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Key Points:

- Model experiments show a north–south dipole response of the South Atlantic Convergence Zone during the mid-Holocene
- The dipole response in precipitation is consistent with the mid-Holocene hydroclimate changes observed in proxy records
- The dipole response is linked to the strength of the South Atlantic subtropical high and the South American low-level Jet

Supporting Information:

Supporting Information may be found in the online version of this article.

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A North–South Dipole Response of the South Atlantic Convergence Zone During the Mid-Holocene

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Abstract The South Atlantic Convergence Zone (SACZ) profoundly modulates precipitation from central to southeastern Brazil in the present-day climate. However, the understanding of its long-term behavior responding to various climate forcings remains limited. Here, we use an isotope-enabled atmospheric general circulation model (ECHAM4.6) to examine the precipitation response of the SACZ during the mid-Holocene about six thousand years ago. The model simulates a northward intensification of the SACZ in the mid-Holocene, resulting in a dipole anomaly pattern relative to today's climate. The mid-Holocene precipitation increased along the northern margin of the SACZ due to the strengthening of easterly winds across the tropical Atlantic, while an eastward deflection of the South American low-level jet reduced moisture transport to southern Brazil, resulting in reduced precipitation along the southern margins of the SACZ. The north–south dipole response in precipitation is consistent with the mid-Holocene hydroclimate change observed in proxy records from the region.

Plain Language Summary The South Atlantic Convergence Zone (SACZ) is a key climatic feature of the South American Summer Monsoon (SASM) season and bears significant importance to the South American population. Understanding the long-term behavior of the convergence zone is therefore vital for predicting future change in rainfall patterns across eastern South America. Using terrestrial climate records and atmospheric general circulation model experiments, we investigated SACZ precipitation over the past 7,000 years. Our findings reveal that rainfall anomalies in northeastern and southern Brazil exhibited a see-saw pattern, while the peak rainfall position over central Brazil remained constant. We show that rainfall along the margins of the SACZ is particularly sensitive to the strength of the SASM. This study therefore holds important implications for water resource management in tropical South America in the face of projected future changes in the SASM.

1. Introduction

1.1. The Modern-Day Precipitation in Tropical South America

The eastern region of South America hosts a wide range of ecoregions, from the humid evergreen tropical forests in the eastern Amazon to the arid Cerrado and Caatinga biome in central and northeastern Brazil (Smith & Mayle, 2018). Sharp transitions in the ecology are a result of several interacting climate features that contribute to the complex hydrology of eastern South America. In addition to the South American Summer Monsoon (SASM) and the Intertropical Convergence Zone (ITCZ), the South Atlantic Convergence Zone (SACZ) also influences precipitation patterns over eastern tropical to subtropical South America.

The SACZ is a region of enhanced convection during the austral summer months (December to February [DJF]) that extends diagonally (northwest to southeast) across central South America (Figure 1a). The SACZ is a result of the convergence between the northerly inflow from the western periphery of the South Atlantic Subtropical High (SASH) over the Atlantic Ocean, and the westerly inflow from the Amazon driven by the Chaco Low (CL) (Kodama, 1993) (Figure 1b). At intra-seasonal timescales, the SACZ is forced by propagating transient and quasi-stationary Rossby waves from the mid-latitudes, but its overall mean position is predominantly controlled by large-scale flow from Amazon convection (Liebmann et al., 2004). Therefore, the climatological position of the SACZ is closely associated with the direction and intensity of the low-level jet (LLJ) that transports moisture

