Contrasting rainfall patterns over North America during the Holocene and Last Interglacial as recorded by sediments of the northern Gulf of Mexico

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[1] The comparison of geochemical and mineralogical characteristics of terrigenous sediments deposited in the northern Gulf of Mexico (GoM) during the Holocene and Last Interglacial (LIG) is used to document the impact of slight differences in insolation and ice-sheet retreat rates on moisture transfer and precipitation patterns over central North America. The records indicate distinct sedimentological signatures over the two time periods, which likely reflect a modification of the main detrital provenance during the LIG compared to the Holocene. Here we postulate that the observed differences in the terrigenous supply during the LIG relative to the Holocene reflect a northeast migration of the main precipitation belt over the Mississippi River watershed likely in response to deglaciation of the Laurentide Ice Sheet prior to the peak in boreal summer insolation and the overall greater increase in boreal summer insolation relative to the Holocene. These combined effects allowed more northward migration of the Jet Stream, Atlantic Warm Pool and Intertropical Convergence Zone than during the Holocene, which may have also forced the Bermuda High farther to the northeast of its present position, thereby pumping more moisture from the GoM and the Caribbean region into both the Upper Mississippi River and northeast Great Lakes area. **Citation:** Montero-Serrano, J.-C., et al. (2011), Contrasting rainfall patterns over North America during the Holocene and Last Interglacial as recorded by sediments of the northern Gulf of Mexico, *Geophys. Res. Lett.*, *38*, L14709, doi:10.1029/2011GL048194.

1. Introduction

[2] Paleoclimate records indicate that the Last Interglacial (LIG) period was generally warmer than present by several degrees in response to elevated boreal summer insolation [*CAPE Last Interglacial Project Members*, 2006]. Delineating the evolution of rainfall patterns over North America during this period will help determine how rising temperatures may impact the position of the main precipitation belt position over the continent. The Gulf of Mexico (GoM) is well situated to document past variations in the distribution of precipitation over North America as a large part of the precipitation falling over North America returns back to the GoM via the Mississippi River System that spans almost half of the United States. Runoff promotes the remobilization of soil and sediment particles that are transported as fluvial suspended load through the afore-mentioned fluvial systems. The nature and volume of the Mississippi River sediment-load are therefore controlled by the geographical position of the precipitation belt over the Mississippi River watershed [*Montero-Serrano et al.*, 2010], itself controlled by atmospheric circulation patterns (Jet Stream, Bermuda High and Intertropical Convergence Zone or ITCZ position) and ocean temperatures (extension of the Atlantic Warm Pool or AWP) that drive the meridional moisture transfer over the central part of North America [*Forman et al.*, 1995; *Davis et al.*, 1997; *Chang and Smith*, 2001; *Ziegler et al.*, 2008; *Montero-Serrano et al.*, 2010].

[3] During the early Holocene (11.5–5 ka), high boreal summer insolation drove rapid retreat of the Laurentide Ice Sheet (LIS) resulting in progressive changes in North American climate [*COHMAP Members*, 1988; *Bartlein et al.*, 1998; *Webb et al.*, 1998; *Shuman et al.*, 2002; *Carlson et al.*, 2007, 2008, 2009]. During this early stage, gradual ice-sheet melting and summer insolation both influenced the mean position of the Jet Stream and Bermuda High, and subsequently, the meridian moisture transfer across the central part of North America [*Lovvorn et al.*, 2001; *Carlson et al.*, 2008, 2009; *Montero-Serrano et al.*, 2010]. During the LIG (~125 ka), however, the LIS deglaciated prior to the peak in boreal summer insolation due to the greater increase in boreal summer insolation relative to the last deglaciation and early Holocene [*Berger and Loutre*, 1991; *CAPE Project Members*, 2001; *CAPE Last Interglacial Project Members*, 2006; *Carlson*, 2008], possibly allowing the development of the full effects of interglacial shortwave radiation in the absence of lingering ice sheets. Under this context, in this article we present geochemical and mineralogical records of sediments deposited in the La Salle Basin and Pigmy Basin [*Montero-Serrano et al.*, 2009, 2010], from northern GoM during the Holocene and Last Interglacial (LIG), in order to document the impact of slight differences in insolation on

