Simulated responses of the West African monsoon and zonal-mean tropical precipitation to early Holocene orbital forcing

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Key Points:

- The West African monsoon, which expands northward in response to early Holocene orbital forcing, does not behave as a simple extension of the zonal-mean ITCZ.
- The ITCZ either responds weakly or shifts southward in boreal summer, counter to the prevailing energetic framework.
- Anomalous southward energy fluxes manifest as increased total gross moist stability rather than a northward ITCZ shift.

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Abstract

This study seeks to improve our mechanistic understanding of how the insolation changes associated with orbital forcing impact the West African monsoon and zonal mean tropical precipitation. We impose early Holocene orbital parameters in simulations with the Geophysical Fluid Dynamics Laboratory AM2.1 atmospheric general circulation model, either with sea surface temperatures prescribed at present-day values or with a 50-meter thermodynamic slab ocean. In both cases, West African Monsoon rainfall expands northward, but in neither case does the summer zonal mean Intertropical Convergence Zone (ITCZ) do the same – responding weakly with prescribed SSTs and shifting southward with a slab ocean lower boundary. This contradicts expectations from the conventional energetic framework for the ITCZ location, given anomalous southward energy fluxes in the deep tropics. These anomalous energy fluxes are not accomplished by a stronger Hadley circulation; instead, they arise from an increase in total gross moist stability in the northern tropics.

1 Introduction

Ample paleoclimate data indicates that 10,000 years ago (10 ka), near the beginning of the Holocene Epoch, much of Northern Africa was substantially wetter than today [e.g., *Tierney et al.*, 2017, and references therein]. This was the peak of the African Humid Period (15 to 5 ka), when increased humidity and vegetation characterized the modern Sahara [*deMenocal*, 2015]. Past modeling studies imply that this largely resulted from an intensification and northward expansion of the West African monsoon [*Joussame et al.*, 1999]. At present, appreciable monsoon rainfall extends only as far north as the Sahel, the transitional region separating the Sahara Desert from the savannas to the south.

Precession is the primary orbital signal modulating Holocene insolation and rainfall over Africa relative to modern conditions [*DeMenocal and Tierney*, 2012]. At 10 ka, perihelion occurred during Northern Hemisphere (NH) summer, as opposed to NH winter today. This intensified the NH seasonal cycle of insolation and weakened the SH seasonal cycle (Fig. 1). A more oblique orbit at 10 ka relative to present modified insolation to a lesser extent, and was responsible for any annual mean insolation changes (Fig. 1, right panel) [*Luan et al.*, 2012]. Meridional gradients in insolation or surface properties can influence monsoons, which are initiated by meridional gradients of subcloud moist static energy (MSE) (nearly equivalently, of subcloud equivalent potential temperature) [*Emanuel*, 1995; *Hurley and Boos*, 2013].

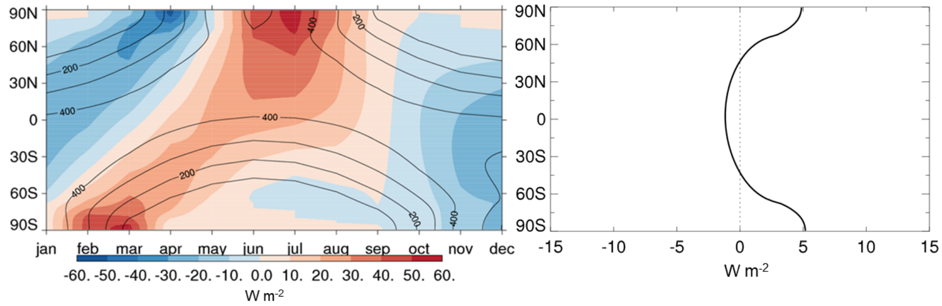

Figure 1. (Left) Annual cycle of insolation (black contours) at present and (color shading) anomalies applied in the 10 ka simulations. (Right) annual mean 10 ka insolation anomalies. All in W m^{-2}

