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The influence of orbital parameters on the North American Monsoon system during the Last Interglacial Period

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Abstract

The response of summer precipitation in the western U.S. to climate variability remains a subject of uncertainty. For example, paleoclimate records indicate the North American monsoon (NAM) was stronger and spatially more extensive during the Holocene, whereas recent modeling suggests a weakened NAM response to increasing temperatures. These illustrate diverging pictures of the NAM response to warming. Here, we examine summer precipitation in the southwestern U.S. related to Last Interglacial insolation forcing. Using a high-resolution climate model, we find that Eemian insolation forcing results in overall wetter conditions throughout most of the southwestern U.S, but significantly drier than present conditions over Arizona. The overall wetter conditions are associated with a northward shift of the anticyclonic circulation aloft and increased moisture in the lower and mid-troposphere during the Eemian. Increased advection of Gulf of Mexico moisture is responsible for increasing precipitation in New Mexico and the northern edges of the NAM region. Drier conditions over Arizona are likely related to reduced local convection and enhanced north/northwest passage of tropical cyclone remnants. These results highlight the spatial complexity of the NAM response to increasing radiative forcing and allow a better understanding of monsoon dynamics and variability in response to a warming climate.

1. Introduction

Precipitation in the southwestern United States is dominated by seasonal monsoonal circulation. The North American Monsoon (NAM) occurs mainly between July and September and provides ~70% of mean annual precipitation to central and northern Mexico and ~35-50% of mean annual precipitation to Arizona and New Mexico in the U.S. (Fig.1a). The NAM shows a strong variability on annual, decadal, and millennial timescales (e.g., Diem et al., 2013; Griffin et al., 2013; Poore et al., 2005) and understanding the response of the monsoonal system to climate change is critical in determining changes in the amount and seasonal distribution of precipitation in this semiarid region of North America. The response of the NAM to increased greenhouse gas forcing and increasing temperature is ambiguous. Previous studies have concluded that global warming was simply delaying the North American monsoon, but changes in total monsoon seasonal rainfall are small and insignificant (Cook and Seager, 2013). In contrast, a recent study by Pascale et al. (2017) highlights the possibility of a strong precipitation reduction in the northern edge of the monsoon in response to warming, with consequences for regional water resources, agriculture and ecosystems. These suggested responses of the NAM to current changes in the climate system are distinct from studies providing causes and characteristics of climatic and monsoonal variations over paleo timescales. Insolation is widely regarded as an important control of climate change on long-timescales, particularly in monsoon regions. A strong correlation between summer monsoon intensity and summer insolation has been observed in monsoon records from Asia, South America, and Africa (Cruz et al., 2005; Kutzbach and Liu, 1997; Liu et al., 2006; Wang et al., 2001). Evidence suggests that during insolation maxima, increased summer land-sea temperature contrasts strengthen monsoon systems and shift the summer position of the Intertropical Convergence Zone (ITCZ) further inland (McKay et al., 2011; Montoya et al., 2000). Several records from the U.S. and Mexico exhibit evidence of increased summer convection and precipitation during the warmest periods of the mid-Holocene (Barron et al., 2012; Metcalfe et al., 2015).

To better understand the interplay between rising temperatures and moisture in the NAM region, we chose to focus on the response of the NAM to shifts in orbital forcings during the Last Interglacial (LIG: ~130 to 116ka). The LIG is the most recent period in Earth history when temperatures are believed to have exceeded those of today (Bakker et al., 2013; CAPE members - Anderson, 2006; Kukla et al., 2002; McKay et al., 2011; Turney and Jones, 2010). In particular, the Eemian (~125 ka) is an interval where the Earth was in an orbital configuration that corresponds with insolation maxima and enhanced summer heating of the Northern hemisphere (Berger and Loutr, 1991). The Eemian was warmer than the present day with higher sea level (Bard et al., 1990) and diminished ice sheets (Cuffey and Marshall, 2000). Climate models suggest that the Eemian was a time of increased Northern-Hemisphere temperature and humidity, with a northward–shifted ITCZ, increased summer land-sea temperature contrast, and intensified monsoon convection (Montoya et al., 2000). Numerous studies have focused on the response of polar temperatures to interglacial forcing but less attention has been paid to the regional hydroclimatic changes at the time. These changes are of interest because the response of terrestrial ecosystems to hydroclimate shifts may have been critical to the carbon cycle during the Eemian (Kleinen et al., 2016). For example, favorable redistributions of rainfall into semi-arid regions such as the Southwestern U.S. may have acted to increase the terrestrial carbon sink.

Here, we use simulations from a regional climate model (RegCM) under LIG and modern forcings to evaluate changes in the strength, timing, duration, and amount of moisture transported from different sources during the NAM season. The simulated periods are linked with different phases of the interglacial climate system that have been identified in paleodata, namely: the maximum and minimum summer insolation in the northern hemisphere (130 ka and 115ka, respectively) as well as the minimum global ice volume (125 ka). Our simulations intend to complement previous LIG simulations done at lower resolution with a focus on monsoonal dynamics. Among other things, these simulations serve as a reference for new and upcoming proxy records in the southwestern U.S. (Pigati et al., 2014). Particularly, the data provide background to consider how global carbon cycle dynamics and ecological systems in the southwestern U.S. might have responded to recent periods in Earth history when summer temperatures exceeded those of today (Brown et al., 2014; Elias, 2014; Strickland et al., 2014) Understanding these variations is critical to forecast seasonal supply of water to and habitat changes in the southwestern U.S. under current warming conditions.

2. Model Description and Setup

RegCM_4.4.5 (Pal et al., 2007) is a fourth generation, three-dimensional regional climate model, based on the original model developed by Giorgi et al. (1993a; 1993b) with a dynamical core that is adopted from the hydrostatic version of the Pennsylvania State University-National Center for Atmospheric Research Mesoscale Model (MM5) (Grell et al., 1994). It is a primitive-equation, hydrostatic, compressible model with sigma-vertical coordinates (Giorgi et al., 1993a). Improvements in the software code and model physics (e.g., representation of convective schemes, surface physics, atmospheric chemistry and aerosols, ocean-air exchanges) allows an enhanced model performance in monsoonal regions. A full description of RegCM4's basic features and details on the historical evolution of RegCM are given in Giorgi et al. (2012).

RegCM_4.4.5 experiments were performed for North America using a horizontal resolution of 55 km and 18 vertical levels. Lateral boundary conditions are based on data from ERA-Interim reanalysis with a spatial resolution of 1.5°x1.5° (EIN15), while sea-surface temperatures (SSTs) were obtained from the NOAA optimum interpolation (OI) SST analysis (Reynolds et al., 2002). Convective precipitation was computed with the MIT-Emanuel scheme (Emanuel, 1991). It has been shown that RegCM simulations with the cumulus convections scheme and its Emanuel closure assumptions lead to improved simulations of precipitation, temperature and low-level wind patterns in comparison to other cloud and convection parameterizations (Pal et al., 2007; Sinha et al., 2019; Velikou and Tolika, 2017). In particular, RegCM has been widely applied in limited-domain, seasonal forecasts and used to simulate climate in high-precipitation monsoonal regions and around the globe (e.g., Diro et al., 2012; Fuentes-Franco et al., 2014; Insel et al., 2009; Sylla et al., 2010). The goal of this study is to quantify the impact of orbital parameters on North American Monsoon dynamics. Our model domain ranges from 128° W to 82° W along the southern domain margin at ~10° N and from 150° W to 60° W along the northern domain margin at ~60° N (Fig. 1). The domain includes parts of the western Pacific and the Gulf of Mexico to accurately simulate climate sensitivity over oceanic regions. We designed 4 experiments to account for different orbital parameter configurations during the LIG and changing greenhouse gas concentrations (Table 1). In particular, we simulated interglacial time slices to capture the obliquity minimum and maximum (MinObliquity-115ka, MaxObliquity-130ka; (Berger and Loutr, 1991)), respectively, and a third time slice that falls between these two. Simulations were 21 years in length and results are based on the last 10 years of the simulations. While the length of spin-up time is dependent on model domain, season, and circulation intensity, previous studies have shown that regional climate models are usually representing a dynamic equilibrium after just a few months (Zhong et al., 2007)

Small discrepancies with observations may arise due to the experimental design, which include the use of present-day vegetation and polar ice sheets as well as consistent sea surface temperatures. Modern boundary conditions for geography, ice sheets, and vegetation follow previous studies simulating temperature and precipitation responses in the United States to interglacial warm periods (e.g., Diffenbaugh et al., 2006; Otto-Bliesner et al., 2013). Moreover, Diffenbaugh et al. (2006) indicated that general precipitation patterns over the U.S. do not change in response to sea surface temperatures changes in orbital-driven warm periods. Moreover, they observed that at least some localities showed greater agreement with the proxy record in experiments without changes in SSTs as compared to a more complete ocean treatment.