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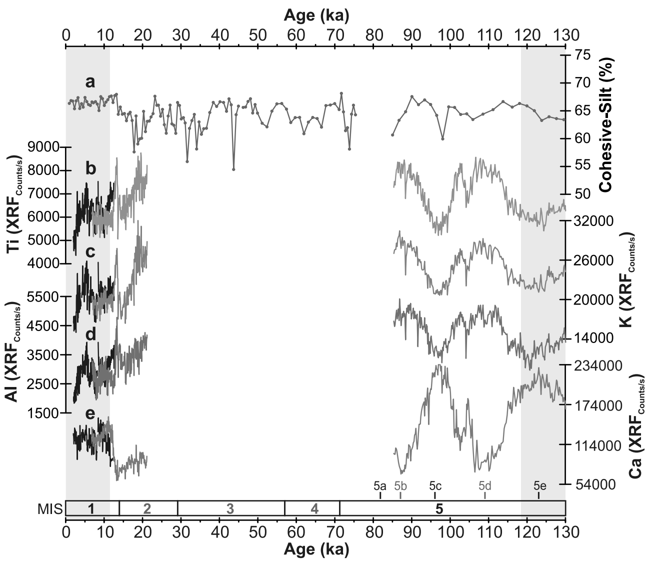

Figure 1. Comparison of sedimentological and geochemical records from the cores MD02-2549 (La Salle Basin; NW GoM) and MD02-2553 (Pigmy Basin; NW GoM; black line [*Montero-Serrano et al.*, 2010]). Note that XRF core-scanning data from core MD02-2553 are used to complete the Holocene interval because top-core sediments core MD02-2549 was too disturbed to be processed on the XRF core-scanning. (a) Cohesive-silt (%), and (b) Ti, (c) K, (d) Al and (e) Ca intensities in counts per second. XRF-core-scanner analyses have accuracy better than 4%. The Holocene and LIG intervals are indicated in gray bands.

moisture transfer and precipitation patterns over the central part of North America.

2. Mississippi River Sedimentary Supply

[4] Situated on the Louisiana continental slope ~400 km southwest of the present-day Mississippi Delta in the northern GoM, the La Salle Basin and Pigmy Basin are ideally located to continuously collect terrigenous sediment from the largest part of North America. Mineralogical and geochemical fluctuations in the La Salle Basin and Pigmy Basin can therefore be attributed to variations in the sources of sediment transported through the Mississippi River system. Indeed, distinct clay mineral assemblages, with specific proportions of illite, chlorite, smectite and kaolinite, characterize the five different geographical provinces of the Mississippi River basin [*Sionneau et al.*, 2008]. The northwest Mississippi and Missouri River province are characterized by high smectite content (S > 50%) whereas the Upper Mississippi River province has high kaolinite content (>20%). The northeast province corresponds to the Great Lakes area and the Ohio and Tennessee River catchments and mainly contributes illite and chlorite (I + C > 40%). The southeast Mississippi River province is kaolinite-rich (>30%) and depleted in smectite (S < 30%). Finally, the Brazos River and southwest Mississippi River province are dominated by illite (I > 30%) and kaolinite (>20%). Within this framework, variations in the smectite *vs.* illite + chlorite ratio [S/(I + C)] and kaolinite abundance are used to track changes in the main detrital sources [*Sionneau et al.*, 2008; *Montero-Serrano et al.*, 2009, 2010; *Sionneau et al.*, 2010], and therefore track migrations of the main precipitation belt over the central part of North America.

3. Materials and Methods

[5] The La Salle Basin (core MD02-2549; 26°25.68′N, 92°33.94′W; 2049 m water depth) and Pigmy Basin (core MD02-2553; 27°11.01′N, 91°25.00′W, 2259 m water depth) sediments cores were collected onboard the R/V Marion Dufresne in 2002. The sites are located on the continental slope in the northern GoM. Sediment samples at ~1–5 cm intervals were processed for grain-size, clay-mineral and geochemical analyses (see Text S1 of the auxiliary material for detailed methods).[1] Briefly, grain-size analyses were carried out on the carbonate-free fraction of the sediment, in order to focus on the detrital fraction, using a Malvern Mastersizer 2000 laser diffractometer followed the method described by *Trentesaux et al.* [2001]. The main grain-size parameter reported here is the cohesive-silt (2–10 μm) content. Changes in the cohesive-silt distribution may be associated with variations in the Mississippi River discharges [e.g., *Montero-Serrano et al.*, 2009]. Clay-mineral associations (smectite, illite, kaolinite and chlorite) were studied using X-ray diffraction following classical protocols [*Bout-Roumazeilles et al.*, 1999]. The aluminum (Al), potassium (K), titanium (Ti) and calcium (Ca) records were determined using the X-ray fluorescence (XRF) core scanner at the Université Bordeaux 1 (EPOC, UMR-CNRS 5805) using standard procedures [e.g., *Richter et al.*, 2006]. In this study, K and Ti records are used as proxies of the detrital sediment sources, complementary to clay mineral proxies.