Based on previous studies linking anomalous cross equatorial energy fluxes to the position of the zonal mean Intertropical Convergence Zone (ITCZ), one would expect this orbitally driven insolation change to shift the ITCZ northward and strengthen its precipitation during NH summer [*Schneider et al.*, 2014; *Bischoff et al.*, 2017]. However, though ITCZ responses to 10 ka-like precessional forcing are generally northward in fully coupled general circulation models (GCMs), they are often southward in slab-ocean simulations, and in more idealized models the direction is sensitive to the land-ocean configuration [*Merlis et al.*, 2013a,c; *Liu et al.*, 2017]. *Liu et al.* [2017] described that in nine of twelve coupled models forced with mid-Holocene orbital parameters, northward ocean heat transport drove a compensating southward atmospheric heat transport, which manifested as a northward ITCZ shift. Three coupled models and a slab ocean model displayed counterintuitive southward ITCZ shifts, for which a physical mechanism was not determined. Further analysis is needed to assess the plausibility of this response and to explicate the underlying processes.

It is also not clear how much an individual continental monsoon system such as the West African Monsoon is influenced by the aforementioned zonal-mean constraints [*Roberts et al.*, 2017] or even by the behavior of the adjacent oceanic ITCZ. Therefore, a particular focus is how the impacts of the imposed insolation gradient on dynamics and rainfall differ between the Sahel and the adjacent Atlantic Ocean.

2 Experimental Design

To clarify the influence of early Holocene orbital forcing on the West African monsoon and the zonal mean climate, we present results from four simulations performed using the Geophysical Fluid Dynamics Laboratory AM2.1 atmospheric general circulation model [*GFDL Global Atmospheric Model Development Team*, 2004]: with either modern or 10 ka orbital parameters, and with either prescribed SSTs or a 50-meter slab ocean. The prescribed SSTs are the climatological annual cycle from the Reynolds Optimum Interpolation dataset [*Reynolds et al.*, 2002] averaged over 1980-1999. The control AM2.1 simulation with a fixed annual cycle of SSTs captures the main features of the observed modern climatology over the Sahel [*Hill et al.*, 2017]. In the 50-meter slab ocean configuration, SSTs are allowed to vary with the atmospheric forcing, and a prescribed horizontal ocean heat flux is calibrated to reproduce present-day SSTs in the control simulation. The choice of idealized ocean components is intended to clarify the role of the SST field in the zonal mean and regional climate response, without the complicating influence of ocean dynamics. The model's land configuration does not feature dynamic vegetation, so associated albedo and soil moisture feedbacks which intensify the monsoon response are muted [e.g., *Patricola and Cook*, 2007]. As such, both experiments underestimate the regional rainfall response compared to paleoclimate proxies [*Tierney et al.*, 2011]. We performed two additional simulations with only 10 ka obliquity or precession; the latter is dominant in the hydrological response (not shown).

The prescribed SST simulations span 17 years, with averages taken over the last 16 years. The slab ocean simulations span 40 years, with averages taken over the last 20 years. We focus primarily on boreal summer (June, July, August, or JJA) mean results, since this spans the period when the imposed insolation forcing is greatest in the tropics as well as the onset of the modern West African monsoon season. We also briefly discuss the annual mean response. Region-mean quantities were computed for the Sahel (land area within the domain 10 to 20° N, 18° W to 40° E) and for the Atlantic ITCZ (ocean area within the domain 0 to 20° N, 60 to 15° W). All vertically defined quantities use pressure-interpolated data, and these results do not differ importantly from those using data on model-native coordinates (not shown).

3 Results

3.1 Atlantic ITCZ and Sahel Responses

In both simulations with 10 ka orbital parameters, the precipitation over the Sahel increases, in some places on the order of 100% (Fig. 2a). This can be interpreted as a northward expansion of the monsoon and is in qualitative agreement with paleoclimate proxies. Precipitation increases over West Africa by up to 2-3 mm day^{-1} in the prescribed SSTs case and up to 3-6 mm day^{-1} in the slab ocean case. Associated near-surface MSE maxima also shift northward (not shown), consistent with the argument that the two features be nearly coincident [*Prive and Plumb*, 2007]. In contrast, precipitation decreases over the Atlantic ITCZ sector with both ocean configurations (Fig. 2a).