3. Results

3.1. Model Validation

A comparison between simulated and observed data indicates that RegCM_4.4.5 performs well in capturing the general climatology in the western part of North America (Fig. 1). The model performance for modern precipitation is assessed by using independent precipitation observations from the Global Precipitation Climatology Centre (GPCC) data base (Schneider et al., 2011). Figure 1a shows the NAM expressed as percent of annual precipitation that falls in July to September (JAS). The model captures the spatial distribution of monsoon precipitation across the western United States and Mexico, including regions of maximum precipitation along the west coast of Mexico (Fig 1b). Moreover, the model is consistent with the climatological monthly precipitation averaged over the main region of the NAM. The region is semiarid with a single precipitation maximum evident in the summer months with averaged maximum precipitation of around 3.5 mm/day (Fig 1c). The model captures the July and August precipitation, but overestimates precipitation in June and September. We attribute this discrepancy to the model resolution and prescribed sea surface temperatures that likely overestimate the moisture component that is transported from the oceans to the land, resulting in higher precipitation rates. A model data comparison indicates a wet bias over the core of the NAM region in southern Mexico, and a dry bias along the western continental Mexican coast. However, the main spatial and temporal patterns of monsoonal precipitation are well established in our model simulations.

3.2. Insolation and Temperature

The changes in the amount of insolation received by the Earth during LIG result from changes in the astronomical configuration. During MaxObliquity (130ka) and in the Eemian (125ka), our study area received more insolation in spring and summer compared to the present-day period (Fig. 2a, b). Focusing on the NAM area, the difference in incoming shortwave flux at the top of the atmosphere between the warm LIG periods and present is approximately 45 Wm^{-2} in June and -25 Wm^{-2} in December. However, MaxObliquity indicates stronger insolation in particular from late February to July, while the Eemian is characterized by stronger insolation from late April to September (Fig. 2a). In contrast, MinObliquity (115 ka) indicates the opposite pattern in insolation with below modern values in spring and summer and above modern values during the fall and winter. The magnitude of changes between MinObliquity and modern is overall smaller with around -20 Wm^{-2} in June and 20 Wm^{-2} in December.

In response to increased insolation in northern hemisphere spring and summer during 130ka and 125 ka, simulated surface temperatures are generally higher during those periods compared to the present-day over the majority of the western and southwestern U.S. Positive temperature anomalies averaged over the NAM region are observed in April, May and June during the early LIG (Fig. 2c, d). Temperature anomalies indicate strong spatial variability with up to 2°C higher temperatures in New Mexico and Arizona, but similar to present temperatures in central and western Mexico (Fig. 3). Warming is stronger and occurs earlier at 130ka in comparison to 125ka. In July and August, surface temperatures are cooler in most parts of the monsoon region with regional temperature differences of up to -1.5° C compared to present. Most cooling is observed along the west coast of Mexico and Baja California. This is opposite to the expected direct radiative effect, and might be due to increased cloudiness, evapotranspiration, and precipitation (Fig. 2e-f, 4). During

MinObliquity, surface temperatures in the southwestern U.S. are generally colder than present throughout the entire spring and summer, corresponding to reduced insolation at that time (Fig. 3).

3.3. North American Monsoon Pattern (Modern versus Eemian)

Simulated precipitation is the sum of large-scale precipitation related to cyclones or frontal systems, and convective precipitation associated with local surface heating and vertical air movement. The NAM system is associated with a dramatic increase in summer precipitation. Averaged over the entire monsoon region, precipitation magnitudes over land reach a maximum around 130 mm/month in July and August (Fig. 2e). Modern precipitation is spatially very variable with the highest precipitation rates in Mexico and significant less precipitation across the southwestern U.S. (Fig. 5a). Precipitation related to the NAM system comes from two distinct sources. Water vapor in the eastern part of the NAM region mainly originates from the Gulf of Mexico (GoM); moisture in Arizona appears to originate from the Gulf of California (GoC) and the eastern tropical Pacific (Fig. 6 ; Comrie and Glenn, 1988). The moisture transport is reflected in the high surface values of specific humidity on either side of the Mexican plateau. The elevated topography blocks and deflects low-level winds and divides the water vapor sources with a moist tongue extending up the Gulf of California on the west side and increased amounts of water vapor extending from the Gulf of Mexico on the east side. Warm air over land is more buoyant and destabilizes the atmospheric column directly above. As a result, atmospheric convection is dominant and most of the monsoonal precipitation is convective in origin (~80-90%, Fig. 2g).

The large-scale, low-level flow over the southwestern U.S. and Mexico is strongly influenced by the subtropical Highs (e.g., Higgins et al., 1997). The strongest flux onto the terrestrial NAM region occurs at low levels by southeasterly and southwesterly winds. Strong northwesterly winds associated with the large-scale circulation in the east Pacific anticyclone occur west of Baja California (Fig. 7a). Along the west coast, the low-level flow is primarily parallel to the continent with little influx of moisture. The large-scale, 500-hPa and 200-hPa wind fields show large anticyclonic rotation over the southwestern U.S. (Fig. 7b, c) and steer moisture transport at lower levels predominantly from the Gulf of Mexico.

In the following paragraphs, we are looking at the dynamics of the monsoon system during the Eemian (125 ka) and how it differs from the present. We will discuss the changes in precipitation, moisture and wind system averaged over the whole NAM region as well as spatial variability within the monsoon region itself. This will allow us to better understand the underlying dynamics and mechanisms responsible for enhanced or reduced monsoonal precipitation and to compare our results to previous GCM studies with much lower resolution.

During the LIG, the overall precipitation pattern and length of the monsoon season is similar to today with a strong summer monsoon and dry winter months. However, during the Eemian, precipitation over the NAM region slightly increases in spring, and is considerably higher in July and August in comparison to the present (Fig. 2e,f). Averaged over the entire monsoon region, monthly precipitation magnitudes were about 24 mm higher in July and 14 mm higher in August. Increased precipitation during the Eemian summer is associated with a slight increase in cloud cover and a large increase in columnar liquid water content (Fig. 4). However, convective precipitation changes very little (Fig. 2g), so most of the additional precipitation must be related to large-scale phenomena. The changes in monsoonal precipitation during the Eemian were not uniform, but indicate strong spatial variability. JJA precipitation increased by up to 60 % in the eastern half of the monsoon region, but decreased by 35 % over Arizona in the northwestern part of the NAM region (Fig. 5c).

