7] In the next section (section 2), we describe the proxy SST records in both the tropical Pacific and the North Atlantic Ocean. The proxy drought records used to verify the model simulations are also described in this section. The climate model and model experiments are introduced in section 3. The results are presented in section 4 followed by discussions of the results in section 5. Section 6 contains the major conclusions of this study.

2. Proxy Data

2.1. Medieval SST Anomalies in the Pacific Ocean

[8] The fossil corals data from Palmyra Island [*Cobb et al.*, 2003] and marine cores off the California coast [*Kennett and Kennett*, 2000] and the southeastern Pacific near coastal South America [*Mohtadi et al.*, 2007; *Rein et al.*, 2004] suggest that the eastern tropical Pacific in medieval times was cooler than modern times. The high-resolution marine core off the California coast [*Kennett and Kennett*, 2000] suggests that the SST there were about 2–3°C cooler than modern values from 700 to 1300 A.D. *Graham et al.* [2007] further argued that the fossil corals data from Palmyra Island suggested SST about −1.5°C cooler than modern values. *Stott et al.* [2004] found that SST in the western tropical Pacific was about 1.0°C warmer than at present. On the basis of the relationship between a warm western and a cool middle and eastern tropical Pacific Ocean during present-day ENSO cycles, strong warming in the western tropical Pacific in medieval times is consistent with a strong cooling in the eastern tropical Pacific Ocean.

[9] Other evidence, however, suggests that the magnitude of medieval cooling in the tropical Pacific was rather weak. For example, *Barron et al.* [2003], *Ostertag-Henning and Stax* [2000], and *Kim et al.* [2004, Figure 3] showed that SSTs off the California coast in medieval times were about 0.2–0.4°C cooler than modern conditions, a value much weaker than the 2–3°C cooling estimated by *Kennett and Kennett* [2000]. R. Seager et al. (Tropical Pacific forcing of North American Medieval megadroughts: Testing the concept with an atmosphere model forced by coral-reconstructed SSTs, submitted to *Journal of Climate*, 2008) provided an alternative interpretation of the fossil corals data from Palmyra Island by regression of δ^{18}O data with the SST. They suggested that the SST change in Palmyra is just a fraction of a degree Celsius, a value much weaker than the −1.5°C cooling estimated by *Graham et al.* [2007].

[10] A lake sediment core retrieved from the southern Ecuadorian Andes shows increased El Nino frequency (warm tropical Pacific) during 900–1310 AD [*Moy et al.*, 2002]. These frequent warm events in medieval times are also supported by the rainfall history recorded in speleo-

Table 1. High-Resolution Proxy Temperature Data in North Atlantic Region Used in This Study[a]

Site	Location	Proxy Sources, Climate Indicator	Sample Resolution	Temperature Anomalies	Reference
GISP (72.6°N, 37.6°W)	Greenland	Borehole temperature	N/A	1.0°C	*Dahl-Jensen et al.* [1998]
M992275 (66.55°N, 17.70°W)	North of Iceland	Diatom	20 years	1.0°C[b]	*Jiang et al.* [2005]
Chesapeake Bay (38.90°N, 76.40°W)	Northeastern U.S.	Mg/Ca of Ostracod Loxoconcha	1–10 years	0.0°C[c]	*Cronin et al.* [2003]
Sargasso Sea (33.69°N, 57.61°W)	Bermuda	$\delta^{18}O$ of *G. ruber*	About 50 years	1.0–1.5°C	*Keiwign* [1996]
GeoB6007–2 (30.85°N, 10.27°W)	Northwest African	Alkenone paleothermometry	About 30 years	0.8–1.0°C	*Kim et al.* [2007]
Pigmy Basin, PBBC-1 (27.19°N, 91.41°W)	Gulf of Mexico	Mg/Ca of *G. ruber*	10 years	1.0°C	*Richey et al.* [2007]
ODP Hole 658C (20.75°N, 18.58°W)	Cap Blanc, Mauritania	Planktonic foraminiferal	About 50 years	0.8°C[b]	*deMonocal et al.* [2000]
Cariaco Basin (10.76°N, 64.70°W)	Southern margin of the Caribbean	$\delta^{18}O$ of *G. ruber*	Annual	1.0°C[d]	*Black et al.* [2004]

[a]The temperature anomalies in the fifth column are the difference between medieval and the modern times.
[b]Averages of warm and the cold season SSTs.
[c]Large temperature fluctuations in medieval time in Chesapeake Bay was documented. The temperature was about 6°C warmer than modern times at around 900 AD but about 4°C cooler at around 950 AD and 1050 AD. Overall the temperature in Chesapeake Bay in medieval times is about the same amplitude as the modern time.
[d]*Black et al.* [2004] suggested that the cooling trend of temperature during the last 2000 years in Cariaco Basin was at least 2°C and hence indicate that the temperature in the medieval times was at least 1°C warmer than the modern times.

them calcite from Panama [*Lachniet et al.*, 2004]. Lake sediment cores from Alaska show that salmon were consistently more abundant from 900 to 1200 AD [*Finney et al.*, 2002]. Because the abundance of salmon is closely related to warm El Nino-like interdecadal variations [*Mantua et al.*, 1997; *Zhang et al.*, 1997], this indicates that the eastern tropical Pacific may have been warmer during medieval times.

[11] In summary, the proxy records in the Pacific Ocean are not in agreement about the SST anomalies in the eastern tropical Pacific Ocean during medieval times. Some show strong cooling (i.e., strong La Nina-like pattern), while some show weak cooling (i.e., weak La Nina-like pattern), and others even show warming. These different SST interpretations complicate our understanding of the role played by the Pacific Ocean on the medieval drought in North America.

2.2. Medieval SST Anomalies in the North Atlantic Ocean

[12] In recent decades, numerous proxy temperatures for the North Atlantic Ocean have been generated [*Kim et al.*,

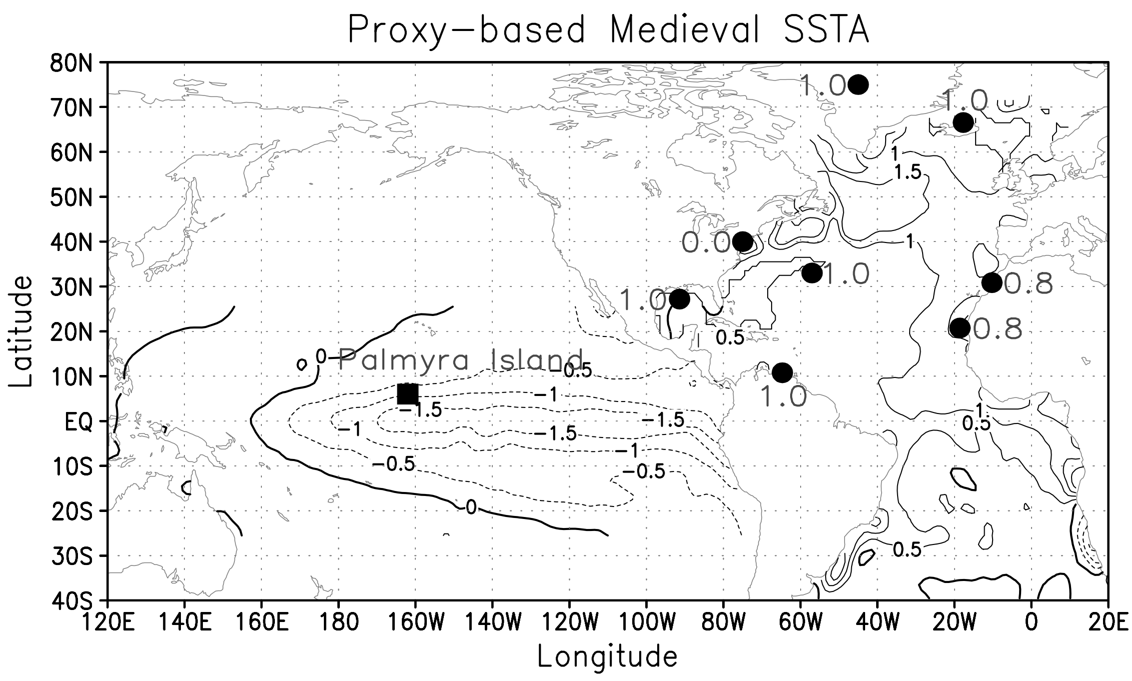

Figure 1. Proxy-inferred sea surface temperature anomalies (°C) in medieval times for CAM 3.0 experiments. Values are differences from modern averages. Square is for Palmyra Island, which was frequently referred to in the text. Dots show the location of high proxy temperature data in North Atlantic Ocean. The temperature differences between medieval and the modern times revealed by those records are also shown (see Table 1 for detail).