[6] The chronostratigraphy of core MD02-2549 is based on tuning of the calcium carbonate content ($CaCO_3$), and spectral lightness (L*) distribution to the global benthic reference stack LR04 [*Lisiecki and Raymo*, 2005]. See Text S2 of the auxiliary material for detailed description of the core MD02-2549 age-model construction. The age model of the core MD02-2553 (Pigmy Basin) is detailed in *Montero-Serrano et al.* [2009, 2010].

4. Results: Geochemical and Mineralogical and Variations

[7] Geochemical and mineralogical and results from core MD02-2549 (La Salle Basin), and complementary data from core MD02-2553 (Pigmy Basin, NW GoM [*Montero-Serrano et al.*, 2009, 2010]) are illustrated in Figures 1 and 2a–2d. All analytical data presented are available in the auxiliary material.

[8] The fine-cohesive fraction (2–10 μm) is the main component of the sediments (54–68%), and shows a steady and rather constant downcore distribution during the Holocene and LIG, and high variability during full glacial conditions (Marine Isotope Stages (MIS) 2–4) (Figure 1a). This indicates no change in the absolute detrital input delivered to the GoM via the Mississippi River discharge during the Holocene and LIG, and suggests that absolute precipitations over North America were not more intense during the LIG relative to the Holocene.

[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2011gl048194. Other auxiliary material files are in the HTML.