The changes in the continental precipitation pattern during the Eemian can be related to changes in tropospheric circulation and divergence fields and associated changes in monsoonal moisture fluxes. Simulated air temperature over the GoM is slightly warmer in the Eemian compared to modern (Fig. 3). Warmer temperatures over the GoM and along a narrow corridor from the east coast of Mexico into New Mexico and the northern part of Arizona provides a basis for stronger moisture transport into the eastern part of the monsoon region. Surface winds increase around 15 % over the Gulf of Mexico and the Gulf of California (Fig 7), transporting more moisture into north-central Mexico, New Mexico and California and leading to increased evapotranspiration (4c, d). Although moisture is concentrated in the lower troposphere over the southwestern U.S., a change in specific humidity is also evident in the middle troposphere (Fig. 6). Higher atmospheric moisture content at 500-hPa across the southwestern U.S. is associated with an increase in middle and higher-level wind speeds, which appears to be a direct consequence of the northward shift of the anticyclonic wind pattern (Fig. 7).

Although most of the monsoon region indicates an increase in precipitation during the Eemian, Arizona shows a pronounced drying (Fig. 5c). The decrease in total precipitation over Arizona correlates with a decrease in evapotranspiration and convection in that area (Fig. 8, 9). Most of the precipitation over the NAM region is convective in origin, but the climatological conditions that promote convection differ between regions (Adams and Comrie, 1997; Douglas et al., 1993). Low-level moisture advection from the Gulf of Mexico is critical for convective activity in the eastern part of the NAM. In the western NAM region, convection depends essentially on the presence of lower-troposphere moisture with intense insolation and elevated topography (Adams and Souza, 2009). Simulated air temperature over the eastern subtropical Pacific and over the Gulf of

California (GoC) is colder in JJA which is in agreement with suggested Eemian cooling in the subtropical Pacific based on Mg/Ca observational data (Leduc et al., 2010).

Lower air temperatures around Baja California may weaken convection (Fig. 9) and moisture supply to the western part of the NAM region. Lower temperatures in southern Arizona correlate with decreased evapotranspiration in the area. In addition, surface winds over Arizona are 35 % higher in comparison to modern (Fig. 7), moving water vapor out of the area to the east. Surface winds are from the southwest but shift from a more meridional to a more zonal direction (i.e., a stronger western component). This could explain an increase in California precipitation, while Arizona experiences drier conditions. Examination of the vertical structure indicates a region of reduced upper-tropospheric (200-hPa) divergence (Suppl. 1) that coincides with reduced mid-tropospheric vertical motion, reduced convection, and reduced monsoon rainfall in Arizona.

3.4 Temporal Monsoon Variability during LIG

Our model simulates positive temperature anomalies in early summer across the western U.S. in response to the dominant orbital forcing mechanism that modifies the incoming solar radiation during the early stages of the LIG. Despite similar orbital forcing configurations during the warm phase of the LIG, the monsoonal climate during 130ka and 125ka is quite different.

Obliquity is largest at 130ka and peaked earlier than precession during the LIG (Crowley and Kim, 1994). The obliquity affects seasonal contrast and results in stronger monthly temperature deviations at 130 ka than 125ka in comparison to present simulations (Fig. 2). However, simulations show that the NAM response is dominated by precession. Positive temperature anomalies averaged over the NAM region are significantly higher in spring at 130 ka than at 125 ka. While July temperature anomalies differ spatially under Eemian conditions, the average temperature across the NAM region is similar to MaxObliquity. This is consistent with a shift in perihelion from earliest May at 130 ka to late July at 125 ka and associated impacts on Northern Hemisphere insolation (Otto-Bliesner et al., 2013).

The timing of perihelion increased the seasonal insolation and temperature contrast; an effect that was amplified by the highly eccentric orbit. The effects can be seen in other climate variables. The overall cooler temperatures in the late summer months during 130 ka taper the monsoonal response. Averaged over the entire NAM region, MaxObliquity indicates a larger positive precipitation anomaly in May, when insolation is the highest, but experiences an overall similar monsoon as present, with slightly higher precipitation magnitudes in June and July (Fig. 2). JJA spatial pattern indicate a maximum increase in precipitation of around 30-50 % in a small northeastern part of the NAM, while large parts of Mexico indicate a modest decrease around 10-20 % or no significant change in precipitation in comparison to today (Fig. 5d). During MaxObliquity, wind patterns suggest an overall reduced moisture flux from both the Gulf of Mexico and the Gulf of California. Moisture changes in the lower and middle troposphere are small in comparison to modern (Fig. 6). Arizona experiences a similar pattern to the Eemian, with a precipitation decrease of up to 35 %. Climate parameters over Arizona indicate a similar response as 125ka with decreasing evapotranspiration and convection in the area.

While we are mainly focusing on the warm periods of the early LIG, we want to present a short summary of climate changes related to MinObliquity in order to provide a comparison in monsoonal variability in relation to orbital parameters. Eccentricity is large throughout the entire LIG. With minimum obliquity and perihelion in January, seasonal contrasts at 115 ka are moderate. In response to lower insolation and lower temperature in spring and summer, the NAM region is slightly dryer with precipitation about 5 to 10 % lower than modern. The decrease in total precipitation is mostly due to a slight decrease in convection and associated less intense storm events throughout the summer. MinObliquity is characterized by a strong reduction in moisture at the lower and middle troposphere. The extent and magnitude of drying is similar to the spatial pattern observed for increased humidity in the Eemian. Maximum decrease in surface moisture is observed in the NAMeast region and north of the core monsoon, while moisture in the middle troposphere mostly decreases in southern California (Fig. 6). The upper level anticyclone weakens and shifts southeast.

4. Discussion

Overall, our simulations suggest a temporally and spatially diverse response to insolation changes in the North American Monsoon region. We contribute the difference in the timing and magnitude of maximum insolation and temperature changes to changes in obliquity and precession. Previous studies (e.g., Bakker et al., 2013; Otto-Bliesner et al., 2013) have shown that the radiative forcing provided by the changes in the three major GHGs is small (< 0.2 W m^{-2}) compared to the forcing provided by the insolation changes. Our simulated June and July temperatures are consistent with results from earlier model inter-comparison studies that show robust Northern Hemisphere July temperature evolution characterized by a maximum between 130 – 125 ka with temperatures 0.3 to 5.3 K above pre-present day (Bakker et al., 2013; Lunt et al., 2013). Proxy datasets of quantitative estimates of mean annual surface temperatures only include a limited number of terrestrial sites in the U.S. However, intact Eemian wood samples have been recovered from sediments of the Ziegler Reservoir in Snowmass Colorado (Pigati et al., 2014). A unit corresponding to MIS 5e has been dated to between ~126 and 120 ka with mean July temperature reconstruction that have been similar to or slightly warmer than they are today (Elias, 2014). Interestingly, the core region of the NAM region, including northwestern Mexico and southwestern Arizona, indicates cooling in July and August. We attribute this pattern to increased cloud cover and an increase in total columnar liquid water content (Fig. 4a, b). The clouds tend to have a negative radiative forcing. While the TOA insolation is significantly higher during the early LIG, the surface net downward shortwave flux is similar to modern in July and August. This pattern is consistent with previous model results that show continental cooling at subtropical northern latitudes associated with the core regions of other monsoon systems such as Asian and African systems (Otto-Bliesner et al., 2013).

Our model indicates northward movement of the mid-level anticyclone and warming over the Gulf of Mexico that facilitates stronger moisture transport into the eastern NAM region. An intensification of precipitation over most of the southwestern U.S. during the Eemian is consistent with previous studies that suggest a more intense NAM in response to increased Northern Hemisphere insolation (Asmerom et al., 2007; Barron et al., 2012; Metcalfe et al., 2015). A recent study by Scussolini et al. (2019) compares simulated hydroclimates in LIG model experiments with proxy data and explores the limitations of data-model comparisons. In very good agreement with our simulation, Scussolini's model ensemble shows higher average precipitation of the NAM during the early LIG by about 34%. The models used in that study indicate considerable variability with the EC-Earth model suggesting a slight decrease in monsoonal precipitation during the LIG (Scussolini et al., 2019). Very few terrestrial LIG proxies exist in the southwestern U.S. and none of them unambiguously project seasonal precipitation anomalies. Multiproxy data from wetland records in Colorado (Miller et al., 2014) and pollen proxies from ancient lakes in California (Bradbury, 1997; Ku et al., 1998; Menking et al., 1997; Reheis et al., 2012) suggest overall wetter conditions during the early LIG, but it is not clear whether these anomalies are related to summer or winter precipitation.