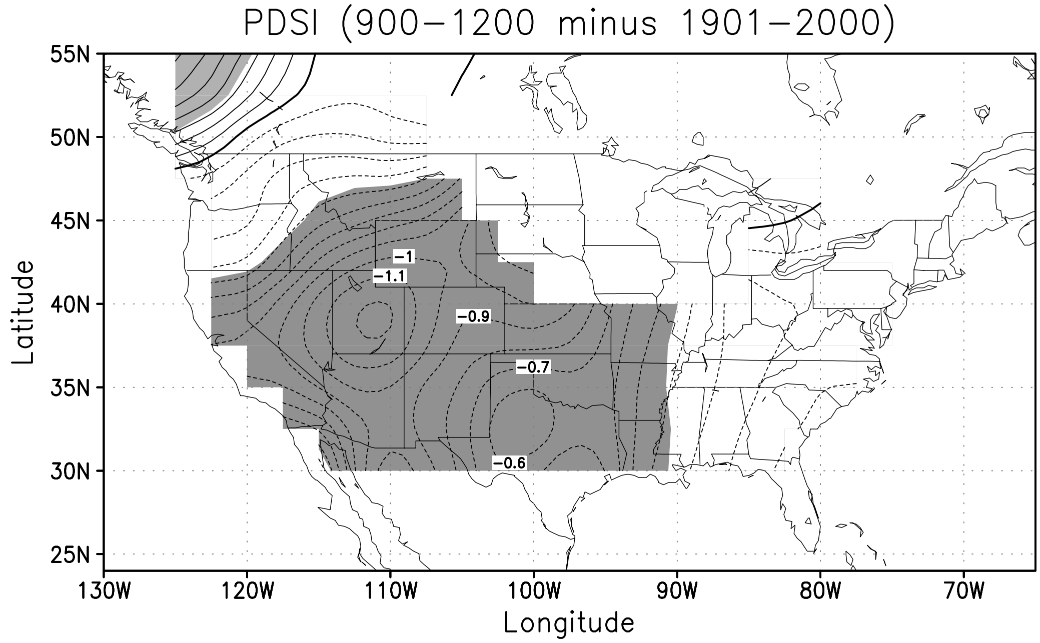

Figure 2. Differences in tree ring reconstructed PDSI for 900–1200 AD minus 1901–2000. Shadings indicate the differences are significant at 95% confidence level by two-tailed student-test.

2004]. Table 1 gives some basic information about the available high-resolution terrestrial and marine proxy temperature data sets used in this study (see Figure 1 for the locations of these records). Except for the Chesapeake Bay, proxy SSTs in medieval times are about 1.0°C warmer than modern times, suggesting that there is a basin-wide warming in the North Atlantic Ocean. This basin-wide warm period was also supported by the empirical orthogonal function analysis of SSTs in Atlantic Ocean during the Holocene [*Kim et al.*, 2004].

2.3. Proxy Drought in North America

[13] The Palmer Drought Severity Index (PDSI) reconstructed from tree ring analyses for North America [*Cook et al.*, 2004] for the last 2000 years was used to examine the spatial and temporal variations of drought during medieval times. The data set covers most of North America, except for the eastern part of Canada. The 2.5° latitude by 2.5° longitude grid of PDSI values was reconstructed from tree rings using the point-by-point regression method [*Cook et al.*, 2004].

[14] Figure 2 shows the difference between the reconstructed PDSI averages for the period 900–1200 AD and the 20th century. Most of the U.S., northern Mexico, and the Canadian Prairie provinces during medieval times were drier than during the 20th century. The largest changes occurred over Utah, Wyoming, and western Nebraska (approximately 36–45°N, 100–115°W). Along the west coast of Canada and in New England, medieval times were slightly wetter than in the 20th century. Owing to the lack of sufficiently long PDSI reconstructions, the magnitude and areal extent of medieval drought in the Mexico cannot be reliably assessed. Three diatom and silicoflagellate records in Gulf of California do suggest that northwest Mexico may have been wetter than modern during the MWP [*Barron and Bukry*, 2006, 2007].

[15] To demonstrate temporal variations and magnitude of the drought, Figure 3 shows the PDSI time series averaged over the western U.S. (30–50°N, 100–125°W) and over the Nebraska Sand Hills region (100–102.5°W, 40–42.5°N). The variations in the Sand Hills coincide closely with the PDSI averaged over the entire western U.S. The correlation between the two PDSI time series is 0.712 for the common period 850–2000 AD, significant at the 95% confidence level. The western U.S. is dry prior to 1300 AD; after that, the drought conditions slowly recovered and the PDSI time series has fluctuated around normal (by present-day standards) conditions since about 1500 AD. Events such as drought in 1850s–1860s, 1890s, 1930s, and 1950s recorded by instrumental measurements [*Herweijer et al.*, 2006; *Cole et al.*, 2002] are shown in the PDSI reconstruction, but the amplitude and duration of those droughts are dwarfed compared to those before 1300 AD. Drought conditions were quite persistent from 900 to 1300 AD, interrupted occasionally by short, "normal" periods around 1100 AD. Particularly severe dry periods occurred around 950 AD,

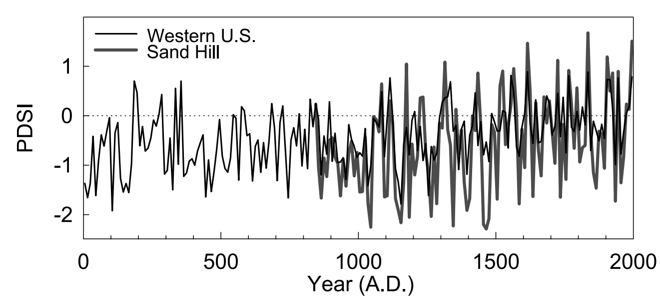

Figure 3. Regional averaged PDSI for the western U.S. (thin line) and the Nebraska Sand Hills (thick line) from 0 to 2000 AD. To retain the low frequency variations in PDSI, only the 10-year averages were shown.

1050 AD, 1150 AD, and 1250 AD, which are also concurrent with Native American migrations in western U.S. [*Benson et al.*, 2007b]. Terrestrial eolian deposits [*Miao et al.*, 2007; *Sridhar et al.*, 2006; *Mason et al.*, 2004] and other evidence summarized in the work of *Graham et al.* [2007] suggest that the medieval drought is quite unique, being the most severe drought during the past 2000 years. This uniqueness is, however, not fully captured in the PDSI variations (Figure 3). The PDSI indicates comparable droughts in the 1st, 2nd, 5th, and 6th centuries. Such a discrepancy is likely caused by the uncertainties in the tree-based PDSI reconstructions. Calibration/verification statistics of the PDSI reconstruction imply that the data are much more reliable after A.D. 800 [*Cook et al.*, 2004].

3. Model Description and Experimental Setup

[16] The atmospheric circulation model used in this study is the Community Atmospheric Model (CAM) version 3.0 [*Collins et al.*, 2006], developed at the National Center for Atmospheric Research. The model includes the Community Land Model (CLM3) and an optional slab ocean/thermodynamic sea ice model combination (not used for our study). The dynamics and physics in CAM3 have been changed substantially compared to implementations in previous versions. These changes have improved simulations of the surface hydrological cycle as well as surface and upper level air temperatures [*Collins et al.*, 2006; *Hack et al.*, 2006]. The configuration used for this study has 26 levels in the vertical and a 42-wave triangular spectral truncation (about 2.8 degrees in latitude and longitude). The model configuration we used is referred to as "data ocean" because SST are specified, as opposed to calculated either thermodynamically only (slab ocean) or with full thermodynamics and dynamics (ocean GCM component). We chose this option because our goal was to investigate the impact of specific, prescribed SST anomalies on North American drought, rather than simulation of the SST anomalies themselves. It is possible that there could be feedbacks between changes due to the drought and the SST anomalies, but we leave that for future work.