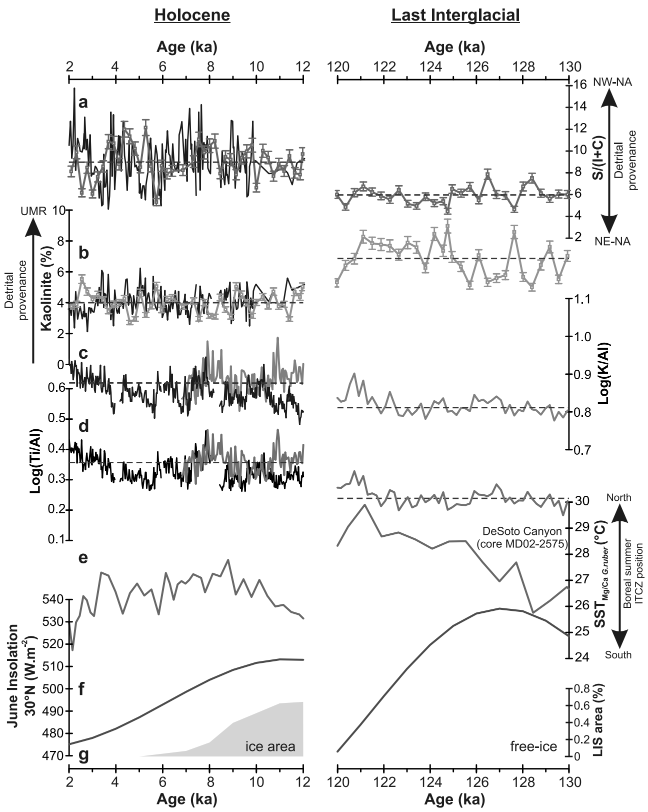

Figure 2. Sedimentological records over the Holocene and Last Interglacial periods. (a, b) Clay mineral variations [S/(I + C) ratio, kaolinite (%)] in the cores MD02-2549 (La Salle Basin; NW GoM) and MD02-2553 (Pigmy Basin; NW GoM; black line [*Montero-Serrano et al.*, 2009, 2010]). (c, d) Log-ratios of K/Al and Ti/Al from cores MD02-2549 (La Salle Basin) and MD02-2553 (Pigmy Basin; black line [*Montero-Serrano et al.*, 2010]). (e) Sea surface temperature ($SST_{Mg/Ca\ G.ruber}$ °C) record from core MD02-2575 (DeSoto Canyon; NE GoM [*Ziegler et al.*, 2008]). The $SST_{Mg/Ca\ G.ruber}$ values in the GoM are controlled by the migration of the northern boundary of the Atlantic Warm Pool (AWP), and hence the position of the Intertropical Convergence Zone (ITCZ) during boreal summer. (f) June insolation at 30°N [*Berger and Loutre*, 1991]. (g) The area of the Laurentide ice sheet (LIS) as a fraction of the area during the Last Glacial Maximum (LGM), adapted from *Shuman et al.* [2005]. The horizontal dotted lines indicate the geometric mean values of the both mineralogical and geochemical data. Based on a simple error propagation, error on S/(I + C) ratio is about 6%.

[9] The XRF core scanner provides a record of the main geochemical variations characterizing the sediments from the La Salle and Pigmy basins (Figures 1b–1e). The relative intensities corresponding to the terrigenous elements (Al, K, Ti) are enhanced during cold periods (e.g., substages 5b and 5d, MIS 2) while Ca concentration - mainly of biogenic origin in the present case [*Montero-Serrano et al.*, 2009, 2010] - is low. Conversely, they are low during warm periods (e.g., substages 5c and 5e, MIS 1) while Ca is relatively enriched. These results suggest that geochemical variations are reacting sensitively to changes affecting the ice volume and summer insolation. Similar results are reported by *Kujau et al.* [2010] in the northeastern Gulf of Mexico (core MD02-2576; DeSoto Canyon) over the last six glacial-interglacial cycles (MIS 1 to 14).

[10] The K and Ti intensities are normalized to Al intensity to remove the effects of differential dilution affecting the aluminosilicate fraction so that changes in the composition of the lithogenic material can be discerned [*Van der Weijden*, 2002]. Under this frame, the K/Al and Ti/Al ratios show similar trends and display systematically lower values during the LIG relative to the Holocene (Figures 2c and 2d). According to their present distribution on North America [*Gustavsson et al.*, 2001], increased relative proportions of K in GoM sediments may reflect greater sediment delivery from the western Mississippi basin, whereas increased relative proportions of Ti denotes sediment supplied from the southeastern Mississippi River region [*Kujau et al.*, 2010]. The K/Al and Ti/Al ratios thus suggest lower terrigenous contributions from the northwest and southeast provinces during the LIG relative to the Holocene. Alternatively, Al is also enriched in kaolinite (39% Al_2O_3) during the hydrolysis process, which could at least partially explain the opposing trends between kaolinite and K/Al-Ti/Al [*Montero-Serrano et al.*, 2010], and the lower K/Al and Ti/Al ratios during the LIG relative to the Holocene (Figures 2b–2d). These observations suggest that the geochemical signature may be partly controlled by the mineralogy and imply not only decreased sediment contributions from the western Mississippi River provinces but also enhanced contributions from the Upper Mississippi River and northeast Great Lakes provinces.

[11] The sedimentary records show significant differences in clay-mineral trends during the early Holocene and LIG (Figures 2a and 2b). The Holocene clay assemblages are dominated by smectite (80–89%), followed by illite (6–13%), kaolinite (3–6%) and chlorite (1–3%), indicating that a significant portion of sediment discharged to the GoM was derived from the northwest Mississippi River province. Although smectite is still the main component of the clay-mineral assemblages (74–84%) during the LIG, illite (8–14%), kaolinite (5–9%) and chlorite (2–4%) all increase in concentration. As a result, the two interglacials have distinctly different S/(I + C) patterns (Figure 2a). The ratio remains constant at 6 ± 2 throughout the LIG whereas the Holocene has higher values up to 9 with greater variability (±3). These mineralogical characteristics suggest a larger contribution of sediment from the illite-rich northeastern Great Lakes province and the kaolinite-rich Upper Mississippi River province during the LIG.