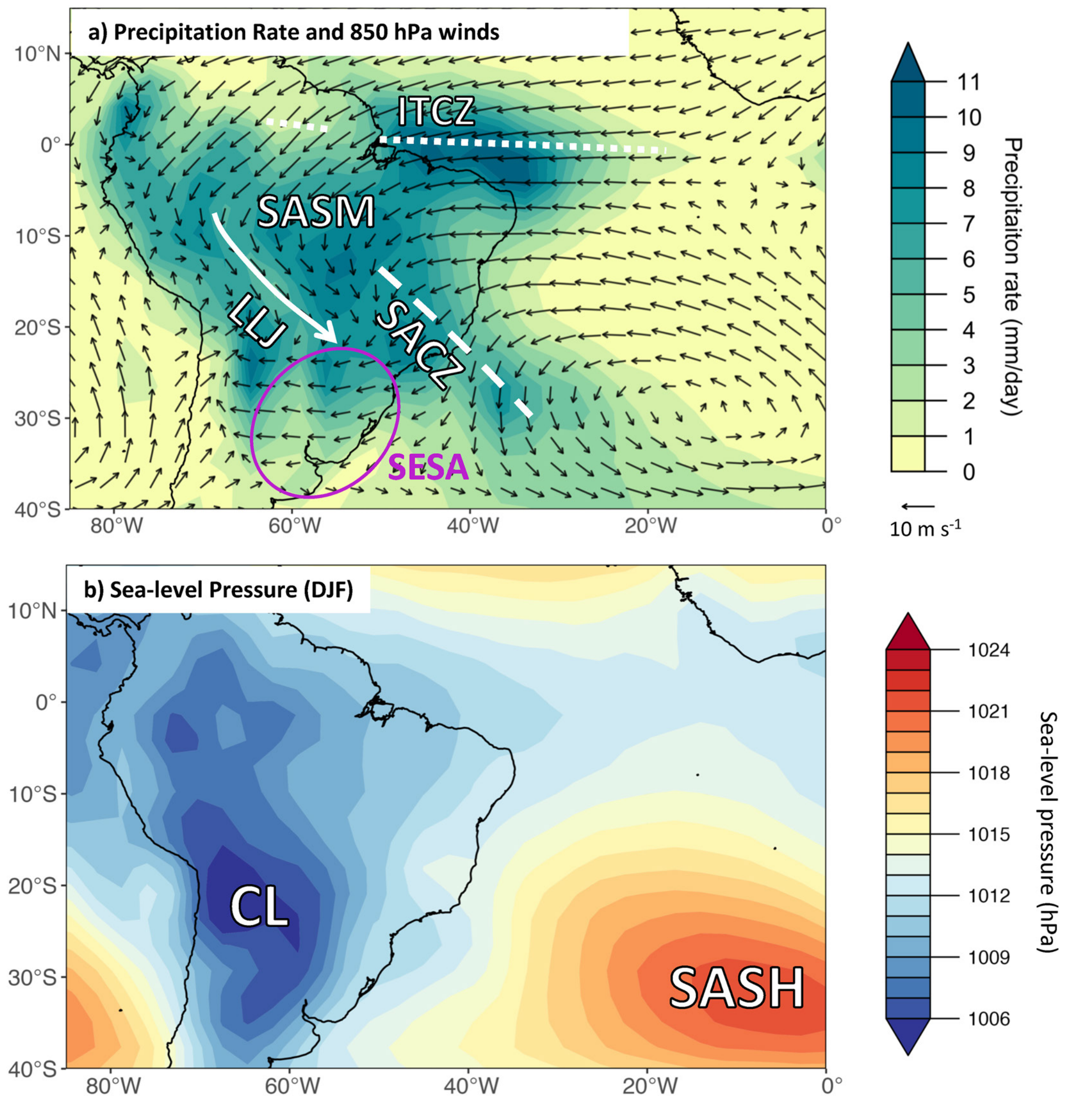

Figure 1. Map of austral summer (December to February [DJF]) modern-day precipitation climatology over South America simulated by the ECHAM4.6–slab ocean. (a) Shading represents the average DJF precipitation. Climate features of the South American Summer Monsoon system are highlighted by the white text for the low-level jet (white arrow), South Atlantic Convergence Zone axis (dashed line) and the Intertropical Convergence Zone (stippled line). The southeastern South America region is highlighted by the purple oval. (b) Averaged sea-level pressure in DJF, showing the Chaco Low over the continent and the South Atlantic Subtropical High over the ocean.

from the Amazon to southeastern South America (SESA), encompassing southern Brazil, Uruguay, parts of Paraguay, and northern Argentina (Figure 1a) (Boers et al., 2014; Zilli et al., 2019).

The present-day variability of the SACZ is associated with latitudinal shifts from its typical position represented by the climatological mean maximum in SACZ precipitation. These latitudinal shifts can modulate rainfall in a north-south pattern between central Brazil and SESA. For instance, the latitudinal migration toward the north or south can either inhibit or support precipitation anomalies in the SESA region (Nielsen et al., 2019), resulting in anti-phased precipitation anomalies flanking the typical SACZ core region over central Brazil and SESA. Observations have shown that the SACZ undergoes migrations at various timescales ranging from intraseasonal to decadal, with these shifts being attributed to factors such as tropical Atlantic sea surface temperature (SST) variability (Jorgetti et al., 2013; Robertson & Mechoso, 2000; Zilli et al., 2019) and the El Niño-Southern Oscillation (Carvalho et al., 2004; De Souza & Ambrizzi, 2006). While modern-day instrumental records suggest that the SACZ can undergo latitudinal shifts in its position, the long-term change in the SACZ due to natural (e.g., Orbital) and anthropogenic forcings are less well understood.