[17] Since the drought in North America in medieval times and its connection with the tropical Pacific SST has previously been the focus of numerous other studies [*Graham et al.*, 2007; *Cook et al.*, 2004, 2007; *Herweijer et al.*, 2006, 2007; Seager et al., submitted manuscript, 2008], our study focuses on the relationship between North Atlantic SST and the medieval drought. A series of experiments was designed to simulate the atmospheric response to prescribed changes in tropical Pacific and North Atlantic SST representative of the medieval warm period. To provide boundary conditions for these experiments, idealized medieval SST anomalies were constructed to be approximately consistent with the proxy data for the tropical Pacific and North Atlantic (Figure 1).

[18] The tropical Pacific SST anomalies were obtained by regression between the Nino 3.4 SST index and observed SST (HadISST) [*Rayner et al.*, 2003] during the period 1870–2006. They were then scaled over the central and eastern equatorial Pacific to give a value for the Nino 3.4 index of approximately $-1.5°C$ (Figure 1). This tropical Pacific SST anomaly pattern is similar to that used by *Graham et al.* [2007], except in the western tropical Pacific where the positive SST anomaly (about 0.5°C) is weaker than in their study (1.0–1.5°C). This strong La Nina-like pattern is also consistent with the SST anomalies revealed by fossil coral data from Palmyra Island [*Cobb et al.*, 2003; *Graham et al.*, 2007] and the marine core off the California Coast [*Kennett and Kennett*, 2000].

[19] The North Atlantic SST anomalies for medieval times were obtained by regression between the AMO SST index (averaged between 0 and 70°N and 0–80°W) and observed SST from 1870 to 2006 [*Rayner et al.*, 2003] and then scaled over the AMO index of approximately 1.0°C, in agreement with the multiple proxy data (Table 1). Larger weightings were applied to scale the SST anomalies over the western and the central North Atlantic Ocean (90–50°W and 20–40°N) so that the maximum values in those regions were on the order of 1.0°C (Figure 1). In summary, the SST anomalies in the Atlantic Ocean represent a typical AMO pattern while those in the tropical Pacific Ocean are a typical strong La Nina-like pattern.

[20] A control run was made using seasonally varying modern climatological SSTs to force the CAM3 model, and four model experiments were conducted to simulate the possible impact of the Atlantic and Pacific SST anomalies on the medieval megadrought in North America. The first experiment (Exp1) used only the SST anomalies in the tropical Pacific Ocean (25°S–25°N and 120E–75°W, see Figure 1). Everywhere else, modern climatological SSTs were used. The SST anomalies in Exp1 are confined to the tropical Pacific Ocean because previous model studies have suggested that the impact of SST in the North Pacific on North American drought is very small [e.g., *Hoerling and Kumar*, 2003]. The second experiment (Exp2) imposed SST anomalies only in the Atlantic Ocean. Experiments 1 and 2 isolate the impacts of strong La Nina-like SST anomalies in the tropical Pacific, and a warm North Atlantic Ocean, respectively, on medieval drought over North America. The third experiment (Exp3) combines the SST anomalies of experiments 1 and 2 (see Figure 1), and examines the impact of both anomalies simultaneously. Because this study focuses on the impact of North Atlantic SST on the medieval drought in North America, a strong tropical Pacific cooling in Exp1 and Exp3 can be considered, conservatively, to reveal the impact of the Atlantic Ocean.

[21] To further evaluate implications of the conflict in reconstructions of SST in the tropical Pacific, a fourth experiment (Exp4) was made, using the same SST anomalies in Exp1 increased by 1.0°C. The negative anomalies in the eastern tropical Pacific become smaller (a weak La Nina-like pattern), and positive anomalies in the western tropical Pacific become stronger. The warmer western tropical Pacific in Exp4 is consistent with proxy data from those regions [*Stott et al.*, 2004]. Weak cooling in the eastern tropical Pacific is consistent with the SST anomalies obtained by *Kim et al.* [2004], *Barron et al.* [2003], and *Ostertag-Henning and Stax* [2000]. A similar pattern was also used by *Shin et al.* [2006] in simulating North American drought during the Mid-Holocene.

[22] Given the large uncertainties in tropical Pacific SST reconstructions for medieval times, the SST patterns used in experiments Exp1, Exp3, and Exp4 are useful in at least comparing the relative roles of Pacific and Atlantic SST

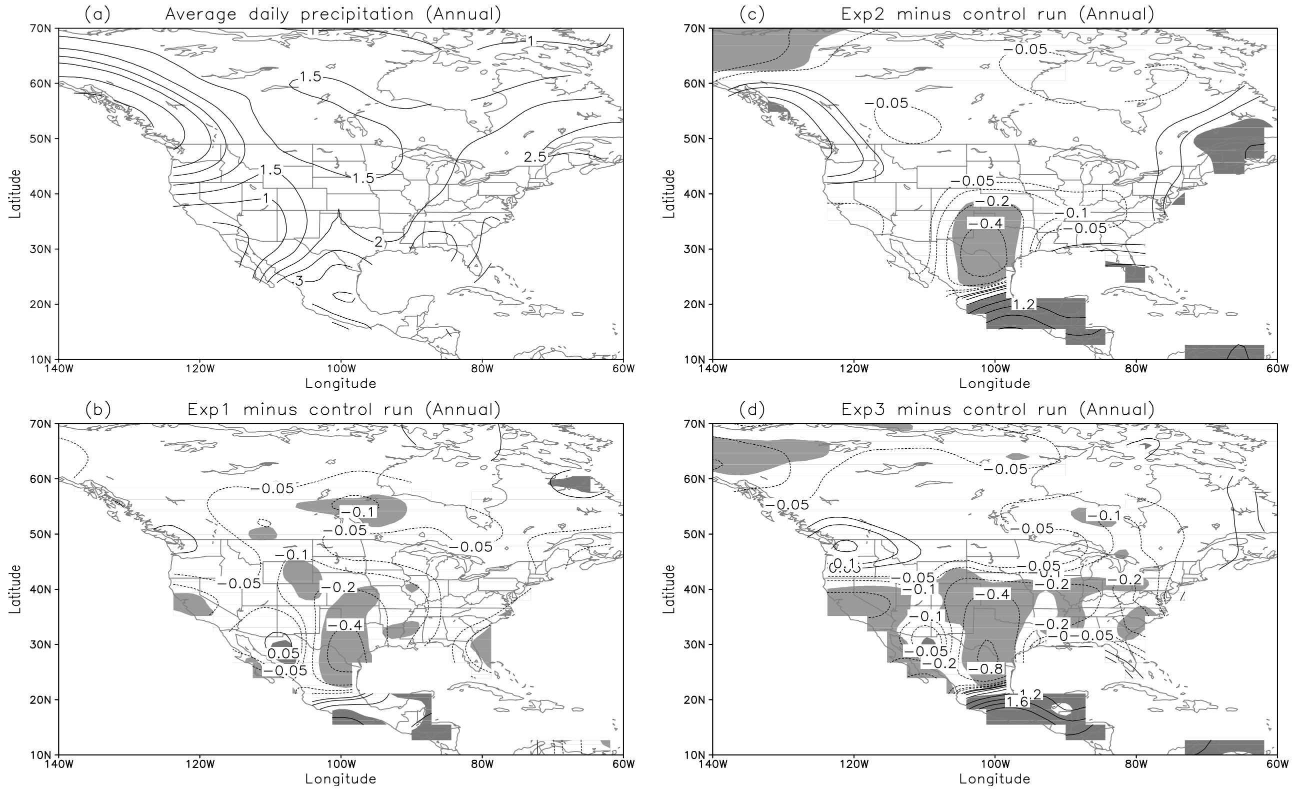

Figure 4. Simulated annual averaged daily precipitation (mm d^{-1}). (a) Control run and the differences between experiments (b) 1, (c) 2, and (d) 3 and the control run. Shadings indicate the differences are significant at 95% confidence level by two-tailed student-test. For clarity, only the precipitation over the land is shown.

anomalies in helping to force the medieval drought. We do recognize that the nature of the Pacific SST anomalies is controversial, and that other choices (e.g., based on the Pacific Decadal Oscillation) could also be relevant. Obviously, more study of potential Pacific forcing is necessary, and especially more proxy evidence will ultimately be necessary to determine the nature of Pacific SST anomalies, and hence any role they may have in forcing North American drought during the MWP.