Our model predicts an increase in monsoonal precipitation over most parts of the southwestern U.S., but also distinctively drier conditions over the northwest corner of the core monsoonal area in Arizona. We are not aware of datasets that can verify or refuse the idea of regional drying in parts of the NAM during the Eemian. Paleoclimate model simulations are usually conducted with lower-resolution general circulation models that provide large-scale information, but do not resolve small-scale regional variations. However, the proposed spatial variability in monsoonal precipitation is consistent with the dual nature of the modern monsoon, where anomalously wet periods in New Mexico do correspond to low precipitation periods in Arizona or vice versa, supporting the evidence of different moisture sources and paths for the two regions (Comrie and Glenn, 1998).

The climate of the Eemian is closely related to the orbital forcing configurations that result in a pronounced seasonal cycle with warmer summers and colder winters. Current and future climate change is associated with greenhouse gas radiative forcing that will most likely result in uniformly warm conditions throughout the year. While the difference in forcing factors might limit our expectations of a direct comparison between the two warming scenarios, positive temperature anomalies and associated patterns in hydroclimate have been proposed in future climate projections. There is observational evidence to suggest that monsoon precipitation is becoming more extreme in the Southwest and northwestern Mexico with increasing surface temperatures (Anderson et al., 2010; Chang et al., 2015; Luong et al., 2017). An overall stronger monsoon can be explained by strong feedbacks between insolation, evapotranspiration, convection, and cloudiness. However, summertime convective activity in the southwestern U.S. is spatially variable and results from complex interactions between atmospheric circulation features and the complex topography (Adams and Souza, 2009). Drier conditions in Arizona may reflect local topographic effects that are critical to the distribution of convective activity. Adams and Comrie (1997) discussed the formation of the NAM in response to temperature contrasts between seasonally warm low land surfaces and elevated areas together with atmospheric moisture supply from nearby maritime source. In the modern context, the thermal contrast in the Gulf of California facilitates the formation of moisture-laden air masses that move northward toward a region of low pressure centered over Arizona (Pascale and Bordoni, 2016; Wu et al., 2009). Our simulations show a decrease in temperature in the low-lying regions of Arizona, which reduces the thermal low and reduces convective precipitation (Fig. 5, 8). Our results are in agreement with Pascal et al. (2017) who highlights the possibility of a strong precipitation reduction in the northwestern edge of the monsoon region in response to increased atmospheric stability and weakened convection with increasing temperatures.

Here, we propose an additional mechanism that might contribute to a spatially variable precipitation pattern. The western NAM region experiences the highest precipitation flux in late August to early September, in contrast to the July precipitation maximum in the eastern NAM region. This pattern may reflect an enhanced influence of tropical Pacific cyclones on precipitation in late summer (Corbosiero et al., 2009; Englehart and Douglas, 2001; Ritchie et al., 2011). Arizona experiences the highest contribution of tropical cyclone remnants to warm-season precipitation (~15-25%; Ritchie et al., 2011). During the Eemian, a decrease in eastern Pacific winds along the coast of Baja California and the northward shift of the upper-level anticyclone (Fig. 7) may allow a more north/northwest path of tropical Pacific cyclones, resulting in higher precipitation in Mexico and/or California and Nevada, but reduced rainfall over Arizona (consistent with the group 3 and 4 tropical cyclone remnants as described by (Ritchie et al., 2011). In this case, precipitation can increase along the west coast of the southwestern U.S., but the topography of southern California and the Sierra Nevada limits penetration of Pacific moisture (Adams and Comrie, 1997), thus resulting in drier conditions over Arizona. Current and future climate projections suggest cyclone intensification in response to a warmer climate (e.g., Balaguru et al., 2018; Bathia et al., 2019; Holland and Bruyère, 2014; Walsh et al., 2016), but it is difficult to simulate hurricane distribution in the past, mostly due to uncertainties in sea surface temperatures and the time-scale involved (Frappier et al., 2007). However, warmer temperatures and a shift in large-scale circulation during the Eemian may have had the potential to increase the tropical cyclone contribution to NAM precipitation in late summer. It is important to note that most of the NAM literature has a strong geographical bias toward the state of Arizona, but differences in precipitation response between the eastern and western NAM regions are very apparent in our model output as well as modern observations (Comrie and Glenn, 1998). Our model simulations suggest that in a warmer climate, NAM regions that are dominated by local convection experience drier conditions, while regions that can pick up large-scale systems, either through enhanced moisture transport from the Gulf of Mexico or increased impact of tropical storms, experience wetter conditions. Our findings are consistent with present-day analysis from the Climate Prediction Center and individual Cooperative Observer Program (COOP) stations with long-term records of precipitation in the southwestern U.S. that indicate a significant increase in mean precipitation in New Mexico, but a decrease in mean monsoon precipitation over Arizona in recent decades (Luong et al., 2017).

The precipitation response to increased solar radiation and associated warming is complex. The NAM region does not experience a uniform response to changing climate conditions. A more detailed analysis with high-resolution models (<25 to 10km resolution) is necessary to account for a thorough analysis of the Gulf of California response to insolation changes. We may not accurately resolve the summertime low-level flow along the Gulf of California which may impact precipitation estimates in the southwestern US. However, our model results are in good agreement with previous studies trying to unravel the NAM history in response to warmer interglacial periods as well as modern observations in a warming climate.

Acknowledgements:

This study was supported by the National Science Foundation grant NSF EAR 1502772. The work was completed in part with resources and assistance provided by the University of Chicago Research Computing Center. We thank two anonymous reviewers for constructive comments on the manuscript.

Figures:

Figure 1: Measured and simulated monsoonal precipitation across North America. (a) Precipitation (in percent of annual precipitation) during the peak NAM season (July, August, September = JAS) based on observations from the Global Precipitation Climatology Centre (GPCC) database from 1981 to 2010. (b) RegCM4 simulated 10-year mean JAS precipitation. Red box highlights the main NAM monsoon region, green box indicates Arizona 'dry" region (see text for explanation). (c) Monthly precipitation flux of observed and simulated precipitation over the monsoon region.

Figure 2: Simulated forcing factors and climatic indices averaged over the North American Monsoon region for 4 cases: modern (black line), 115 ka (blue line), 125ka (green line), and 130 ka (red line). (a) Incoming solar radiation at the top of the atmosphere indicates higher incoming shortwave flux during the early LIG. (b) Surface net shortwave flux highlights cloud feedbacks during the summer months. (c) Surface temperature and highlighted differences in temperature between case study and modern. (e) and (f) Total precipitation and difference in precipitation between case study and modern. (g) Convective precipitation. Large differences in total precipitation, but small differences in convective precipitation during the Eemian highlights the impact of additional large-scale transport of moisture into the study area.

Figure 3: Simulated temperature differences between LIG and modern from May to August. Top row: Difference in temperature between MinObliquity and modern. Middle row: Temperature differences between Eemian and modern. Bottom row: Temperature difference between MaxObliquity and modern. The monthly maps indicate surface temperature with fixed ocean temperature. Notice lower temperatures in July and August in the NAM region. The right column shows near surface air temperature differences averaged over June, July, August. Although sea surface temperatures have been held constant in the model, the air temperature increases over the Gulf of Mexico and decreases over the Gulf of California during the Eemian and 130 ka.