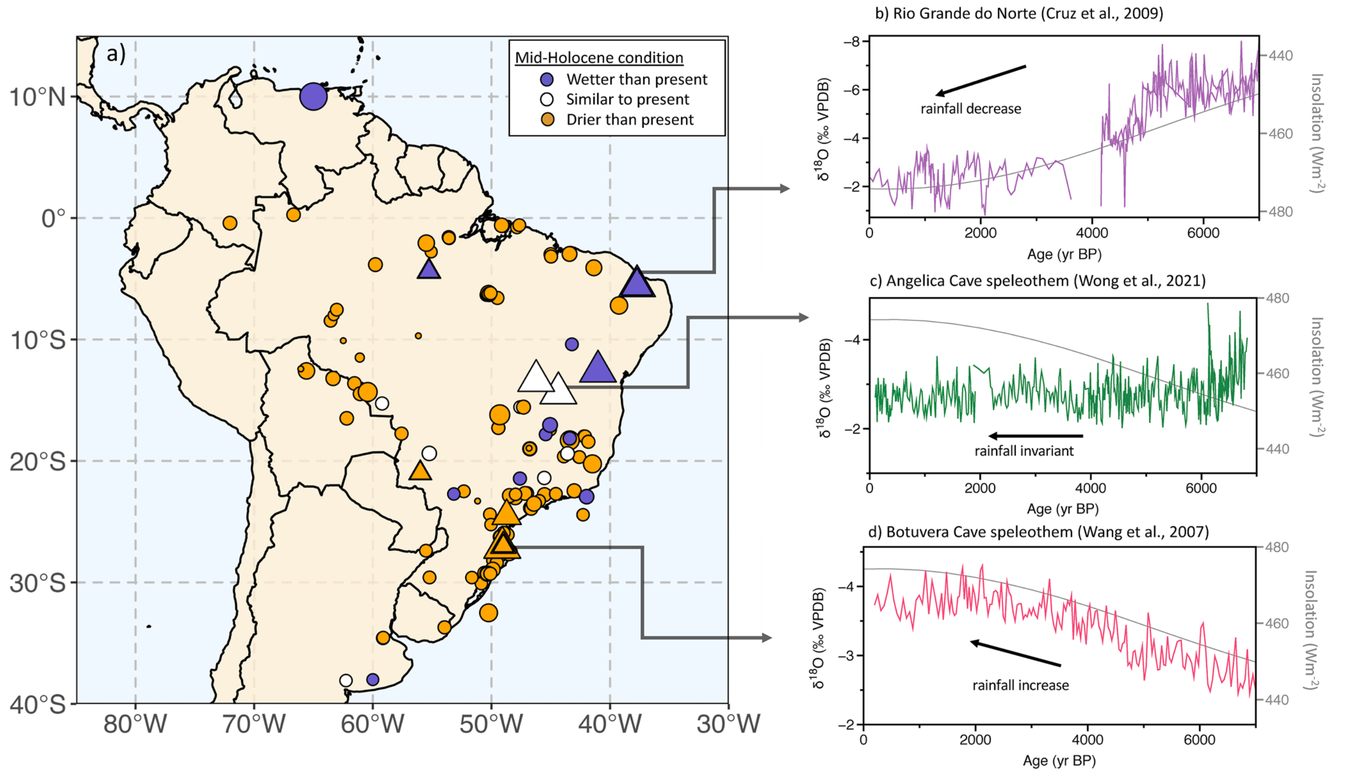

Figure 2. Hydroclimate proxy records across tropical South America that indicate mid-Holocene conditions. (a) Map of hydroclimate records and the interpreted mid-Holocene conditions where a wetter, similar, or drier condition is indicated by the purple, white, and orange colors, respectively. The size of the symbols represent the quality of the records based on Gorenstein et al. (2022). Circles are sediment and soil records while triangles are speleothem records. See Table S2 in Supporting Information S1 for individual references. (b) The Rio Grande Norte speleothem $\delta^{18}O$ record from northeastern Brazil (Cruz et al., 2009). (c) The Angelica Cave speleothem $\delta^{18}O$ record from central Brazil (Wong et al., 2021a). (d) Botuvera Cave speleothem $\delta^{18}O$ record from southern Brazil (X. Wang et al., 2007). The gray curve in panels (b–d) represents January insolation values at 15°S (Laskar et al., 2004).

1.2. Precipitation Change During the Mid-Holocene

The mid-Holocene, defined by the Paleoclimate Modelling Intercomparison Project Phase 4 (PMIP4) as the time period around 6 thousand years ago before present (kyr BP) (Otto-Bliesner et al., 2017), is particularly appropriate for studying long-term climate change because there are numerous, well-dated proxy records of the hydroclimate of South America and of the large, orbitally induced changes in insolation, while the continental geometry, orography and greenhouse gas concentrations are very similar to that in the pre-industrial period.