5. Discussion: Modifications of the Detrital Provenance Related to the Position of the Precipitation Belt Over North America

[12] We hypothesize that the different detrital provenances during the LIG when compared to the Holocene were related to the extent of the LIS and the degree of boreal summer insolation increase, which affected regional atmospheric circulation and the position of the precipitation belt over North America. Variation in the positions and intensities of the Bermuda High, Jet Stream, ITCZ and AWP control the inland transfer and distribution of moisture to North America [*Montero-Serrano et al.*, 2010]. Slight differences in mean atmospheric circulation during the LIG

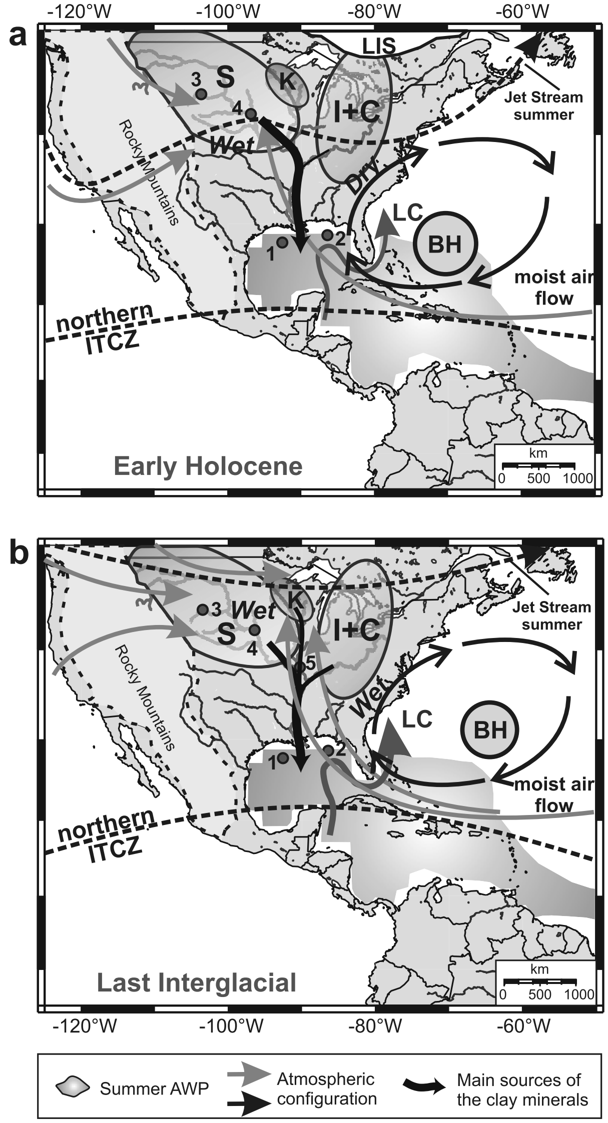

Figure 3. Schematic scenarios of the atmosphere-ocean-continent interactions from middle-latitude North America during the (a) early Holocene and (b) Last Interglacial periods, and their paleoclimatic implications. Note the anomalous wet conditions extended over North America during the Last Interglacial period. The Jet Stream position denotes the approximate boundaries of air masses originating from tropical, pacific and polar-source regions and constrains the main moisture transfers over the North American continent. The averaged position of the Atlantic Warm Pool (AWP) and Intertropical Convergence Zone (ITCZ) for Northern Hemisphere summer is indicated (adapted from *Nürnberg et al.* [2008] and *Ziegler et al.* [2008]). Gray shade in the GoM and the Caribbean region denotes the northward advection of the AWP into the GoM. BH and LC denote the Bermuda High and Loop Current, respectively. Numbers at each sites show location of selected localities discussed in this study: (1) La Salle Basin (MD02-2549), (2) DeSoto Canyon (MD02-2575 [*Nürnberg et al.*, 2008; *Ziegler et al.*, 2008]), (3) northern High Plains and Colorado Piedmont [*Forman et al.*, 1995; *Muhs et al.*, 1999], (4) Missouri valley [*Forman and Pierson*, 2002], (5) Mississippi River valley [*Forman and Pierson*, 2002].

