South American Climate during the Early Eocene: Impact of a Narrower Atlantic and Higher Atmospheric CO$_2$

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ABSTRACT

The Cenozoic climate of tropical South America was fundamental to the development of its biota, the most biodiverse on Earth. No previous studies have explicitly addressed how the very different atmospheric composition and Atlantic geometry during the early Eocene (ca. 55 Ma) may have affected South American climate. At that time, the Atlantic Ocean was approximately half of its current width and the CO$_2$ concentration of Earth’s atmosphere ranged from $\sim$550 to $\sim$1500 ppm or even higher. Climate model simulations were performed to examine the effects of these major state changes on the climate of tropical South America.

Reducing the width of the Atlantic by approximately half produces significant drying relative to modern climate. Drying is only partly offset by an enhancement of precipitation due to the higher CO$_2$ of the early Eocene. The main mechanism for drier conditions is simple. Low-level air crosses the tropical Atlantic from North Africa in much less time for a narrower Atlantic (2 days) than for the modern Atlantic (ca. 6 days); as a result, much less water is evaporated into the air and thus there is far lower moisture imported to the continent in the Eocene simulation than in the modern control. The progressive wetting (during the mid- to late-Cenozoic) of the Amazon due to the widening Atlantic and the rising Andes, only partly offset by decreasing CO$_2$ values, may have been partly responsible for the accumulating biodiversity of this, the most biodiverse region on Earth.
Tropical South America, and its Andean and Amazon forests, is the most biodiverse region on Earth (Antonelli et al. 2018). It is believed that this biodiversity remained steady (e.g., Close et al. 2019) or increased (e.g., Condamine et al. 2012) through the Cenozoic (ca. 66 Ma to present day), perhaps because of a relatively stable, warm and wet tropical climate. Following the breakup of Gondwanaland and opening of the South Atlantic Ocean, beginning effectively in the early Cretaceous (ca. 140 Ma), the South American continent separated from Africa along a nearly zonal trajectory. Throughout the entire Cenozoic, the present-day South American equator was within 3° distance from its current latitude (Seton et al. 2012); that is, tropical South America has occupied approximately the same latitude for nearly the entire (largely Cenozoic) history of its angiosperm-dominated rain forest. However, during this same time period, the Atlantic Ocean more than doubled in width, global CO₂ apparently decreased dramatically along with global temperatures, and the Andean Cordillera achieved its current altitude becoming a formidable, continuous, longitudinal orographic barrier. All three factors surely played significant roles in the evolving climate and biodiversity of the South American tropics. The development of several, more distal, geographic features, such as the opening of the Drake Passage (ca. 40 Ma, Scher and Martin 2006; Lagabielle et al. 2009), the progressive northward drift of the African plate (Nilsson et al. 2013), the posited initiation of Pacific Walker circulation during the Pliocene (e.g., Wara et al. 2005), and the closure of the Isthmus of Panama (e.g., O’Dea et al. 2016), may also have affected the evolving Cenozoic climate of South America.