Paleo-hydroclimate proxy records along the eastern region of South America often show contrasting signals across latitudes during the mid-Holocene (Figure 2). Broadly, there is a north–south anti-phased pattern in precipitation trends. Along coastal northeastern Brazil, speleothem records indicate wetter mid-Holocene conditions compared to the modern-day, as evidenced by an increasing $\delta^{18}O$ trend from the mid-Holocene to the pre-industrial (Figure 2b). Several hypotheses have been put forward to explain these observations, including a southward migration of the ITCZ (Chiessi et al., 2021), a weakened SASM and correspondingly reduced subsidence in the northeast due to a weaker Nordeste Low (Cruz et al., 2009), or teleconnections with the African continent (Cook et al., 2004; Liu & Battisti, 2015).

Further south, in the vicinity of the SACZ, several speleothem and pollen records from central to central-eastern Brazil instead show similar mid-Holocene moisture conditions as the modern-day, suggesting little-to-no change in precipitation near the SACZ axis (Figure 2c) (Strikis et al., 2011; Wong et al., 2021b). Over SESA, the majority of hydroclimate records show drier mid-Holocene conditions (e.g., Figure 2c). Drier conditions over SESA could be a result of a weaker transport of moisture from the Amazon to the subtropics by the LLJ (X. Wang et al., 2007). However, some studies propose that the SACZ may have migrated latitudinally southwards toward the late-Holocene to its present position over SESA (Bernal et al., 2016; Perez Filho et al., 2022; X. Wang et al., 2006), which has been used to explain drier mid-Holocene conditions in southern Brazil compared to today. However, there has yet to be a close examination of the SACZ response to orbital-scale insolation forcing.

In this study, we investigate how the SACZ responded to the insolation changes over the mid-to-late Holocene by employing an isotope-enabled atmospheric general circulation model (AGCM) coupled to a slab ocean model (ECHAM4.6–slab ocean) in order to simulate the precipitation change between the mid-Holocene and pre-industrial period. We conduct a transect analysis across the SACZ to evaluate how the SACZ responded to mid-Holocene forcings and its contribution to changes in regional rainfall. These isotope-enabled experiments will allow us to directly compare the model result with proxy data in the region and thus provide insight into the sensitivity of local precipitation to various climate factors. This comparison will also serve as a testbed to better understand the capability of our climate models in representing climate responses over the region to different levels of orbital forcing. Thus, the finding of this research has direct implications for both paleo and modern climate communities.

2. Methods

2.1. Model Simulations

The AGCM used in this study is the ECHAM4.6 developed at the Max Planck Institute for Meteorology. The ECHAM4.6 model was run with a spectral T42 resolution (approximately 2.78° lat. × 2.78° long.) with 19 vertical levels of atmosphere (Roeckner et al., 1996). Although the newer version of this model, ECHAM6, has a higher resolution at T64 (approximately 1.876° lat. × 1.876° long.), we favor version 4.6 which already has a sufficient spatial resolution to investigate large-scale precipitation patterns such as the SACZ. Importantly, the ECHAM4.6 is equipped with a module that allows us to simulate the evolution of water isotopes that can be compared to the $\delta^{18}O$ records in the region (Hoffmann et al., 1998). To simulate thermodynamic ocean feedback, the ECHAM4.6 atmospheric component is coupled to a 50 m slab ocean model. We additionally prescribe a cyclostationary heat flux (known as the "q-flux") to account for the seasonal cycle of heat input to the atmosphere caused by oceanic circulation (Battisti et al., 2014). Hence, change in ocean heat transport convergence are not accounted for in the model.

To investigate mid-Holocene precipitation change, we simulate the mid-Holocene and pre-industrial climate. Differences in physical parameters between these two time periods mainly lie in the changes in orbital configuration which result in differences in the distribution of solar radiation at the Earth's top of atmosphere. Specific values for the orbital parameters and trace gas concentrations used are shown in Table S1 in Supporting Information S1 and follow the experimental design protocol for the PMIP4/CMIP6 simulations described in Otto-Bliesner et al. (2017).

The pre-industrial scenario refers to the climate before the 1850s, prior to significant anthropogenic influence; therefore, CO_2 is set at 284.3 ppmv. The orbital parameters are very similar to modern-day values. Compared to the pre-industrial period, the mid-Holocene received significantly lower Southern Hemisphere summer insolation–about 30 W/m^2 less at 10°S (Laskar et al., 2004). For the mid-Holocene and pre-industrial scenarios, each experiment was run for 41 years. The first year of the model run is discarded to avoid any problems with equilibration during the model spin-up. Since the model is equipped with a slab ocean model, we believe that our simulation doesn't require a long spin-up which is normally needed for a fully coupled model. In the 40-year simulation, the mean state of most climate fields (e.g., rainfall, wind circulation, etc.) in the first half is very similar to those in the second half, indicating that the simulation operates under an equilibrium state throughout the whole integration period.