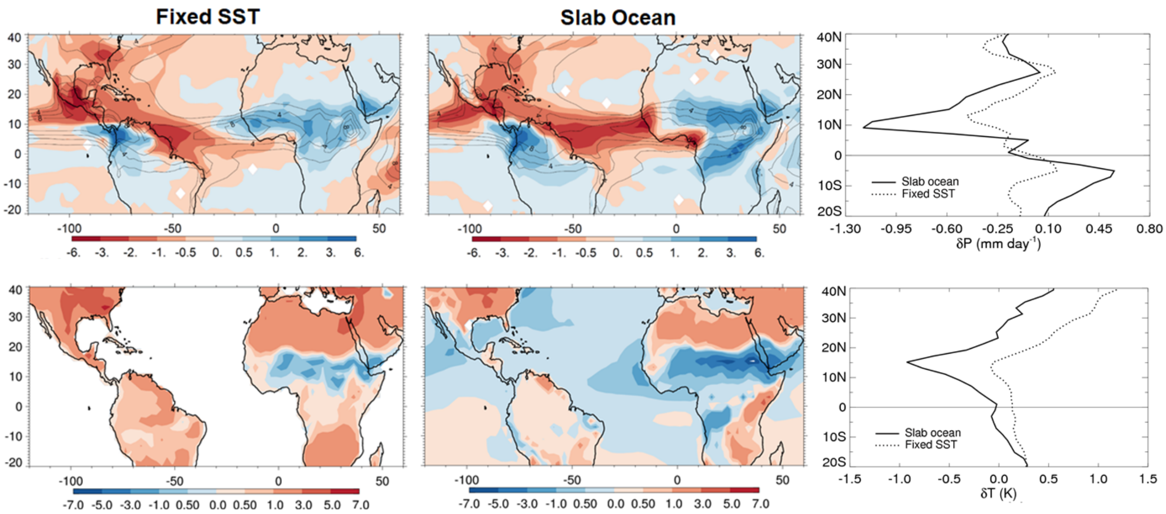

Figure 2. (Top row) JJA precipitation anomalies (10 ka-control, mm day^{-1}) in the fixed SSTs and slab ocean experiments. In the right panel, precipitation anomalies are averaged over all longitudes. (Bottom row) As above, but for temperature anomalies (K). The green boxes delimit the North Atlantic ITCZ region and the Sahel region, which are assessed in Fig. 3 with ocean-only and land-only regional averages, respectively. The color bar intervals are pseudo-logarithmic.

JJA surface temperatures decrease over the Sahel in the 10 ka simulations as precipitation increases, despite the insolation forcing (Fig. 2b). In a supply-limited evaporative regime such as the semi-arid Sahel, surface temperature and precipitation are generally tightly anti-correlated due to the impact of rainfall on the surface energy budget [e.g., *Berg et al.*, 2015]. In the prescribed SSTs case, the maximum cooling over the Sahel is between 1 and 2 K, and in the slab ocean experiment, the Sahel cools by up to 7 K (Fig. 2b). In the slab ocean simulation, cold Atlantic SST anomalies off the West coast of Africa during JJA reduce the cross-equatorial SST gradient. The positive insolation anomaly peaks in June, but due to the relatively deep, 50-meter mixed layer in the slab ocean simulations, the Atlantic SST response lags the insolation by 2-3 months (not shown), such that JJA SSTs actually cool relative to the present day [*Donohoe et al.*, 2014]. The precipitation response is similarly phase-lagged, due to the strong control over tropical oceans of SSTs on rainfall [e.g., *Neelin and Held*, 1987]. However, over the Sahel, the maximum precipitation anomaly occurs in JJA, in phase with the insolation anomaly, presumably due to the low land heat capacity.