Figure 4: Simulated forcing factors and climate variable averaged over the North American Monsoon region for 4 cases: modern (black line), 115 ka (blue line), 125ka (green line), and 130

ka (red line). (a) Total cloud fraction (b) Total liquid water content. (c) and (d) Total evapotranspiration flux and difference in evapotranspiration between case studies and modern. All graphs indicate an increase in atmospheric moisture during the early LIG.

Figure 5: Simulated precipitation differences (in percentage) between LIG and modern for July, August, September (JAS). (a) Simulated JAS precipitation (in mm/day) over the U.S. (b) Difference in precipitation between MinObliquity and modern; (c) Precipitation differences between Eemian and modern; (d) Precipitation difference between MaxObliquity and modern. Notice strong duality pattern between Arizona and eastern monsoon region during 125 ka.

Figure 6: Distribution of specific humidity averaged over JAS. (a) Surface moisture; (b-d) Difference in surface specific humidity between LIG case studies and modern; (e) Modern humidity at 500 hPa. Map view shows distinct moisture sources for Arizona and New Mexico; (f-h) Humidity difference at 500 hPa between LIG case studies and modern. Notice the increase in humidity at different atmospheric levels during the Eemian.

Figure 7: Wind patterns averaged over JAS in the Modern and during the Eemian. (a-c) Modern winds at the surface, 500-hPa, and 200-hPa. The model realistically simulates the anticyclonic patterns at mid- and high-levels. (d-e) Vectors are showing difference in wind magnitude under Eemian and modern conditions. Vector colors indicate magnitude, positive and negative signs are related to the change in physical direction of winds.

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Table 1: Forcings and boundary conditions used in RegCM simulations.

Supplement Figure 1: Difference in moisture and upper-level divergence between Eemian and modern.

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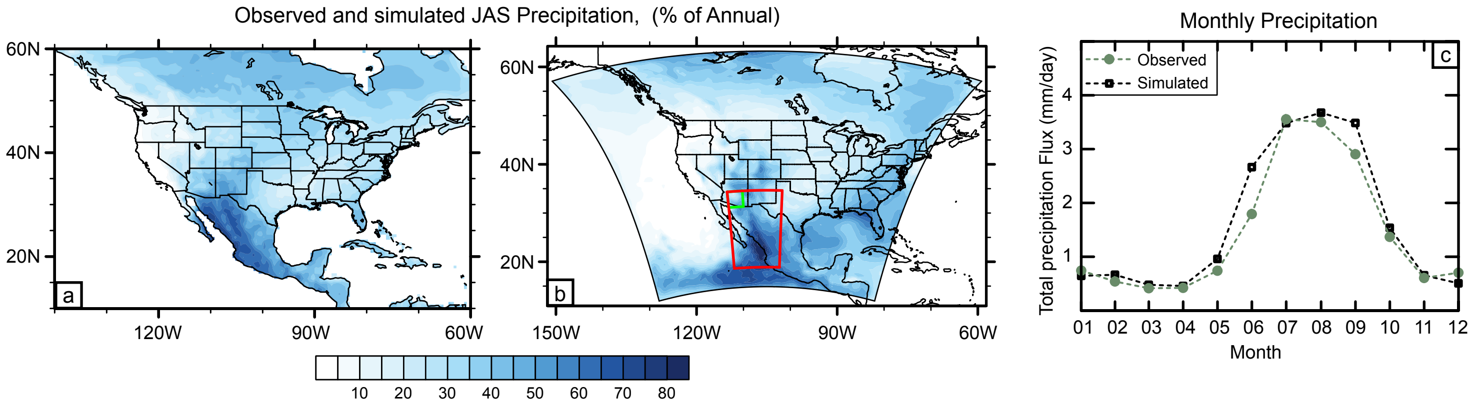


Figure 1: Measured and simulated monsoonal precipitation across North America. (a) Precipitation (in percent of annual precipitation) during the peak NAM season (July, August, September = JAS) based on observations from the Global Precipitation Climatology Centre (GPCC) database from 1981 to 2010. (b) RegCM4 simulated 10-year mean JAS precipitation. Red box highlights the main NAM monsoon region, green box indicates Arizona ‘dry” region (see text for explanation). (c) Monthly precipitation flux of observed and simulated precipitation over the monsoon region.

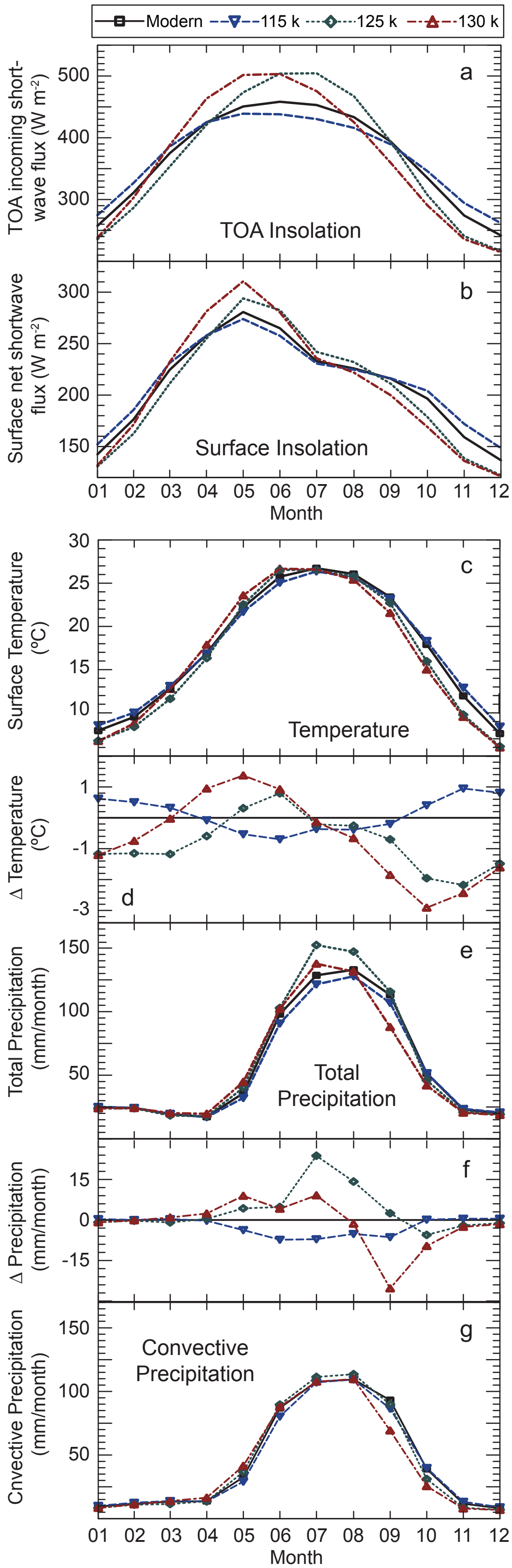


Figure 2: Simulated forcing factors and climatic indices averaged over the North American Monsoon region for 4 cases: modern (black line), 115 ka (blue line), 125ka (green line), and 130 ka (red line). (a) Incoming solar radiation at the top of the atmosphere indicates higher incoming shortwave flux during the early LIG. (b) Surface net shortwave flux highlights cloud feedbacks during the summer months. (c) and (d) Surface temperature and highlighted differences in temperature between case studies and modern. (e) and (f) Total precipitation and differences in precipitation between case studies and modern. (g) Convective precipitation. Large differences in total precipitation, but small differences in convective precipitation duitn the Eemian highlights the impact of additional large-scale transport of moisture into the study area.