One limitation of this modeling approach is that the full feedback of deeper ocean dynamics may not be well reflected by the slab ocean model. On the other hand, by incorporating a slab ocean and the q-flux correction step, our model minimizes biases associated with a full ocean model, such as the double ITCZ bias (Samanta et al., 2019) and SST biases over the Southern Ocean (C. Wang et al., 2014).

2.2. Hydroclimate Proxies

The model results are compared to a compilation of existing hydroclimate proxies, based on the compilation by Gorenstein et al. (2022) and Prado et al. (2013) that consist of sediment, soil and speleothem records spanning the mid-to-late Holocene. Each of the records indicates either a wetter, drier, or similar-to-present mid-Holocene climate and includes a quality index based on sampling resolution and the number of dates within

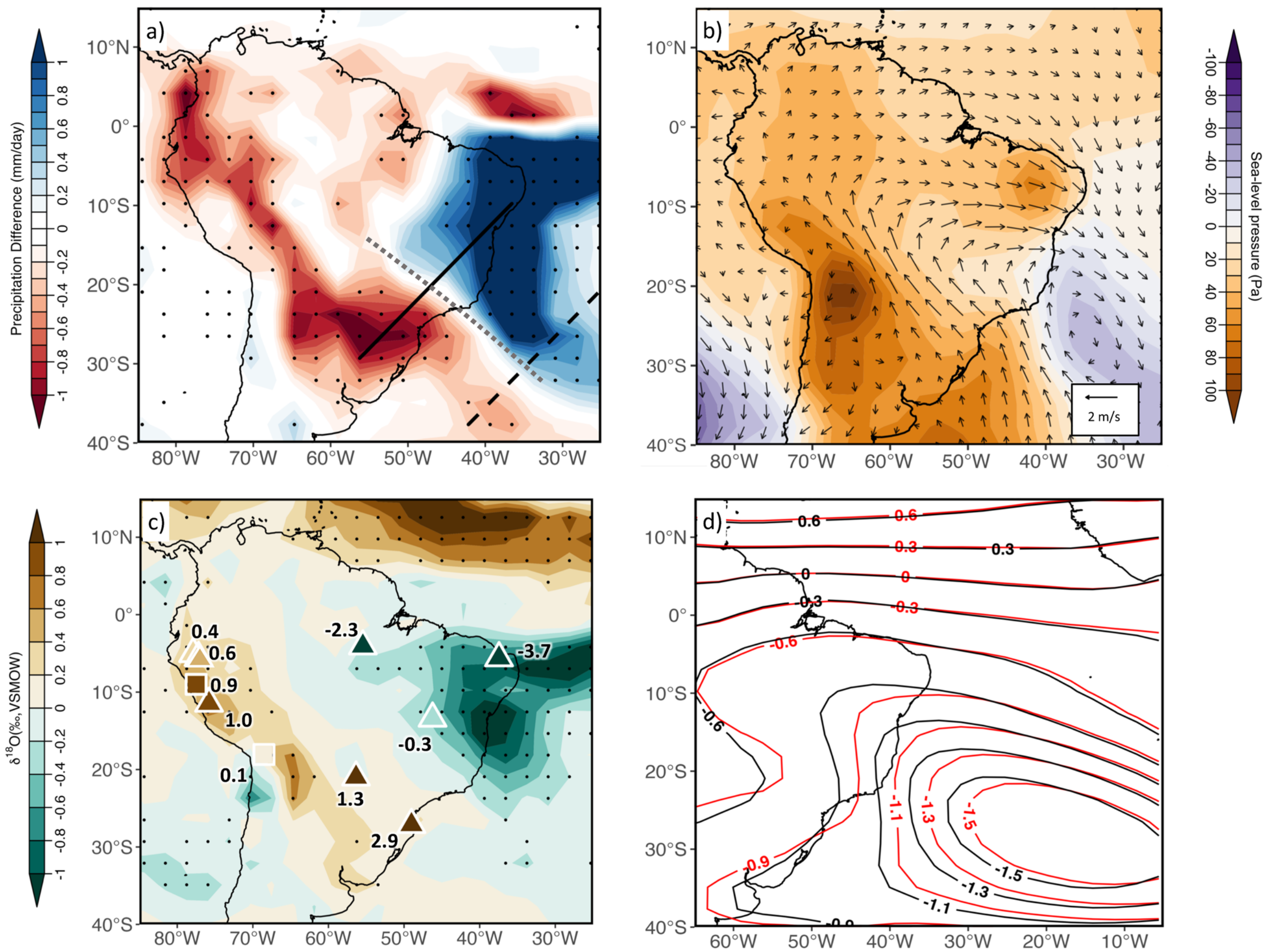

Figure 3. Comparisons between the mid-Holocene and pre-industrial scenarios simulated by the ECHAM4.6–slab ocean model (mid-Holocene minus pre-industrial). (a) Difference in the average austral summer (December to February [DJF]) precipitation. Solid and dashed diagonal lines show the transect used in Figure 4 over the land and ocean component of the South Atlantic Convergence Zone (SACZ) respectively. Dotted gray line indicates the climatological position of the SACZ in the modern-day simulation. (b) Background colors indicate the change in DJF sea-level pressure. Vectors represent the change in average DJF winds. (c) Background colors indicates the change in the mean $\delta^{18}O$ simulated by the ECHAM4.6 (based on monthly precipitation-weighted $\delta^{18}O$). The colored symbols indicate $\delta^{18}O$ difference between the mid-Holocene and pre-industrial in speleothem (triangle) and ice-core (square) records listed in Table S3 in Supporting Information S1. Values next to each symbol is the observed difference in the $\delta^{18}O$ value between the mid-Holocene and pre-industrial. Dotted regions in panels (a, b) indicate where the