We now analyze terms of the column-integrated MSE budget in the Sahel and Atlantic regions; see e.g., *Hill et al.* [2017] Section 4(a) for a summary of the underlying theory. Fig. 3 shows the regionally and seasonally averaged vertical velocity in pressure coordinates, ω, as well as the vertical MSE profile. Over the Sahel, anomalous ascent above approximately 700 hPa corresponds to a deepening of the circulation and greater vertical export of MSE. The JJA subcloud (850 hPa) meridional MSE gradient decreases over the Sahel in the 10 ka simulations (not shown), which reduces horizontal MSE advection and necessitates more vertical MSE export. Consequently, the ascent profile deepens over the Sahel (Fig. 3b). There is a zero crossing in the ω anomaly profile over the Sahel only, and it occurs near the minimum ($\sim$700 hPa) in the MSE profile (Fig. 3), likely because this is where the static stability ($\partial MSE/\partial p$) changes sign [*Hill et al.*, 2017]. The combined precipitation, circulation, and energetic responses over the Sahel with either lower boundary condition bear resemblance to those induced by uniform SST cooling in AM2.1 described by *Hill et al.* [2017, c.f. their Fig. 13].

Over the Atlantic sector, the vertical velocity weakens at all altitudes, with the strongest weakening at 400 hPa with both ocean configurations. This upper tropospheric descent implies a shallowing of the circulation, and thus a reduction in the vertical export of MSE. The lack of a dipole structure in $\delta\omega$ over the Atlantic suggests distinct dynamical mechanisms in the two regions. The dipole response over the Sahel may be locally forced by a change in the horizontal MSE gradient, while the $\delta\omega$ profile over the Atlantic may be a manifestation of the large-scale circulation adjustment. The North Atlantic vertical velocity weakens much more in the slab ocean experiment than the fixed SSTs experiment, and is consistent with the Hadley cell adjustment described in Section 3.2.2.

The anomalous descent over the Atlantic ITCZ sector motivated a surface energy budget analysis. Averaged over this region, an anomalous energy flux into the ocean (driven by shortwave and latent heat) outweighs the positive solar forcing at TOA (not shown). To first order, the reduced upward latent heat flux (-9.51 and -6.81 W m^{-2} in the fixed SST and slab ocean experiments, respectively) is caused by a weakening of the prevailing easterlies. The net-column cooling is amplified in the slab ocean experiment (shortwave flux anomaly of -16.1 W m^{-2}, versus -10.1 W m^{-2} in the fixed SSTs experiment) due to the phase lag of the SSTs