may explain the observed changes in terrigenous sources. Boreal summer insolation was significantly higher during the early LIG relative to the early Holocene and likely caused generally warmer boreal summer temperatures during the LIG [*Berger and Loutre*, 1991; *CAPE Project Members*, 2001; *CAPE Last Interglacial Project Members*, 2006], which may have increased the latitudinal temperature gradient [*Kaspar et al.*, 2007] and modified atmospheric moisture transfer patterns. The greater increase in boreal summer insolation also drove faster retreat of the LIS, with the LIS greatly diminished by the peak in LIG insolation [*Carlson*, 2008]. In contrast, the LIS persisted until ~6 ka in the mid-Holocene, lagging peak insolation by 5–6 ka [*Carlson et al.*, 2007, 2008]. As a result, the presence or absence of the LIS likely modified the mean position of the Jet Stream and Bermuda High [*COHMAP Members*, 1988; *Forman et al.*, 1995; *Bartlein et al.*, 1998; *Webb et al.*, 1998; *Shuman et al.*, 2002].

[13] During the early Holocene, the geochemical characteristics and clay-mineral assemblages suggest a dominant moisture source from the smectite-rich northwest Mississippi River province (Figures 2a and 3a). The lingering LIS and its strong anticyclonic cell may have forced the mid-latitude Jet Stream south [*COHMAP Members*, 1988; *Forman et al.*, 1995; *Shuman et al.*, 2002; *Carlson et al.*, 2008, 2009] of the Upper Mississippi River and northeast Great Lakes Provinces. The Bermuda High was likely situated southwest of its current position (Figure 3a) in agreement with configurations proposed by *Forman et al.* [1995] and *Montero-Serrano et al.* [2010]. In order to improve this synoptic scenario, we also account for variations in the AWP and ITCZ that may modulate moisture transfer toward the central part of North America [*Lovvorn et al.*, 2001]. Indeed, high sea surface temperature ($SST_{Mg/Ca\ \ G.ruber}$) values in the GoM (Figure 2e), induced by the insolation maxima during the early Holocene (Figure 2f), suggest a more pronounced AWP and a northward migration of the average position of the ITCZ during summer [*Ziegler et al.*, 2008]. Such an atmospheric-ocean configuration would favour moisture delivery from the GoM and nearby tropical waters to the northwest Mississippi River province (Figure 3a).

[14] The geochemical and mineralogical proxies indicate a more mixed provenance of sediment supplied during the LIG from the northwest (smectite-rich) and Upper (kaolinite-rich) Mississippi River provinces and the illite-rich northeast Great Lake province. These results suggest that the main moisture flux reached the northwest to northeast Mississippi River watershed during the LIG (Figure 3b), increasing the area of the North America continent that was influenced by the precipitation belt. The extent of the Sangamon paleosol (points 3 to 5 on Figure 3b) supports our interpretation and implies a warm/wet climate across much of the Mississippi River watershed during the LIG [*Ruhe et al.*, 1974; *Forman et al.*, 1995; *Muhs et al.*, 1999; *Hall and Anderson*, 2000; *Forman and Pierson*, 2002]. These paleosols did not develop in the north Mississippi River watershed during the early Holocene because the persistent LIS likely diverted moisture sources further south (Figure 3b).

[15] The specific rainfall distribution suggested by our results for the LIG implies changes to mean atmospheric circulation patterns from those of the early Holocene (Figure 3b). For instance, the overall greater increase in

boreal summer insolation and the disappearance of the LIS near its peak (Figure 2f) likely allowed northward migration of the Jet Stream during the LIG relative to the Holocene, bringing more moisture to the Upper Mississippi River and northeast Great Lakes provinces. Theses interpretations are in general agreement with previous Northern Hemisphere climate models of the LIG [e.g., *Harrison et al.*, 1995]. Similarly, the greater increase in boreal summer insolation (Figure 2f) led to a maximum penetration of Caribbean surface waters into the GoM, and therefore, to higher $SST_{Mg/Ca\ G.ruber}$ values in this area (Figure 2e). These observations suggest a more expanded AWP and more northern position of the ITCZ during the LIG relative to the early Holocene [*Ziegler et al.*, 2008]. These positions may have also forced the Bermuda High further to the northeast when compared to its early Holocene position, thereby transferring even more moisture from the GoM and the Caribbean region to the Upper Mississippi River and northeast Great Lakes area (Figure 3b). Together, our clay-mineralogical and geochemical results and hypothesized changes in atmospheric circulation suggest an overall wetter mid-continental North America during the LIG and highlight the sensitivity of atmospheric circulation and moisture transfer patterns to small changes in radiative forcing.

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