[23] In each experiment, the same SST anomalies were applied to all seasons. Other forcing such as the greenhouse gases and the total solar irradiance remain the same as in the (present-day) control run. The control and each experiment were run for 15 years. To remove the possible impact of initialization and equilibration on the model results, only the output for the last 14 years of each run was analyzed in this study, similar to *Sutton and Hodson* [2007]. The results of the control and the experiments 1–3 are presented in the next section, with the results of Exp 4 discussed in section 5.

4. Model Results

[24] We emphasize model results for temperature and precipitation, since these are primary factors in drought, as well as related circulation and moisture transport changes that lead to the changes in temperature and precipitation. Much of the paleodata that indicates the MWP drought is in the form of PDSI values based on dendrochronological analyses. From these analyses it is not possible to distinguish temperature and precipitation separately. Seager at al. (submitted manuscript, 2008) argue that while technically possible, it makes little sense to compute a PDSI from model output of temperature and precipitation. They instead suggest a procedure that involves regression of model output to observed or reconstructed PDSI during a known period, but this is simply not applicable to our simulation strategy. Furthermore, the work of *Guttman* [1998] shows that on interannual and longer timescales, variations in the PDSI are closely related to those in precipitation. Finally, since the PDSI is by definition an index, all it indicates is a relative, not an absolute measure of drought "intensity". Our approach is to compare the patterns of relative drought as indicated by the model results and proxy-based PDSI values.

4.1. Annual Averaged Temperature and Precipitation Over North America

[25] Figure 4a shows the annual precipitation simulated by the control run for North America. Both the magnitude and spatial distribution of the simulated precipitation are similar to climatic mean precipitation simulated by using the observed monthly sea surface temperature [*Hack et al.*, 2006]. Figure 4a also resembles the observed climatic mean precipitation over North American (figure omitted). The primary features in the annual precipitation distribution are the precipitation maxima over the northwestern coast of North America and over the Central America. The latter is closely related to the location of the intertropical convergence

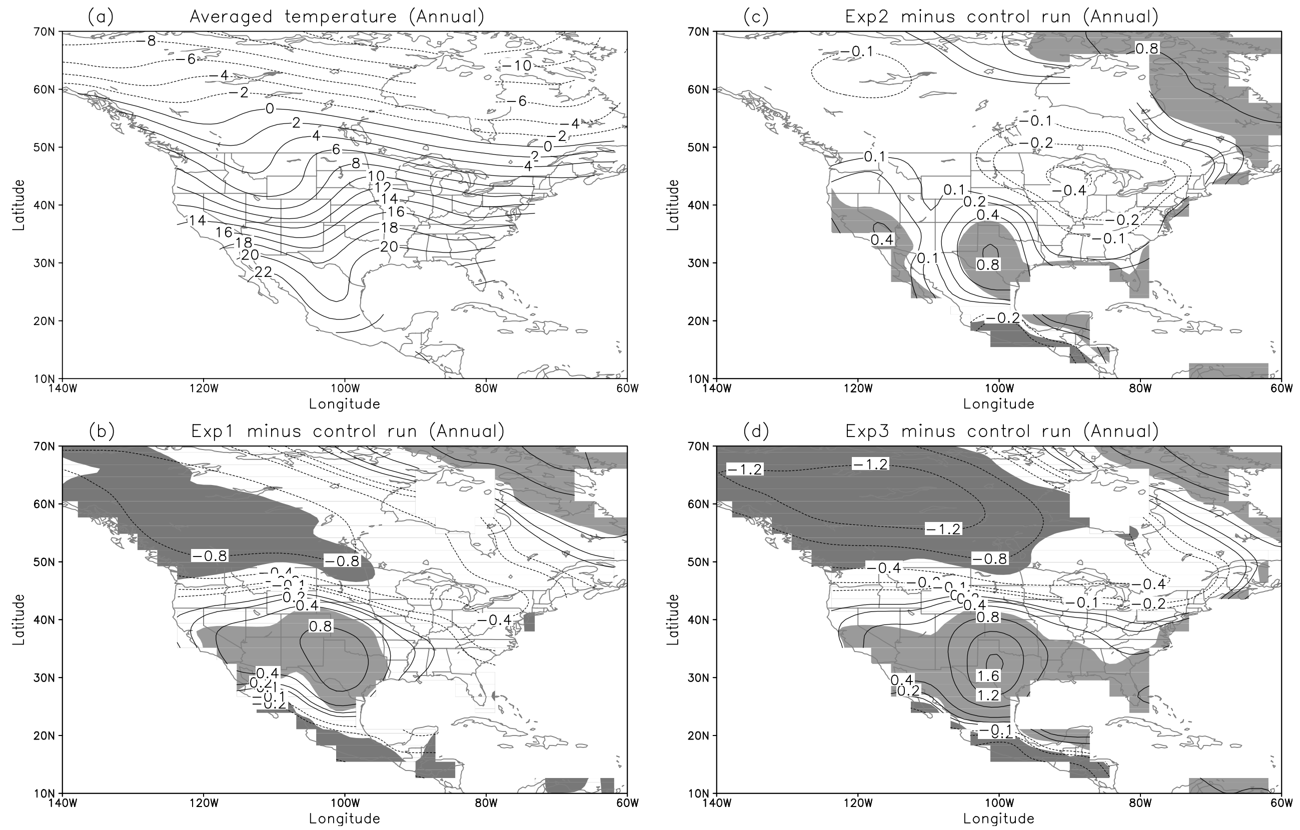

Figure 5. Same as Figure 4 but for surface air temperature.

zone (ITCZ) in the eastern tropical Pacific region. In the southern and southeastern U.S. precipitation is usually greater than 2 mm d^{-1} with precipitation gradually decreasing toward a minimum over the northern High Plains and central Canada. In the southwestern U.S., northwestern Mexico, and the Baja peninsula, the annual mean precipitation is usually less than 0.5 mm d^{-1}.

[26] The differences in the simulated annual precipitation between experiments 1–3 and the control run are also shown in Figure 4. Our simulations capture the major dry features that occurred during medieval times in North America. The strong La Nina-like pattern (Exp1) shows 0.1–0.4 mm d^{-1} reductions (about 10–20% of the annual average, significant at 95% confidence level) in annual precipitation over California, the southern High Plains, and central Canada. In the eastern U.S. the reductions of precipitation are usually less than 5% of the annual average and are statistically insignificant from the control run. Increases in precipitation are found in Central America, consistent with the observed relationship between a northward displacement of the ITCZ and a cool tropical Pacific [*Hu and Feng*, 2002].

[27] The precipitation response to the Atlantic warming (Exp2) shows broadly similar features as Exp1, with smaller precipitation changes in Canada and the central Canada-U.S. border. Significant precipitation reduction is found in the southern High Plains. Increased precipitation occurs in the Pacific Northwest, New England, and Central America. The impact of the combined strong La Nina and warm North Atlantic (Exp3) shows significant reductions in annual precipitation over most of U.S. The largest reductions (>30%) are located in the southern High Plains. In Central America precipitation increased, mainly associated with the warm Atlantic SST anomalies. Over New England and the Pacific Northwest, precipitation is slightly increased. Comparison of Figures 2 and 4 suggests that the cold tropical Pacific and warm North Atlantic together controlled the drought over North America during medieval times. The cold tropical Pacific alone can simulate essentially the intensity of drought but the wetter conditions for the New England regions are not simulated. The warm North Atlantic (Exp2) alone can simulate the drought areal extent but the drought of the west coast of the U.S. is rather weak. The two working together, however, best explain the severity and longevity of the drought.