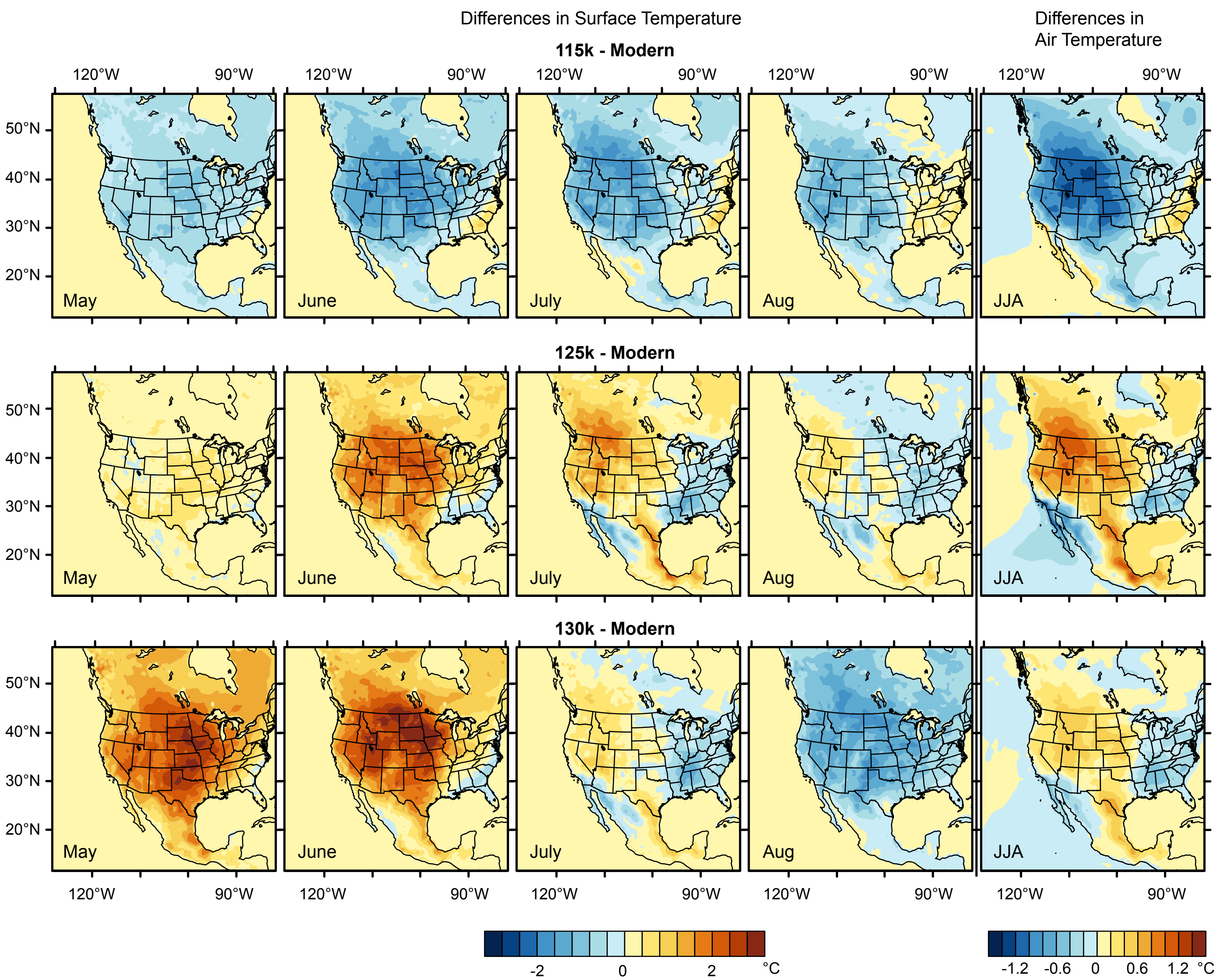


Figure 3: Simulated temperature differences between LIG and modern from May to August. Top row: Difference in temperature between MinObliquity and modern. Middle row: Temperature differences between Eemian and modern. Bottom row: Temperature difference between MaxObliquity and modern. The monthly maps indicate surface temperature with fixed ocean temperature. Notice lower temperatures in July and August in the NAM region. The right column shows near surface air temperature differences averaged over June, July, August. Air temperature increases over the Gulf of Mexico and decreases over the Gulf of California during the Eemian and 130 ka.

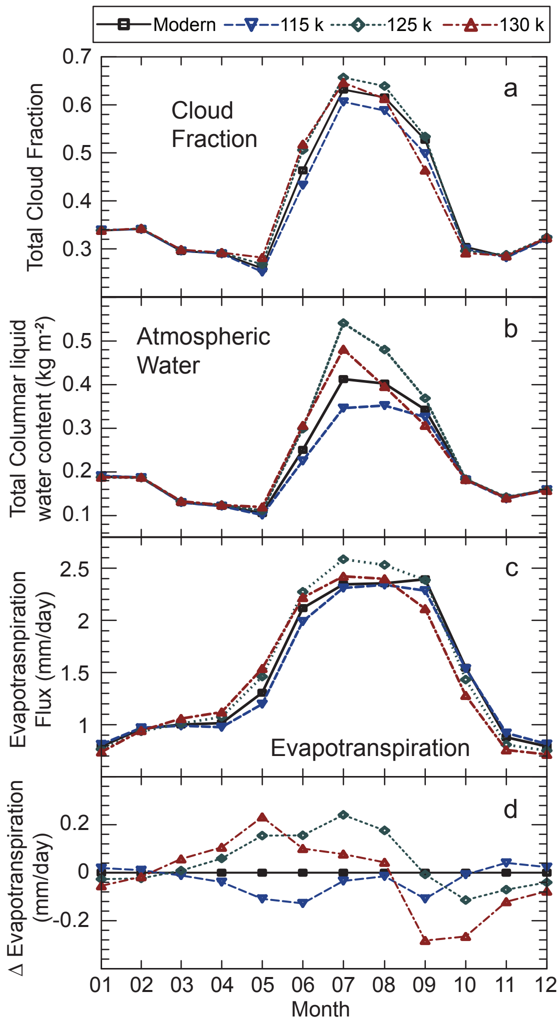
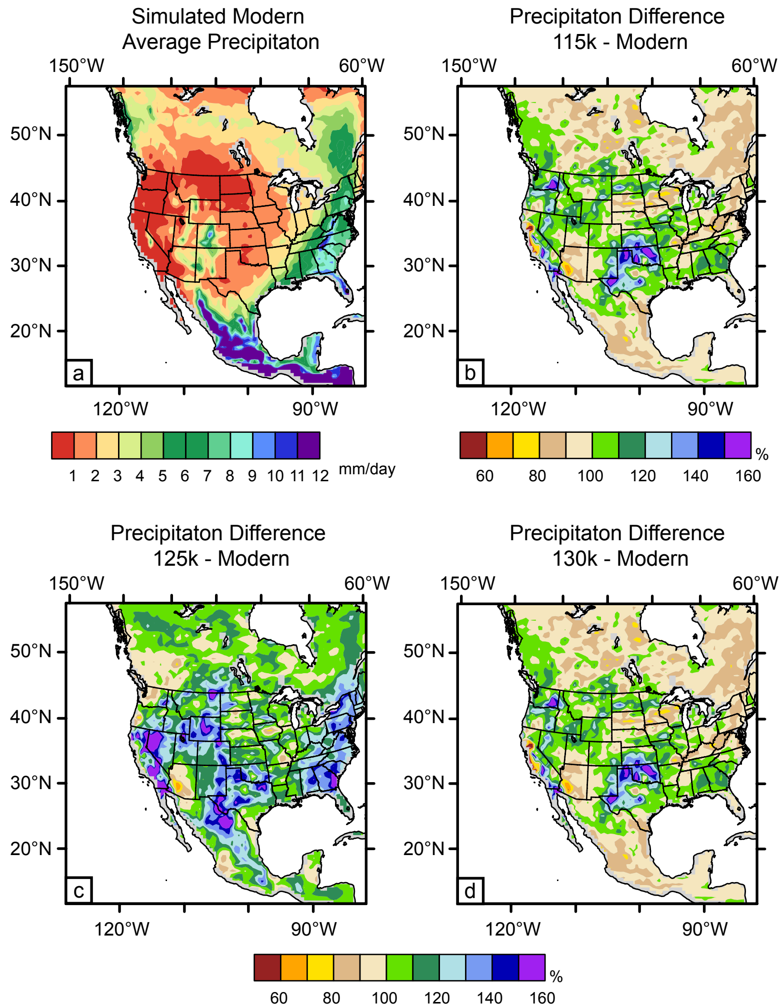