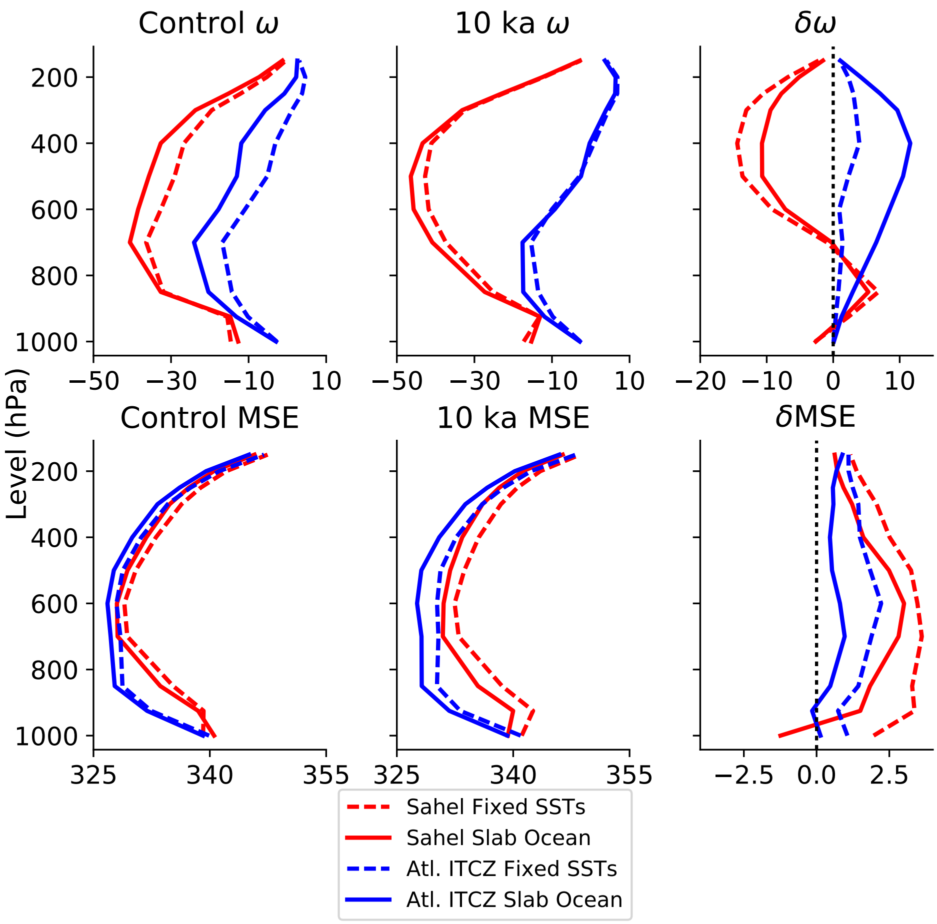

Figure 3. JJA vertical profiles of (top row) ω (hPa/day) and (bottom row) MSE (K) in the control and 10 ka simulations, and their anomalies (10 ka - control). Results are averaged over the Sahel (10° to 20° N; 18° W to 40° E) and North Atlantic ITCZ (0° to 20° N; 60° to 15° W) regions.

relative to the insolation forcing (not shown). The decrease of net energetic forcing over the North Atlantic sector is consistent with weakened convection there [c.f., *Neelin and Held*, 1987].

The vertical structure of ω varies more between regions than the MSE profile (Fig. 3) [c.f., *Back and Bretherton*, 2006]. The distinct ω responses over the North Atlantic (0 to 20° N, 60° W to 15° W) and the Sahel (10 to 20° N, 18° W to 40° E) in JJA imply an anomalous zonal circulation, and a consequent suppression of precipitation over the North Atlantic sector. The subcloud MSE increases more over the Sahel than over the tropical North Atlantic with both ocean configurations (Fig. 3), and is associated with an enhanced monsoon circulation that shifts precipitation from ocean to land (Fig. 2).

3.2 Zonal Mean Response

Despite enhanced JJA NH insolation and associated southward anomalous cross-equatorial energy fluxes (discussed below), the zonal-mean ITCZ shifts southward in JJA in both 10 ka simulations, though to a much lesser extent in the fixed SSTs case (Fig. 2, right column). This runs counter to the prediction of energy flux equator theory, the results of many fully coupled GCMs [*Liu et al.*, 2017], and the locally northward rainfall migration over North Africa previously described. The zonal mean precipitation is more suppressed in the NH than it is enhanced in the SH (i.e., it is not a symmetric ITCZ shift), particularly in the slab ocean case.

3.2.1 Atmospheric Heat Transport

The total atmospheric heat transport (AHT) is the zonally and meridionally integrated net energetic forcing term (equal to the total atmospheric energy flux divergence), which comprises the sum of the top-of-atmosphere radiative and surface radiative, sensible heat, and latent heat fluxes into the atmosphere [e.g., Eq. A4 of *Hill et al.*, 2015]. As alluded to above, the 10 ka forcing induces anomalous southward energy transport throughout the tropics, peaking at ~0.6 PW near $15°$N in both fixed SSTs and slab ocean cases (Fig. 4). The total gross moist stability is the ratio of AHT(ϕ) to the mass transport $\Psi(\phi)$ integrated to the pressure height of maximum intensity [*Kang et al.*, 2009].

3.2.2 Hadley Circulation

Based on the zonal mean meridional streamfunction [calculated c.f. Eq. A5 of *Hill et al.*, 2015], the JJA southward energy flux is not accomplished by a stronger Hadley cell mass flux in either experiment (Fig. 4). The JJA mass flux does not change appreciably in the prescribed SSTs experiment, and the circulation actually weakens in the slab ocean case with a maximum magnitude of $35 - 40 \times 10^9$ kg s^{-1} (approximately 20%).