[28] The surface air temperature difference between the experiments and the control run are shown in Figure 5. In Exp 1, temperatures are warmer in the southern High Plains and southwestern U.S. but cooler than modern times in Canada, the eastern U.S., and Central America. The temperatures in Exp2 are similar to Exp1 except that the southeastern U.S. is warmer. The temperatures in Exp3 are similar to Exp2 except the amplitude of warming is larger in the southern High Plains; the cooling in Canada also becomes stronger. Overall, the model experiments show a mixed warm/cool pattern over North America but with generally warmer conditions over the major drought regions as would be expected [e.g., *Oglesby and Erickson*, 1989].

4.2. Precipitation for April, May, and June

[29] In the central and northern High Plains states (Kansas, Nebraska, the Dakotas, approximately 95–105°W

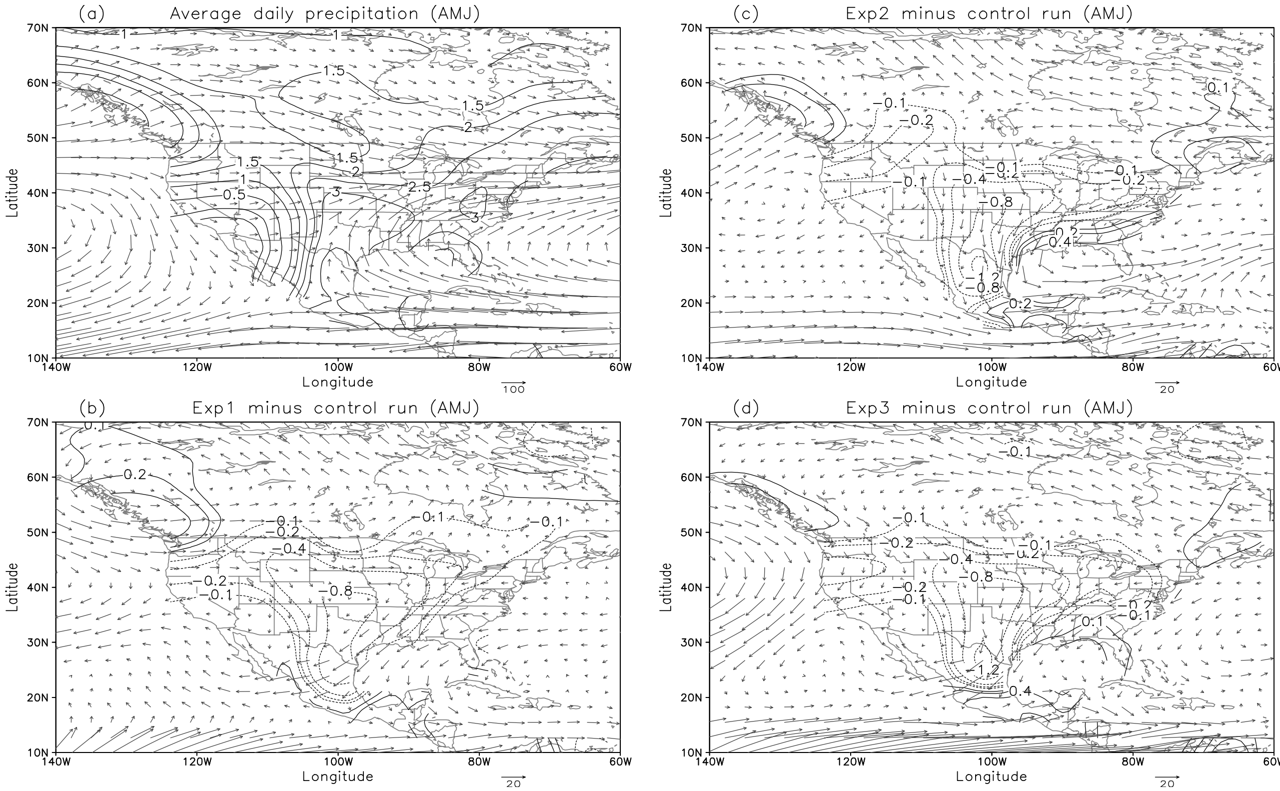

Figure 6. Simulated April–May–June averaged daily precipitation (mm d^{-1}, contours) and 1000–700 hPa integrated moisture flux (kg/ms, vectors). (a) Control run and the differences between experiments (b) 1, (c) 2, and (d) 3 and the control run. For clarity, only the precipitation over the land is shown.

and 35–50°N), nearly 50% of annual total precipitation occurs during late spring and early summer [*Tang and Reiter*, 1984]. Therefore, large reductions during April–June (AMJ) could be the main cause of the medieval drought in those regions. Figure 6 shows the averaged AMJ precipitation for the control run and the differences with experiments 1–3. In the control run, the daily averaged precipitation shows peaks around the Canadian Pacific coast, eastern Mexico, and the southern High Plains. The southwestern U.S. and northwestern Mexico are in the premonsoon dry period with the daily precipitation rate less than 0.1mm d^{-1}. The precipitation rate in the High Plains regions is much higher than the annual average, primarily fueled by the strong moisture flux from the Gulf of Mexico and the Caribbean Sea (Figure 6a).

[30] When compared to the control run, Exp 1 shows reduced precipitation over the contiguous U.S. Large reductions (0.4–0.8 mm d^{-1}, about 20–30% less than the control run) occur over the central and southern High Plains. Central America and the Canadian west coast are slight wetter (<10%) than in the control run. In Exp2, the dry anomalies are similar to Exp1 except the dry conditions occurring in New England in Exp1 are replaced by wet anomalies. The area of large precipitation reduction in the central and southern High Plains is also slightly smaller than in Exp1. When the cold tropical Pacific and the warm North Atlantic SST anomalies were combined (Exp3), precipitation over most of the U.S., except the southeastern U.S. and New England, is reduced. The precipitation in the northwestern U.S. and the High Plains is 0.3–1.2 mm d^{-1} (about 20–40%) less than modern values. In summary, these three experiments all show reduced AMJ precipitation in most of the contiguous U.S. with especially large reductions in the central and southern High Plains, suggesting that the medieval drought in those regions is a consequence of both the cold tropical Pacific and warm North Atlantic. For all three experiments, moisture flux anomalies are directed toward the southwest or south in the southern High Plains, indicating that the moisture flux from the Gulf of Mexico was reduced. These reduced moisture fluxes and the associated moisture divergence decrease the chance for rainfall development, causing the dry conditions in the High Plains.

[31] The circulation and moisture flux anomalies in Exp2 and Exp3 are similar to previous observational and modeling studies. For example, Figure 6b shows that when the tropical Pacific Ocean is cold, moisture flux anomalies in the central and eastern U.S. are directed southwest. These anomalous moisture fluxes are similar to those of the severe North American drought in 1988 [*Lyon and Dole*, 1995]. When the North Atlantic is warm (Figure 6c), the moisture flux anomaly is directed southward over the High Plains and is associated with a low-level cyclonic anomaly north of the Caribbean. This pattern is similar to recent observational and modeling studies of the effect of the tropical Atlantic Ocean on moisture flux [*Wang et al.*, 2006, 2007].

4.3. Precipitation for July and August

[32] Rainfall in the 3-month period of July–September accounts for nearly 50% of the annual precipitation in the