difference is significant at a 95% confidence level. (d) Contours show the stream function (10^{-7} m^2s^{-1}) calculated by the U and V winds in the mid-Holocene scenario (red) and pre-industrial scenario (black). The stream function is used to highlight changes in the subtropical high intensity and position between the two scenarios.

the mid-Holocene timeframe (Figure 2) (Text S1 and Table S2 in Supporting Information S1). The simulated $\delta^{18}O$ values are additionally compared to the observed $\delta^{18}O$ difference in regional proxy records (Text S1 and Table S3 in Supporting Information S1). To further investigate the SACZ dipole response, the precipitation change across the SACZ is highlighted by comparing the precipitation change along two southwest to northeast transects that are perpendicular to the SACZ indicated by the black solid and dashed lines in Figure 3a: one along the eastern edge of the continent (between 10°S, 38°W and 30°S, 58°W) and the other the ocean (between 18°S, 22°W and 38°S, 42°W), following the approach used by Zilli et al. (2019).

3. Results

Compared to modern-day reanalysis data, the ECHAM4.6–slab ocean model is able to adequately simulate the large-scale precipitation features that characterize the SASM season, including the deep convection over the Amazon and the SACZ as a diagonal rainfall band extending southeast from the western Amazon into the tropical Atlantic off the coast of southern Brazil (Figure S1 in Supporting Information S1). The mid-Holocene scenario

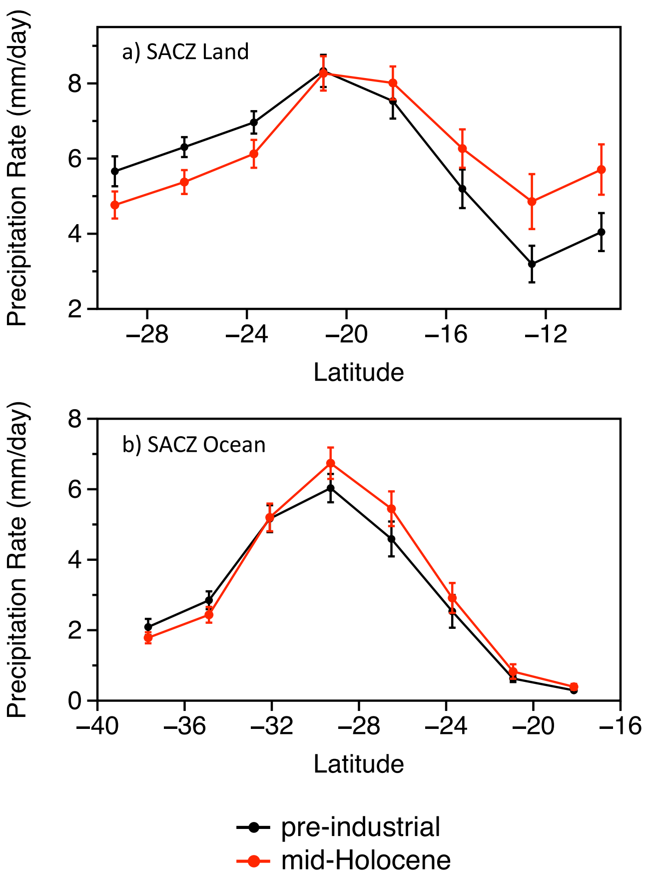

Figure 4. Average austral summer precipitation rates across the South Atlantic Convergence Zone (SACZ) in the mid-Holocene (red) and pre-industrial simulations (black). (a) Precipitation along a transect perpendicular to the SACZ over land (~10°S, 38°W to ~30°S, 58°W). Error bars indicates the 95% confidence level based on the Student's t-distribution. (b) Same as (a) but for the oceanic component of the SACZ (~18°S, 22°W to ~38°S, 42°W). Locations for the transects are plotted in Figure 3a.