The Hadley circulation is governed by different physical regimes throughout the seasonal cycle, following variations in the value of the local Rossby number (Ro), defined as the negative ratio of the relative and planetary vorticities [*Merlis et al.*, 2013a]. In the slab ocean experiment, the JJA Hadley cell weakens only in the NH ascending branch, through a secondary clockwise circulation that opposes the climatological overturning (Fig. 4). This is consistent with a regime in which the summer-hemisphere flank of the cross-equatorial Hadley cell conserves angular momentum (Ro≈1) [*Merlis et al.*, 2013a]. In this regime, the Hadley cell re-

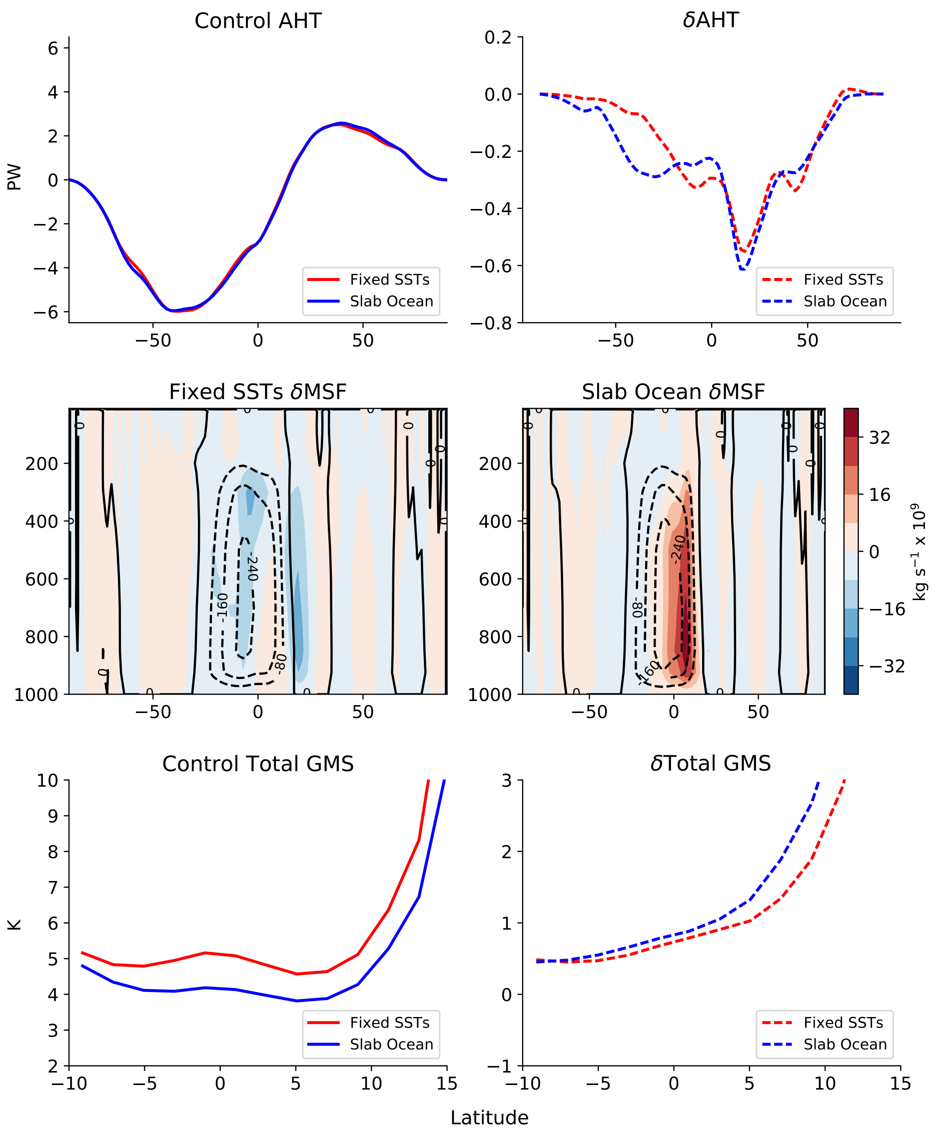

Figure 4. Results from the JJA zonal mean energetic analysis. (Top row) Atmospheric heat transport (AHT) (left) in the control simulations and (right) the anomalies (10 ka-control). Positive values indicate northward heat transport. (Middle row) Meridional mass streamfunction (MSF). Red indicates a clockwise circulation anomaly; black contours show control values. (Bottom row) Total gross moist stability (GMS) (left) in the control simulations and (right) the anomalies.