Figure 4: Simulated forcing factors and climate variables averaged over the North American Monsoon region for 4 cases: modern (black line), 115 ka (blue line), 125ka (green line), and 130 ka (red line). (a) Total cloud fraction (b) Total liquid water content. (c) and (d) Total evapotranspiration flux and difference in evapotranspiration between case studies and modern. All graphs indicate an increase in atmospheric moisture during the early LIG.



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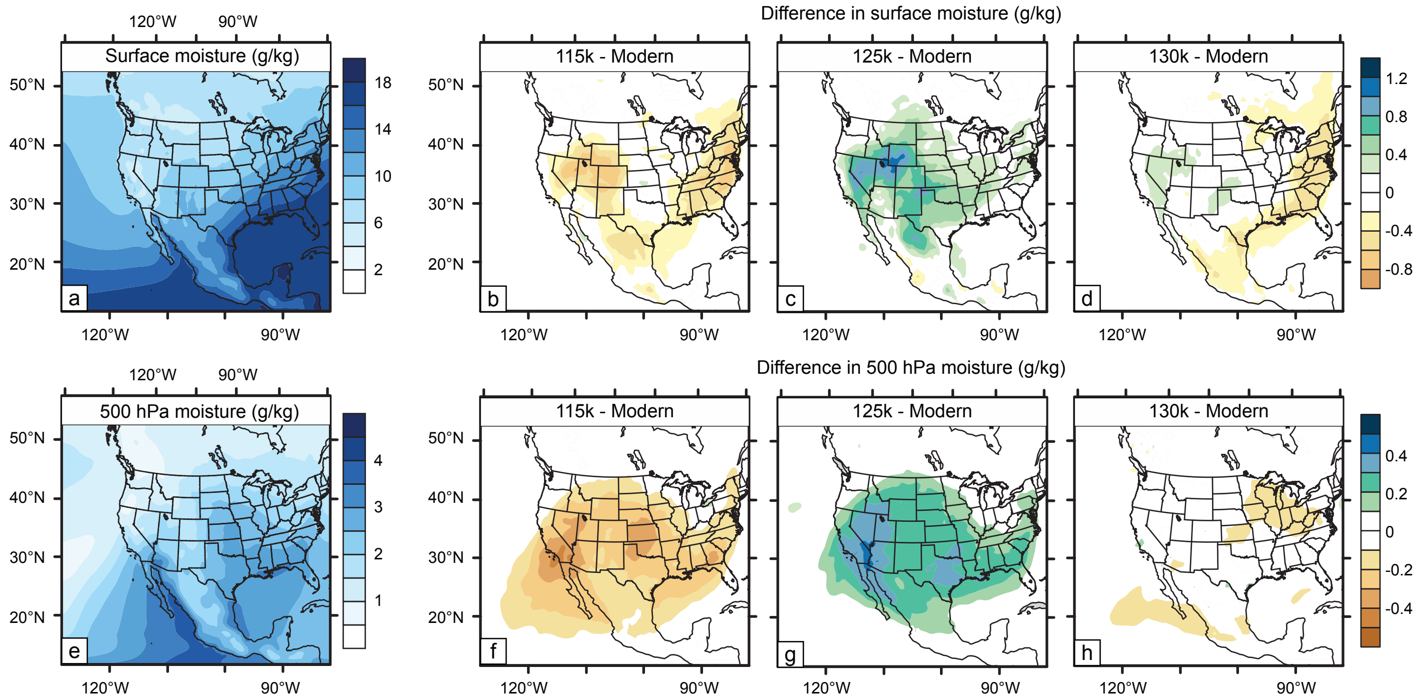


Figure 6: Distribution of specific humidity averaged over July, August, September. (a) Surface moisture; (b-d) Difference in surface specific humidity between LIG case studies and modern; (e) Modern humidity at 500 hPa; (f-h) Humidity difference at 500 hPa between (d) LIG case studies and modern. Notice the increase in humidity at different atmospheric levels during the Eemian.

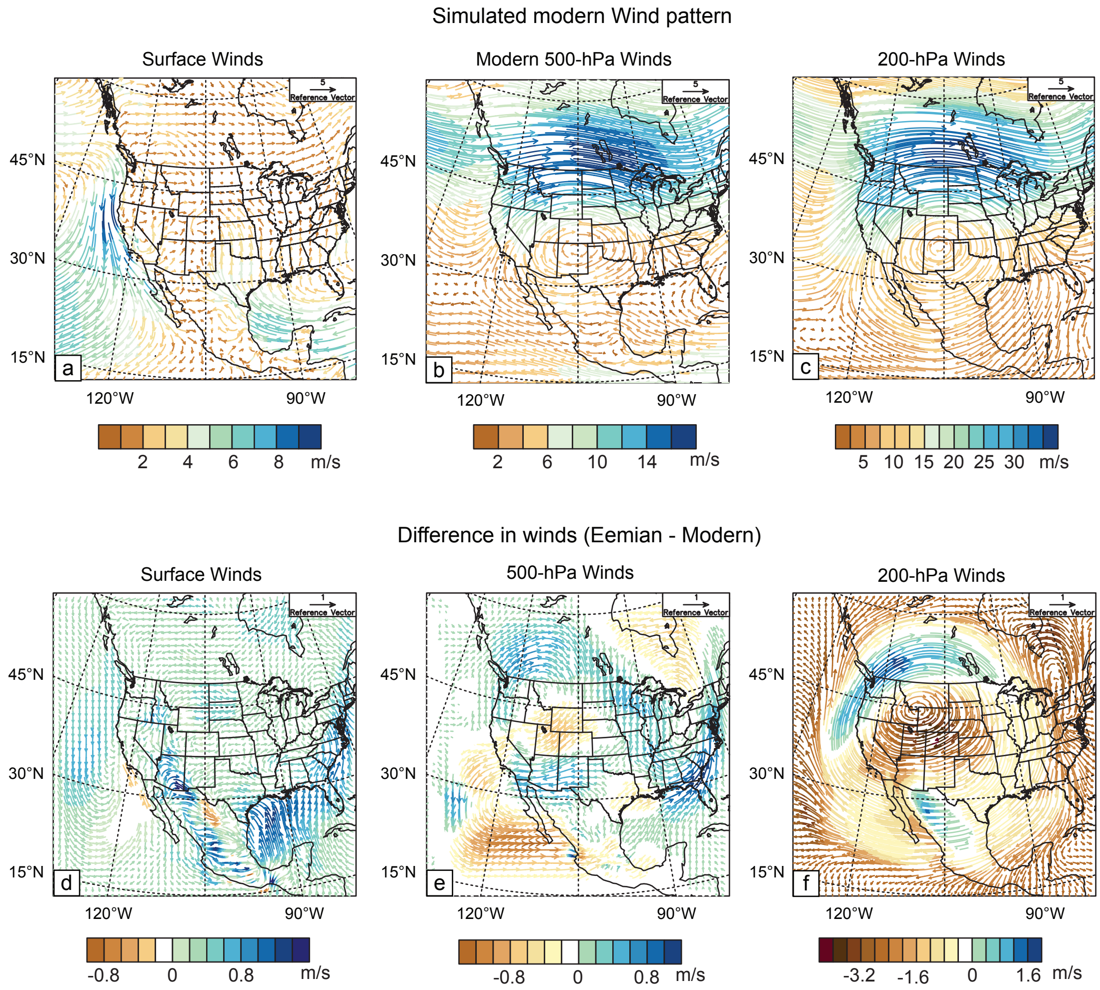
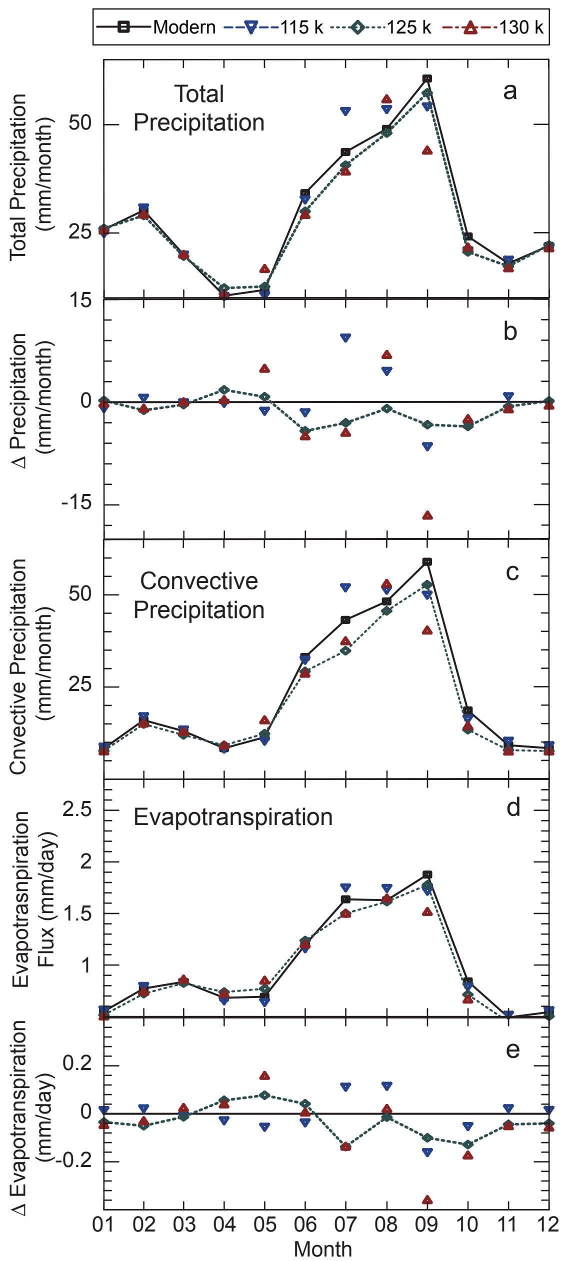