generates higher austral summer precipitation along the northeastern coast of Brazil and western tropical Atlantic than in the modern-day simulation (Figure 3a). In addition to the previously noted southward intensification of the ITCZ over the Atlantic (e.g., Chiessi et al., 2021) and the weakened Nordeste Low (e.g., Cruz et al., 2009) (Figure S2 in Supporting Information S1), the higher precipitation off the northeastern coast is associated with an intensified convection over the northern margin of the SACZ. This northward intensification is further evident in the 850 hPa wind field (Figure 3b) that shows a prominent cyclonic anomaly and lower sea-level pressures (SLP) over the ocean adjacent to southeastern Brazil during the mid-Holocene (centered around 25°S, 35°W in Figure 3b), related to the ascending motion caused by increased convective activity in the SACZ.

Lower DJF precipitation in the mid-Holocene scenario is simulated along the western Amazon and Andes to SESA. The reduction in precipitation over SESA is related to an overall weaker summer monsoon and the resulting reduction in the amount of moisture delivered by the weakened LLJ. Furthermore, a higher SLP over northern Argentina (due to a weaker CL system) and the reduced SLP around the SACZ region creates a pressure gradient that favors a more eastward deflection of the LLJ toward the SACZ whilst diminishing the intensity of the LLJ's southward penetration to the subtropics (seen in the wind field change in Figure 3b).

The north–south anti-phased anomalies in Figure 3a are bisected by a diagonal zone with little-to-no precipitation change that runs approximately along the central axis of the SACZ. This implies that despite precipitation changes to the north and south of the SACZ, precipitation near the central axis remained relatively constant. Overall, the simulated change in mid-Holocene precipitation shows a broad agreement with hydroclimate proxy interpretations, particularly in the northeastern coast (e.g., Chiessi et al., 2021; Cruz et al., 2009) and SESA (e.g., Behling et al., 2001; X. Wang et al., 2007; Ward et al., 2019) (Figures 2 and 3a).

The northeast–southwest anti-phased pattern is mirrored in the annual mean $\delta^{18}O$ based on monthly precipitation-weighted $\delta^{18}O$ (Figure 3c). The changes in the annual mean $\delta^{18}O$ is dominantly caused by changes related to austral summertime precipitation (Figure S3 in Supporting Information S1). The precipitation $\delta^{18}O$ changes in the mid-Holocene compared to the pre-industrial climate are negative over the northeastern coast and positive over the western Amazon to SESA. The general correspondence between the simulated changes in precipitation amount and $\delta^{18}O$ values is consistent with the "amount effect" mechanism that is commonly used to interpret $\delta^{18}O$ records in the tropics. Although simulated $\delta^{18}O$ shows a similar spatial pattern in terms of the direction of $\delta^{18}O$ change exhibited by the proxy records, the magnitude of $\delta^{18}O$ change is underestimated in the model. For instance, the Rio Grande do Norte speleothem record along the northeastern coast (Figure 3c) (Cruz et al., 2009) shows a $\delta^{18}O$ difference of −4.2‰ compared to the >−1‰ change in the model. Similarly, in the Botuvera Cave speleothem record in southern Brazil, the difference is up to 2.9‰, compared to <0.3‰ change in the model. This issue is not unique to the ECHAM4.6, as it has been noted by other isotope-enabled simulations (e.g., Cauquoin et al., 2019; Tabor et al., 2020) and is likely due to a climate model's tendency to underestimate summer rainfall amount across the Amazon. Nevertheless, although the absolute values of $\delta^{18}O$ may not be directly comparable to the $\delta^{18}O$ proxy records, the direction of precipitation change is captured in the model.

4. SACZ Mid-Holocene Response

4.1. Description of SACZ Response

The austral summer precipitation across the SACZ axis shows that the latitudinal position of the peak SACZ rainfall does not change in the mid-Holocene compared to the modern (Figure 4), suggesting that there is no latitudinal displacement of the core SACZ axis, or at least that no latitudinal movement can be detected at the model resolution. However, there is a clear latitudinal difference in precipitation response over the land component of the SACZ during the austral summer: toward the equator, rainfall rates were higher during the mid-Holocene than the pre-industrial, while the opposite is true along the southern margin. In effect, continental precipitation in the mid-Holocene is distributed more symmetrically around the axis of maximum precipitation than it is in the modern-day simulation (Figure 4a). A similar transect across the oceanic component of the SACZ shows that the latitudinal position of peak precipitation remains the same as well, suggesting that, similar to the land component, there is no shift in the core SACZ position (Figure 4b). However, the magnitude of rainfall change along the flanks of the SACZ is less than that seen on the land transect, which is due to the reduced contribution from the LLJ and ITCZ moisture. The stationary latitudinal position of the peak rainfall over both land and ocean between the mid-Holocene and the present, therefore, suggests that the SACZ responded in a north–south dipole rather than an overall latitudinal displacement of the core SACZ axis.