sponds directly to the TOA energy balance [*Held and Hou*, 1980], while in the winter hemisphere it is restricted by extratropical eddies and nonlinear momentum fluxes [*Walker and Schneider*, 2006; *Merlis et al.*, 2013a]. The Hadley circulation is to first order tied to the SST pattern, and is therefore strongly constrained with a fixed SST field [*Singh et al.*, 2017]. In the slab ocean experiment, colder SST anomalies in the NH tropics slow the Hadley circulation. By contrast, in the fixed SSTs experiment, the NH Hadley cell in JJA does not change appreciably, though it manages to achieve a similar AHT (Fig. 4). Given that the Hadley circulation maintains its strength in the fixed SSTs experiment, the zonal mean precipitation changes very little.

3.2.3 Total Gross Moist Stability

The total GMS is the efficiency of the export of energy by the total circulation, including the mean meridional circulation, stationary eddies, and transient eddies [*Peters et al.*, 2008]. In the 10 ka simulations the total GMS increases in the NH tropics with either ocean configuration (Fig. 4). In the slab ocean case, this more than compensates for the weakened overturning strength, thus generating southward energy flux anomalies. In the fixed SSTs case, the increase in total GMS is more modest, but is large enough to balance the energy perturbation, since the Hadley circulation is unresponsive to the forcing absent SST gradient anomalies.

The total GMS increase is reflected in elevated equivalent potential temperature aloft, which is likely linked to changes over land in the Northern tropics, including widespread warming and increased tropospheric relative humidity (not shown). This demonstrates that even with modest surface MSE fluctuations over ocean, the zonal mean energetic stratification of the atmosphere can dominate the zonal mean climate response to forcing.

This response contradicts the simplistic picture in which tropical total GMS is set by the surface meridional MSE gradient, which is constrained by the minimal (or nonexistent) SST response in the simulations. This understanding is based on two assumptions of tropical climate: that moist convection homogenizes MSE in the ascending branch of the Hadley cell, and that there is a weak temperature gradient aloft which sets the MSE in the upper Hadley cell branch to that of the ascending region [*Held*, 2001]. In this framework, the total GMS is set by the surface meridional MSE contrast across the latitudinal extent of the Hadley cell, and would not be expected to change significantly in a climate with fixed SSTs.

3.3 Annual Mean Climate Response

The annual mean Hadley circulation anomaly in the slab ocean experiment qualitatively resembles the JJA response, with reduced ascent north of the equator (anomaly with maximum magnitude of $20-25\times10^9$ kg s^{-1} or up to 40% of the climatological circulation strength;

not shown). Since the branch of the cross-equatorial Hadley cell in the summer hemisphere is most responsive to radiative changes, the annual mean circulation change depends on the superposition of these solstitial changes throughout the year [*Merlis et al.*, 2013a,b]. In the 10 ka simulations, the seasonal cycle strengthens in the NH and weakens in the SH compared to the present. Therefore, the summer ascending branch changes more in JJA than DJF, and the annual mean anomaly resembles the JJA anomaly. In the slab ocean experiment only, the zonal mean cooling and drying in the northern tropics and warming and moistening in the southern tropics are also evident in the annual mean climate response, consistent with *Clement et al.* [2004]. There is not a clear annual mean ITCZ shift in the fixed SSTs experiment, which suggests that the annual mean ITCZ shift due to 10 ka orbital forcing is caused by a rectification of seasonally varying rainfall changes associated with Hadley cell dynamics, for which anomalous SST gradients are crucial.