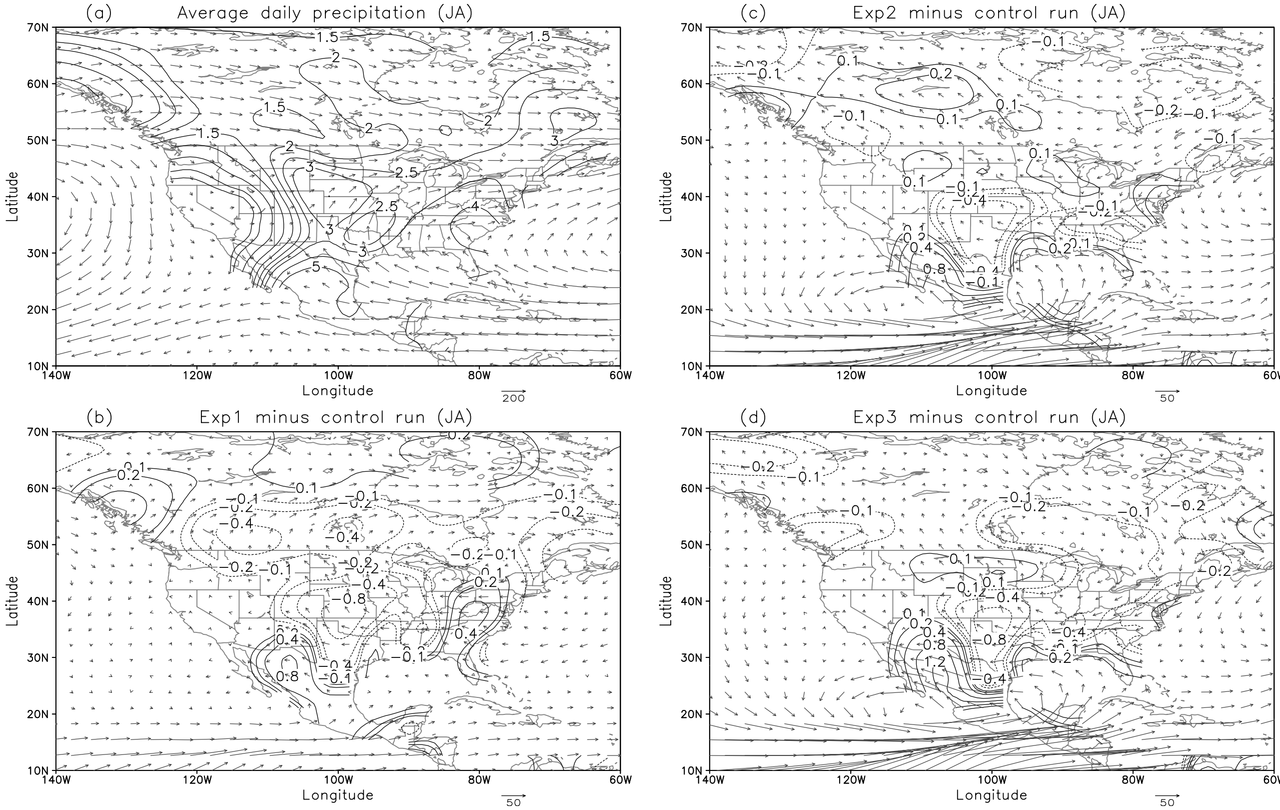

Figure 7. Same as Figure 6 but for July–August.

semiarid southwest and northern Mexico. This relatively wet period, often referred to as the North American monsoon season, contrasts with the much drier months of the rest of the year. The North American monsoon often begins in early July and ends in mid-September. Associated with the monsoon onset, rainfall in the central U.S. and the southern High Plains decreases [*Higgins et al.*, 1999]. For each of the experiments, a 0.4–0.8 mm d^{-1} increase in precipitation occurred over the southwestern U.S. and northern Mexico during the monsoon season (July and August) (Figure 7), suggesting a stronger North American monsoon. Accompanying the wetter monsoon, precipitation in the central U.S. and the southern High Plains was 0.4–0.8 mm d^{-1} (about 10–20%) less than in the control run. These results are consistent with the observed out-of-phase relationship between northwestern Mexico monsoon rainfall and summer rainfall in the central U.S. and the southern High Plains [*Higgins et al.*, 1999; *Hu and Feng*, 2008]. The wet monsoon in northwestern Mexico in our model experiments is consistent with the diatom and silicoflagellate records in Gulf of California [*Barron and Bukry*, 2006, 2007]. The wet monsoon in the southwestern U.S., however, is not consistent with proxy data in Figure 2 for reasons that remain to be understood.

[33] Though both a cool tropical Pacific Ocean and warm North Atlantic Ocean can induce a wet monsoon in northwestern Mexico and the southwestern U.S., the moisture flux anomalies associated with the wet monsoon differ in the three experiments. For example, in Exp1 an anomalous easterly moisture flux dominants the eastern half of the U.S. The moisture flux anomalies enhance divergence (reduce convergence) over the central U.S., resulting in drought there. The anomalous westerly moisture flux in the eastern tropical Pacific, curving to the north along the west coast of Mexico, suggests enhanced moisture transport from the Gulf of California. Such anomalous moisture flux transport provides abundant moisture to northwestern Mexico and the southwestern U.S., resulting in excess monsoon rainfall. The moisture flux from the Gulf of Mexico, however, remains essentially unchanged in Exp 1, supporting observational studies showing that the low level jet in Gulf of Mexico is unrelated to ENSO variations in summer [*Hu and Feng*, 2001b].

[34] Substantial differences in anomalous moisture flux are found in Exp2 when compared to Exp1. In particular, the large easterly anomalous moisture flux in eastern U.S. in Exp1 disappears, with essentially no changes in moisture flux from the control run. The westerly moisture flux anomalies in the eastern tropical Pacific are larger and extend farther east into the Gulf of Mexico. The anomalous moisture flux then becomes northward and northwestward, thereby influencing the central U.S. by creating a strong moisture divergence there. In addition, the anomalous moisture fluxes from the Gulf of Mexico also curve northwestward to influence northwestern Mexico and the southwestern U.S. These moisture fluxes and the moisture fluxes from the Gulf of California together transport more moisture to the monsoon region, resulting in excess monsoon rainfall there.

[35] Comparing and contrasting experiments 1 and 2 suggests that the variations of monsoon rainfall are influenced by very different low level flows and moisture fluxes.

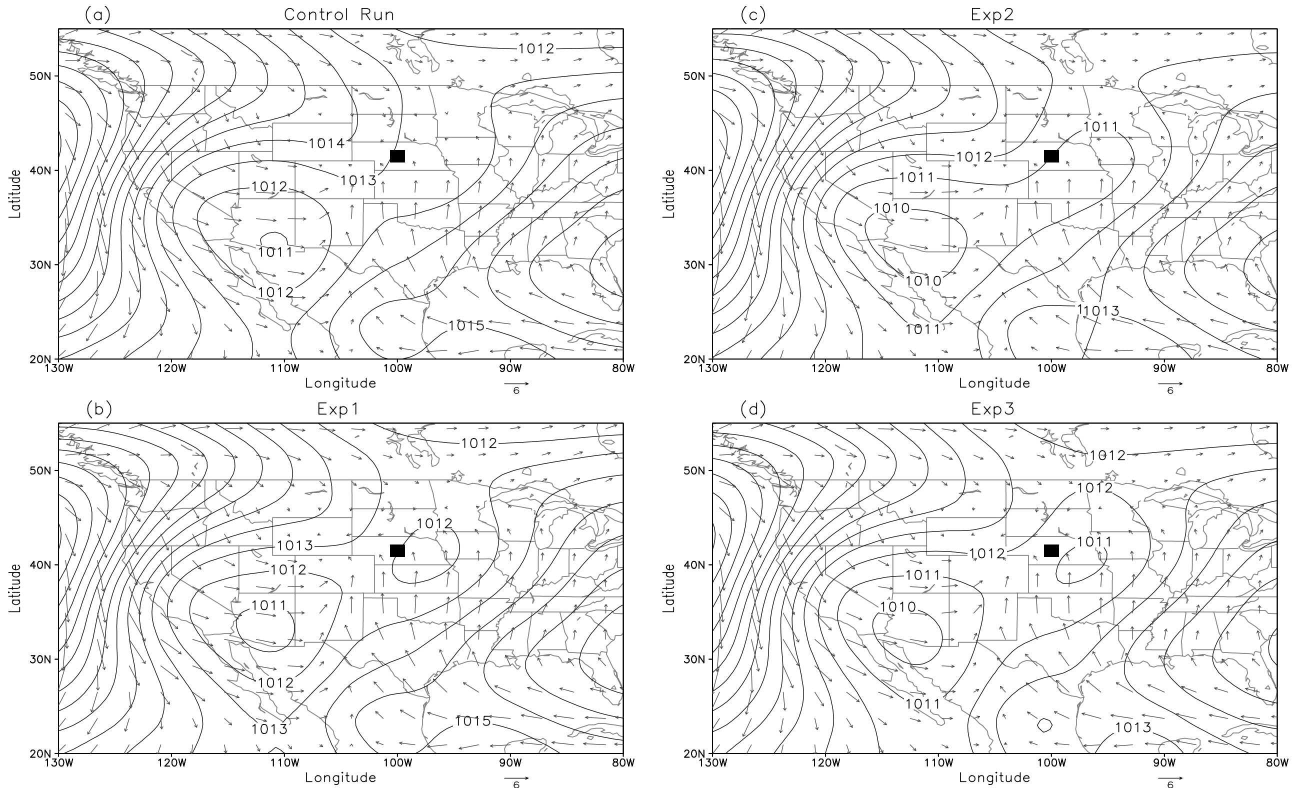

Figure 8. Simulated June–July–August averaged sea level pressure (hPa, contours) and surface wind speed (m/s, vectors). (a) Control run and experiments (b) 1, (c) 2, and (d) 3. Square shows the location from where the medieval wind direction change was identified [*Sridhar et al.*, 2006].