4.2. Mechanisms for the Dipole SACZ Response

The distribution of the precipitation in the SACZ is closely associated with the two moisture sources that converge to form the SACZ, that is, the westerly inflow from continental moisture flux and the northeasterly flow from the western flank of the SASH (Kodama, 1993; Nogués-Paegle & Mo, 1997; Saulo et al., 2000). The westerly continental flux is affected by the direction and intensity of the LLJ (Boers et al., 2014; Zilli et al., 2019). Modern-day observations have shown that when the LLJ has a strong eastward component, moisture is channeled toward the SACZ over central Brazil. The intensified convergence over central Brazil results in a compensatory subsidence over the southwest that suppresses rainfall in SESA (Gandu & Silva Dias, 1998), as well as limiting the southward extent of the LLJ (Robertson & Mechoso, 2000). In the opposite phase, the LLJ has a stronger southward component, bringing moisture toward Argentina and SESA, with subsidence located over eastern Brazil. Therefore, the intensified convection over SESA is associated with a weaker SACZ over central Brazil. In our mid-Holocene simulations, a higher pressure over northern Argentina and SESA associated with the weakened CL (due to less intensive Amazonian convection) and the low pressure region under the SACZ (Figure 3b) inhibits the southwards flow and instead forces Amazonian moisture eastwards toward the SACZ over central-eastern Brazil, rather than allowing the LLJ to prevail southwards over SESA. During the pre-industrial, the opposite is true: a deeper CL resulting from enhanced SASM convection promotes a stronger LLJ over the SESA and a weaker SACZ over central Brazil.

Precipitation intensity along the northern margin of the SACZ is largely dependent on the SASH circulation (Zilli et al., 2019). During austral summer, the SASH is sustained by the Southern Hemisphere monsoons and the zonal SST gradient across the Atlantic (Miyasaka & Nakamura, 2010; Reboita et al., 2019; Seager et al., 2003). The SASM is also important in sustaining the SASH as the Kelvin wave response to monsoon convection toward the east contributes to the subsidence that enhances the subtropical anticyclone (Gill, 1980; Rodwell & Hoskins, 2001; Seager et al., 2003). In the mid-Holocene scenario, there is a contraction of the SASH along its western boundary (Figure 3d), which is consistent with a reduced SASM intensity and subsidence over the Atlantic. The western contraction of the SASH steepens the zonal pressure gradient across the Atlantic, causing an acceleration of wind speeds along the northern and western flanks of the SASH (Figure 3b) (Pontes et al., 2020; Zilli et al., 2019). This northerly flow gives rise to the prominent low-level convergence along the northeastern coast and along the equatorward margin of the SACZ. The stronger easterly flow across the tropical Atlantic leading to SACZ convergence is similar to the previous investigations by Liu and Battisti (2015), although the authors attributed the flow instead to a Rossby wave response to South African precipitation. The strengthening due to increased convective activity in the SACZ, contributes to the prominent cyclonic anomaly over the ocean adjacent to southeastern Brazil during the mid-Holocene (i.e., the cyclonic anomaly centered around 25°S, 35°W in Figure 3b). Cyclogenesis over this region has previously been noted by Grimm et al. (2007) and Nielsen et al. (2019) to correspond with northernmost SACZ conditions.

5. Conclusion

The simulations and hydroclimate records both show that, in response to changes in insolation from the mid-Holocene to today, the centroid of SACZ precipitation shifts northward, resulting in a north–south pattern in precipitation anomalies, rather than an overall latitudinal migration of the SACZ. One key goal of this study is to understand how the SACZ was strengthened during the mid-Holocene. Our simulations suggest that the northward intensification of the SACZ during the mid-Holocene was due to a stronger easterly circulation across the tropical Atlantic producing intense moisture convergence in the equatorward margin of the SACZ. The southwards transport of continental moisture along the LLJ is concurrently reduced due to a weakened CL, and is instead channeled eastwards toward the SACZ which limits the penetration of moisture toward SESA. This study therefore provides new insight to the behaviors of the SACZ during the mid-Holocene and aids the further interpretation of $\delta^{18}O$ proxy records in the region.

Data Availability Statement

The results of the ECHAM4.6 model simulation in this study is available at Wong (2023a, 2023b), for the pre-industrial and mid-Holocene scenarios, respectively. The ERA5 data set is available in Hersbach et al. (2023). The data set containing paleoclimate records used in Figure 2 is compiled in Gorenstein et al. (2022). The Angelica Cave speleothem $\delta^{18}O$ record is available at Wong et al. (2021a).

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