Figure 7: Wind patterns averaged over JAS in the Modern and during the Eemian. (a-c) Modern winds at the surface, 500-hPa, and 200-hPa. The model realistically simulates the anticyclonic patterns at mid- and high-levels. (d-e) Vectors are showing difference in wind magnitude under Eemian and modern conditions. Vector colors indicate magnitude, positive and negative signs are related to the change in physical direction of winds.



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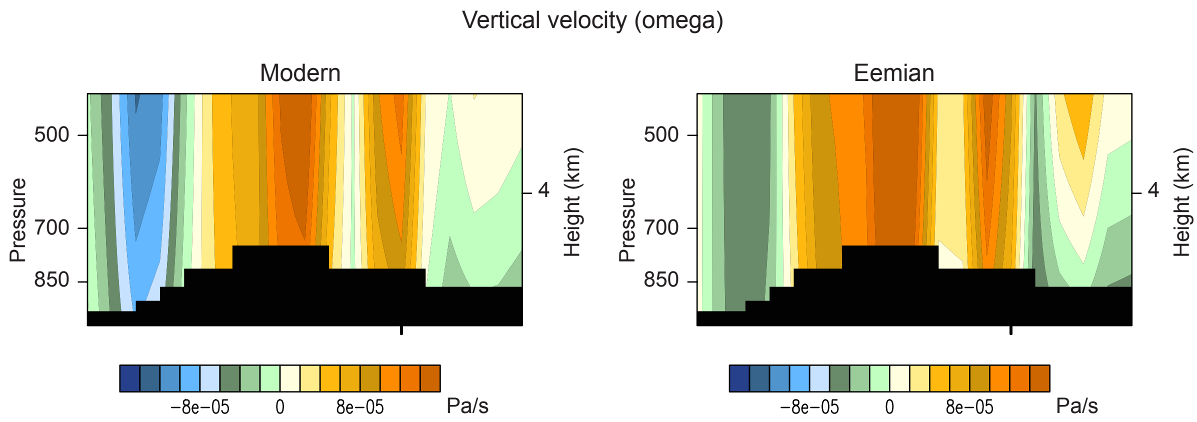
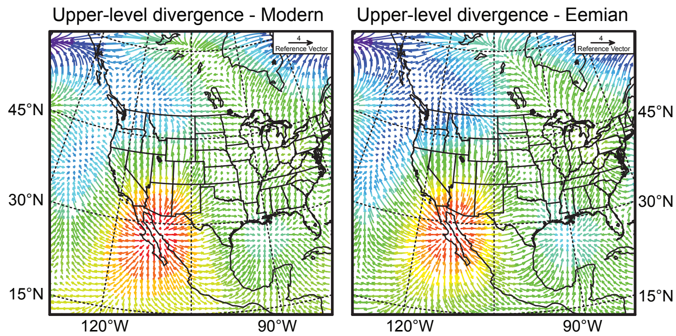


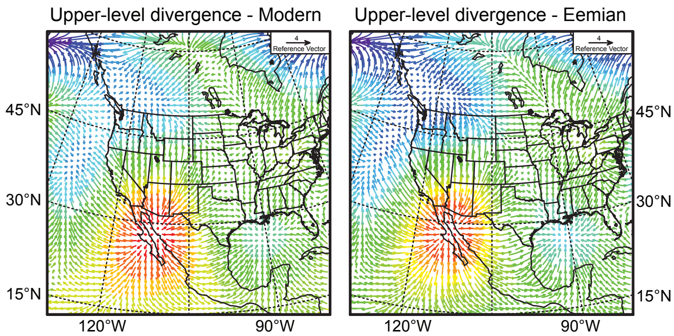
Figure 9: Vertical velocity (omega) across the NAM domain at around 32N during JAS. Height/pressure-longitudinal profile with negative values indicating strong upward air component. (a) Modern simulations. (b) Simulations with Eemian boundary conditions. Notice the reduction in vertical velocity on the western side (southern Arizona).

Table 1: Eemian forcings and boundary conditions:

Time*	Orbital Parameters**			Trace Gases		
	ecc	obl	peri	CO_2 (ppmv)	CH_4 (ppbv)	N_2O (ppbv)
0	0.016724	23.446	0.01636	355, 280	760	270
115,000	0.043983	22.438	109.54	273	472	251
125,000	0.042308	23.818	304.76	276	640	263
130,000	0.040129	24.247	225.73	257	512	239

Notes: *Time is in ka; **Orbital parameters are ecc = eccentricity, obl = obliquity, and peri = presession (Berger and Loutre); Trace gases are from http://www.ncdc.noaa.gov/paleo/icecore.html


Upper-level divergence - Modern
Upper-level divergence - Eemian
Reference Vector
45°N
30°N
15°N
120°W
90°W


Upper-level divergence - Modern
Upper-level divergence - Eemian
4
Reference Vector
45°N
30°N
15°N
120°W
90°W