The tropical Pacific SST mainly influences the moisture from the Gulf of California, whereas the Atlantic SST influences the moisture flux from both the Gulf of Mexico and Gulf of California. The moisture flux and rainfall anomalies in Exp3 are similar to a combination of experiments 1 and 2, suggesting that the overall model response is broadly linear with respect to the SST variations in tropical Pacific and the North Atlantic Ocean.

4.4. Circulation Changes in the Central U.S.

[36] *Sridhar et al.* [2006] identified a change in surface wind direction during medieval times by comparing the orientation of sand dunes in the Sand Hills of central and western Nebraska (approximately 98–103°W and 40–43°N) with that expected from modern surface winds. They concluded that the prevailing warm season surface wind was southwesterly during medieval times, markedly different from the southerly to southeasterly wind at present. Because the summer wind direction over the High Plains (including the Sand Hills) is influenced by the orientation of the Rocky Mountains and also by the heat low in the mountainous regions [*Tang and Reiter*, 1984], the changes of wind directions in medieval times suggest that the heat low in the mountainous regions may have been displaced well north of its modern location. This shift in the heat low and wind direction was not, however, reproduced in any of the model experiments. As shown in Figure 8a, the heat low in modern times is located mainly in the southwestern U.S., centered over Arizona. A weak trough of low pressure extends northeastward from the heat low to about the boundary between Nebraska and Iowa (around 42°N, 95°W). Southwesterlies are observed in southern Colorado and New Mexico (approximately 105–110°W and 30–37°N), far southwest of the Sand Hills. This low pressure system and the prevailing winds are consistent with modern observations [*Tang and Reiter*, 1984; *Sridhar et al.*, 2006]. Each of the experiments simulated a stronger heat low, but the location was essentially unchanged compared to the control run (Figure 8). The possible reasons for this discrepancy are discussed in section 5.

5. Discussion

[37] Our major result is that SST anomalies in both the Pacific and Atlantic Oceans likely had an impact on drought in North America during medieval times. The region of drought related to a strong La Nina-like pattern in the tropical Pacific is generally similar to the drought pattern reconstructed by tree ring data. As shown in section 2.1, the evidence for medieval SST patterns in the tropical Pacific is controversial and different reconstructions appear to conflict with each other. To evaluate the impact of possible weak cooling in the tropical Pacific on North American drought, the results of Exp4 are shown in Figure 9. Annual averaged daily precipitation and temperature from Exp4 are quite different from those in Exp1. Dry conditions for the western U.S. in Exp4 are much weaker than in Exp1 (Figure 4b). Moreover, dry conditions for the central and eastern U.S. in Exp1 disappear, being replaced by a 0.2–0.4 mm d^{-1} increase (significant at 95% confidence level) in precipitation. The region with warm temperatures in the western and

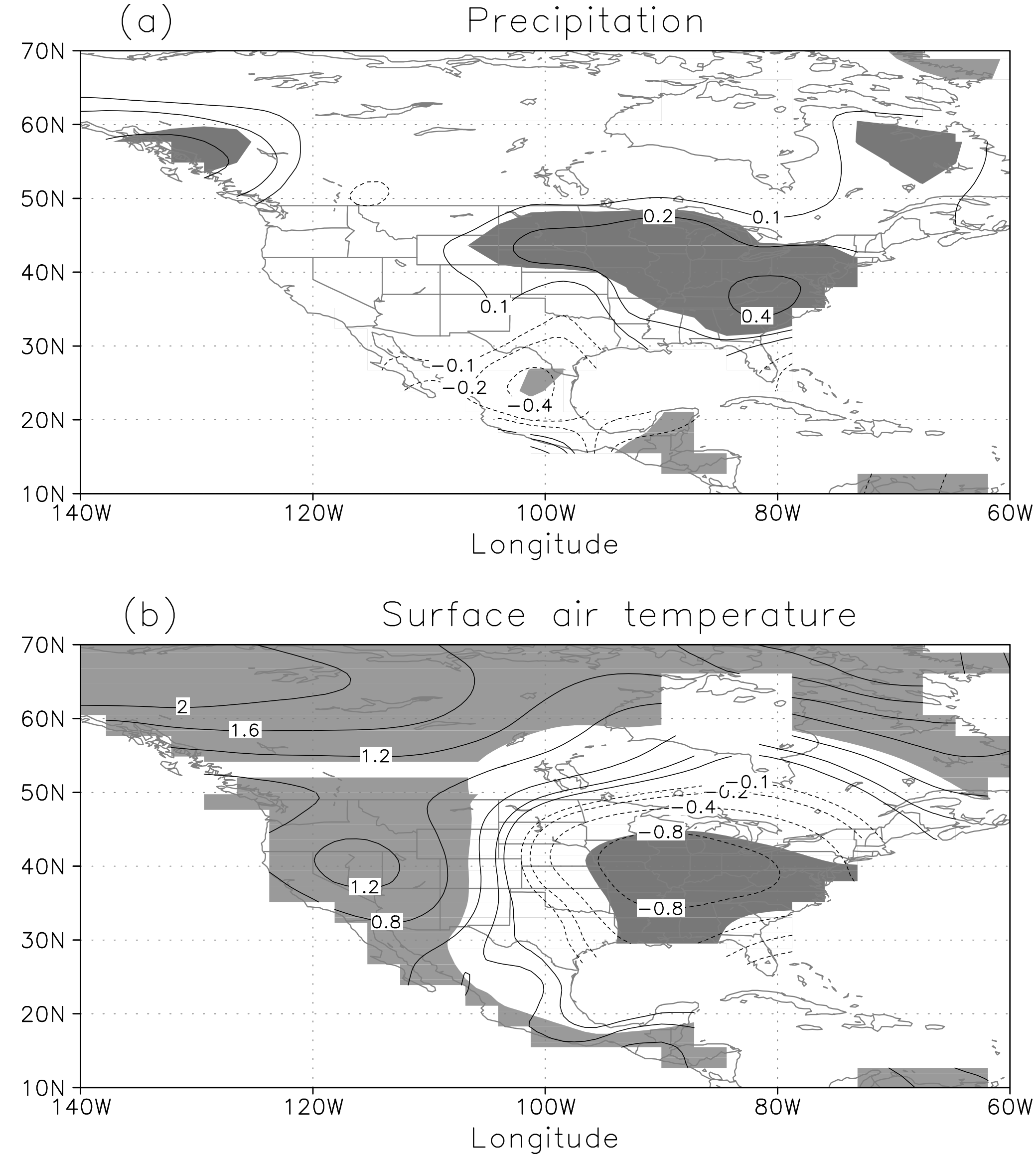

Figure 9. Differences of (a) annual averaged daily precipitation and (b) surface air temperature of experiment 4 from the control run. Shadings indicate the differences are significant at 95% confidence level by two-tailed student-test.

central U.S. in Exp1 shrinks in Exp4, and the cooling in western Canada in Exp1 is replaced by strong warming. Comparing Figures 4 and 9 suggests that the impact of the Pacific Ocean SST anomalies on medieval drought in North America could be overestimated if the La Nina-like cooling in tropical Pacific Ocean was not as strong as some studies suggest. *Seager et al.* [2005, submitted manuscript, 2008] and *Cook et al.* [2007] suggested that a weak cooling in the eastern tropical Pacific Ocean could cause the medieval drought in North America, which differs from our results shown in Figure 9. This could be due to the different SST imposed outside the tropical Pacific Ocean. *Seager et al.* [2005, submitted manuscript, 2008] forced their model with specified tropical Pacific SSTs but coupled their model to a uniform 75 m deep mixed-layer ocean elsewhere, whereas in our Exp4, the CAM was forced by specified climatological SST outside the tropical Pacific Ocean.