4 Discussion

This study highlights that zonally symmetric orbital forcing can engender highly zonally asymmetric hydrological and thermal responses in the tropics. Regional differences in the temperature, MSE, and ω perturbations give rise to differing precipitation responses over the Sahel and the adjacent North Atlantic ITCZ. In both prescribed SST and slab ocean experiments, moistening over Africa in JJA is accompanied by a counterintuitive zonal mean energetic and precipitation response. The JJA zonal-mean climate is dominated by the reduced precipitation over the Northern tropical ocean.

The phasing of the Hadley cell regime and the insolation forcing determines where the circulation will be most sensitive to local energetic anomalies. Our experiments support that when SSTs are fixed, the circulation strength is constrained and the total GMS adjusts to achieve the cross-equatorial energy flux. When SSTs in a 50-meter slab ocean interact with the forcing, they are anomalously cool in the NH tropics in JJA, and result in a weaker Hadley circulation. The lag response of SSTs to insolation forcing amplifies both the regional and zonal mean JJA precipitation responses.

The results shown here are consistent with a reduced July, August, September mean Hadley cell mass flux in the *Merlis et al.* [2013a] aquaplanet experiment with 10 ka precession. It is interesting that the zonal mean circulation changes on an aquaplanet of 5-meter depth are consistent with those in our study, which includes a substantially deeper mixed layer, full continental geometry, and a more comprehensive representation of atmospheric physics. The reduced mass flux in the *Merlis et al.* [2013a,c] aquaplanet experiment was accompanied by an increase in NH tropical precipitation, which is not the case in our simulations. In the 5-meter aquaplanet experiment, the surface heat capacity is small enough that the surface temperature changes are seasonally in phase with the insolation changes, driving increased surface specific humidity that leads to enhanced precipitation in the NH tropical summer, despite a weakening of the Hadley circulation. The influence of the slab ocean depth on the SST field and the associated precipitation response warrants further study. Also in contrast to our study, in simulations with a zonally-symmetric subtropical continent, the summer Hadley cell mass flux increased and the ITCZ moved northward [*Merlis et al.*, 2013b,c].

The simple predictive model for the annual mean tropical precipitation response to orbital forcing proposed by *Bischoff, Schneider, and Meckler* [2017] does not capture the zonal mean response to 10 ka orbital forcing reported here. That model predicts a strengthening of NH tropical precipitation, dominated by enhanced precipitation in NH summer. The assumption that the ITCZ position is proportional to the cross equatorial atmospheric energy flux relies on a modest response of the total GMS, and does not account for the influence of zonal inhomogeneity.

Liu et al. [2017] assessed twelve coupled model simulations with mid-Holocene orbital parameters, and found that three models displayed southward ITCZ shifts, consistent with their ECHAM4.6 slab ocean simulation and the results reported here. They posited that this was due to radiative feedbacks or the inadequacy of the energetic framework. Our analysis supports the latter, in that anomalous energy transports are not, as commonly assumed, generated purely through changes in overturning strength and associated ITCZ shifts.

It is difficult to validate any simulated zonal mean precipitation response to orbital forcing based on available paleoclimate proxy records, due to ambiguity in whether these proxies are tracking seasonal or annual trends, combined with the scarcity of data over the ocean [*Tigchelaar and Timmermann*, 2016]. Our results show that rainfall over the Sahel is not an extension of the ITCZ, so one cannot simply deduce the zonal mean climate change from local proxies [*Roberts et al.*, 2017].

In summary, an energetics-based analysis elucidates the regional and zonal mean tropical precipitation responses to Holocene orbital forcing. Enhanced vertical export of MSE via deepening ascent intensifies rainfall over the Sahel and North Africa with 10 ka orbital parameters, even without SST changes. A southward (minimal) JJA ITCZ shift in the slab ocean (fixed SSTs) experiment is accompanied by an increase in the total GMS, and in the slab ocean experiment by a weakening of the Hadley circulation in the hemisphere with a brighter summer. The mechanisms we describe may provide a window into the varying hydrological responses of coupled models to Holocene orbital forcing.

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