[38] Some evidence does suggest that the tropical Pacific Ocean in medieval times may have been warmer than in modern times [*Moy et al.*, 2002; *Finney et al.*, 2002; *Lachniet et al.*, 2004]. Because a warm tropical Pacific could cause excess precipitation in the central U.S. [*Hu and Feng*, 2001a; *Ting and Wang*, 1997; *Trenberth and Guillemot*, 1996], the possibility of warmer than modern conditions in the tropical Pacific during medieval times casts additional doubt on the role of Pacific for medieval drought in North America.

[39] The aspects of drought related to a warm North Atlantic occurred mainly in the western and south-central U.S., consistent with observed relationships between multi-decadal shifts in the warm North Atlantic (AMO) and drought frequency in the U.S. [*McCabe et al.*, 2004]. The simulated sea level pressure in the western and central U.S. is lower than in the control run (Figure 8c) and the moisture

flux from the Gulf of Mexico is weaker (Figure 6c); these results are consistent with previous observational studies on the impact of AMO on drought in North America [e.g., *Hu and Feng*, 2008; *Wang et al.*, 2006]. The high resolution proxy data (Table 1) as well as other proxy data analyzed by *Kim et al.* [2004] all suggest that the North Atlantic in medieval times was consistently warmer than the modern average. The consistent evidence for warming in the North Atlantic Ocean and the conflicting evidence for cooling in the tropical Pacific Ocean (some proxies show strong cooling, while others show weak cooling or warming) during medieval times suggest that the role of the Atlantic Ocean on medieval drought may have previously been underestimated. Further study is therefore necessary to identify the full impact of North Atlantic SST anomalies on drought in North America, both at present and during the past.

[40] The SST variations in the tropical Pacific and North Atlantic could also interact with each other during medieval times. By summarizing previous model studies, *Seager et al.* [2007] argued that a medieval La Nina-like pattern could have been caused by high solar irradiance and reduced volcanism. The La Nina-like pattern could then induce a stronger meridional overturning circulation, and hence a warm North Atlantic Ocean, by moving the southern midlatitude westerlies poleward, thereby increasing the exchange of relatively salty water from the Indian Ocean into the South Atlantic Ocean and driving stronger Southern Ocean upwelling. This plausible mechanism could explain the proxy records that show cooling in the tropical Pacific and a warm North Atlantic. It also supports our model results that both the tropical Pacific and the North Atlantic impacted the medieval drought in the North America.

[41] Other observational and modeling studies, however, suggest that the North Atlantic played a more active role in influencing the tropical Pacific Ocean. For example, *Wang et al.* [2006, 2007] showed that a warm North Atlantic is associated with a stronger and larger Atlantic warm pool, which can induce westerly trade wind anomalies in the Caribbean that carry across Central America into the Pacific, and vice versa for a cool North Atlantic. Consistent with this, *Xie et al.* [2007] in their modeling study found that a North Atlantic cooling (e.g., the Younger-Dryas) could result in anomalous easterlies in the eastern Pacific and cooling in the equatorial eastern Pacific. It is therefore reasonable (on physical grounds) to argue that the warm North Atlantic in medieval times should result in a tropical Pacific warming. This mechanism could also explain the warm North Atlantic and proxy records indicating a relatively warm tropical Pacific Ocean [*Moy et al.*, 2002; *Finney et al.*, 2002; *Lachniet et al.*, 2004]. If this mechanism operated, the North Atlantic could play a dominant role on the medieval drought in North America because the warm tropical Pacific by itself should lead to wet conditions in the western and central U.S. These two mechanisms (the cool tropical Pacific inducing a warm North Atlantic, and the warm North Atlantic inducing a warm tropical Pacific) demonstrate the agreed-upon warming in North Atlantic Ocean but controversial SST anomalies in the tropical Pacific Ocean during medieval times. However, it must be emphasized that both mechanisms, at this point, are ideas that need to be proven or disproven. Links between the North Atlantic and the tropical Pacific Ocean remain poorly understood at this time because diverse results have been obtained by previous modeling studies. For example, the newly developed GFDL global coupled ocean-atmospheric model showed that a cold North Atlantic could induce a more El Nino-like Pacific Ocean [*Zhang and Delworth*, 2005]. *Timmermann et al.* [2007] examined a number of models and found that a cold North Atlantic induced primarily asymmetric SST anomalies in the tropical Pacific with warm to the south and cold to the north. These results differ from the modeling study of *Xie et al.* [2007], whose results are consistent with the recent observational and modeling studies of *Wang et al.* [2006, 2007].

[42] Though the medieval drought in North America was reasonably simulated by the cool tropical Pacific and warm North Atlantic Ocean SST anomalies, the wind direction change revealed by sand dune orientation in the Nebraska Sand Hills [*Sridhar et al.*, 2006] was not reproduced by any of the model experiments (Figure 9). The circulation simulated in all of the model runs was broadly similar to that at present; less moisture is simply transported into this region. We speculate that either the model resolution is too coarse to distinguish this more local effect, or that land cover changes associated with the activated dunes provided a feedback that allowed southwesterlies aloft to be brought down to the surface, replacing the southerly to southeasterly winds that occur today. This will be the focus of future study.

6. Conclusions

[43] Terrestrial late Holocene proxy records suggest that between approximately 800–1300 AD North America experienced severe centennial-scale drought. This megadrought increased the incidence of wildfire and led to dune mobilization. This drought has previously been associated with La Nina-like conditions in the tropical Pacific Ocean. This study used a synthesis of proxy SST data from the North Atlantic Ocean to show that the medieval drought may also be linked to a warm North Atlantic Ocean. The CAM model was then used to investigate the separate and combined influences of both the tropical Pacific and North Atlantic Oceans on this drought.

[44] Four model experiments were made with prescribed SST anomalies in the tropical Pacific and/or Atlantic Oceans and climatological SSTs elsewhere. The model captured the major dry features that occurred during medieval times in the High Plains and the western U.S. When the tropical Pacific has a cool anomaly (strong La Nina-like pattern), annual precipitation in High Plains and the western U.S. is about 0.1–0.4 mm d^{-1} (10–20%) less than present-day conditions. The eastern U.S. is also somewhat drier. When the North Atlantic Ocean has a warm anomaly, annual precipitation in the High Plains and the western U.S. is about 5–20% less than the present. The Pacific Northwest and the northeastern U.S. are slightly wetter. When both a relatively cool tropical Pacific and warm North Atlantic Ocean are combined, the entire U.S., except the Pacific Northwest and New England, are significantly drier. The model results confirm previous studies [e.g., *Graham et al.*, 2007] that strong cooling in the tropical Pacific may be associated with medieval drought in North America. Our model results further demonstrate that the North Atlantic also may be an important factor influencing this drought.

The cold tropical Pacific alone can simulate the drought intensity while the warm North Atlantic alone can simulate the drought's areal extent. The two in combination, however, may be necessary to explain the severity and longevity of the drought during the medieval period.

[45] During spring, the low-level moisture flux anomalies in each experiment (the cool tropical Pacific, or the warm North Atlantic, or both) are directed southward or southwestward in the southern High Plains. Those moisture flux anomalies and the accompanying moisture divergence produce less chance for rainfall development, resulting in dry conditions in the High Plains. Though the magnitude of the precipitation reductions differ between the experiments, each experiment produced at least 20% less rainfall in the rainy season (April–May–June) of the High Plains, large enough to initiate the observed sand dune mobilization [*Forman et al.*, 2001].

[46] In the North American monsoon region (the southwestern U.S. and northwestern Mexico), each model experiment can simulate wet monsoon conditions. The observed out-of-phase relationship between the monsoon rainfall in northwestern Mexico and southwestern U.S. and the summer rainfall in the central U.S. and the southern High Plains [*Higgins et al.*, 1999] are well simulated in each of the model experiments. The moisture fluxes associated with the wet monsoon are, however, different in the various experiments. The tropical Pacific SST mainly influences the moisture flux from Gulf of California whereas the North Atlantic SST influences the moisture flux from both the Gulf of Mexico and the Gulf of California.

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