The deep-sea oxygen isotopic record from benthic foraminifera indicates that the early Eocene (ca. 55 Ma) was the warmest period on Earth in the past 65 million years (Zachos et al. 2001). Estimates of the global mean surface temperature at that time range between 4 and 14°C greater
than the pre-Industrial value (Jones et al. 2011; Caballero and Huber 2013). Atlantic tropical sea-
surface temperatures (SST) may have peaked at $35^\circ$C during the early Eocene and at $38^\circ$C during
the Paleocene-Eocene thermal maximum (PETM) event (ca. 56 Ma) (Cramwinckel et al. 2018).
The warm Eocene is likely a result of both higher atmospheric CO$_2$ and the different plate-tectonic-
related configuration of oceans and continents. Compared to today, the Eocene was characterized
by a narrower Atlantic basin, a narrower and shallower Drake passage, a more southward position
of Australia and Africa, an open Panama seaway, land connections between North America and
Europe through Greenland, and an Indian sub-continent isolated from Asia (Seton et al. 2012).
Although a multi-model comparison (Lunt et al. 2012) finds that atmospheric CO$_2$ concentrations
of 2500-6500 ppm yield optimal agreement with climate model results, a recent review of actual
proxy determinations concludes that the most reliable atmospheric CO$_2$ concentrations were in the
range of 1000 ± 500 ppm throughout most of the Eocene (Anagnostou et al. 2016).
Pollen data from Colombia and Venezuela suggest that the biodiversity of northern tropical
South America rainforest reached a maximum during the early Eocene (Jaramillo et al. 2006),
possibly exceeding modern-day values, despite, or perhaps because of, the greater global mean
surface temperature and higher atmospheric CO$_2$ concentration. The high biodiversity during the
early Eocene indicated by the pollen data is also thought to be due in part to a humid climate
in tropical South America (Jaramillo et al. 2006), but there are as yet no paleoclimate records
from the Amazon that can substantiate or refute this hypothesis. On the other hand, many studies
have explored the global climate of the early Eocene using numerical models (Huber and Sloan
2001; Huber et al. 2004; Heinemann et al. 2009; Lunt et al. 2010; Winguth et al. 2010; Huber and
Caballero 2011). While the goal of each of these studies was to reproduce the global climate of
the early Eocene using realistic boundary conditions and forcings, the studies did not allow for the
attribution of the observed large-scale climate changes of the period.
Of the three factors that we previously identified as most likely to be paramount in forcing the Eocene climate of tropical South America — Andean uplift, the narrower Atlantic, and higher concentrations of atmospheric CO$_2$ — only the first has been the subject of focused study. In fact, several previous climate modeling studies have explicitly addressed the question: what is the impact of the Andes on the climate of tropical South America? In all models (Lenters and Cook 1995; Garreaud et al. 2010; Ehlers and Poulsen 2009), the rate of precipitation in most parts of tropical South America is dependent on the presence of a continuous, high, north-south oriented Andean Cordillera. For example, Lenters and Cook (1995) found that the presence of the Andes produced higher orographic precipitation over the eastern flanks of the range and higher precipitation in the eastern lowlands due to an intensified South American summer monsoon, when compared to their “no-mountains” simulation. Likewise, Garreaud et al. (2010) found that Andean topography intensified the South American summer monsoon (SASM) and produced a broad region of increased precipitation from the southern Amazon to the southern sub-tropics of South America, while equatorial South America became drier. Although the results of the climate simulations are broadly consistent, the timing of Andean uplift itself is poorly known. Considerable paleoaltimetry data exist for the eastern Cordillera, but there is a dearth of such data for the western Cordillera, the volcanic arc, throughout much of the Andes. That said, it has been proposed (Garzione et al. 2017) that in the Central Andes a western Cordillera with elevation $\geq$ 2km was attained prior to 45 Ma. As previous modeling results have shown a non-linear response of precipitation to elevation, such that raising Andean elevations above 2 km produced much less climate response than values below 2 km (Takahashi and Battisti 2007; Garreaud et al. 2010), we have taken the liberty to use modern topography in our current study. In any case, if the Eocene Andes were far lower than modern, the dry Eocene conditions that we simulate in our study would only have been further exacerbated.
2. Model and Experimental Design

For this study, we used the ECHAM atmospheric general circulation model, version 4.6 (ECHAM4.6; Roeckner et al. 1996). The ECHAM model is a spectral model with T42 resolution (approximately 2.8° in latitude and longitude) with 19 vertical levels, and is coupled to a 50-m slab ocean. We first perform a modern-day experiment (called “Wide_353CO2”), whereby the model is configured with present-day continental geometry, orography, and orbital parameters; and with an atmospheric CO$_2$ concentration of 353 ppm, and other greenhouse gas concentrations and aerosol distributions from 1850 (Table 1). A climatological Q-flux with seasonal cycle is prescribed to the slab ocean in the modern-day simulation to account for the ocean heat flux convergence by ocean currents and for biases in the surface heat flux due to biases in the atmospheric model. Using ECHAM 4.6 coupled to a slab ocean does not allow for changes in the ocean circulation; possible effects of ocean circulation change are explored in section 4b.

There were certainly many geometric and forcing differences of importance to the global climate of the early Eocene. But in this study, for reasons elucidated previously, we isolate the impact of the two factors that we believe were important in shaping the Eocene climate of tropical South America: a narrower Atlantic Ocean and a higher atmospheric CO$_2$ concentration. We undertake a Narrow_1000CO2 experiment, in which the atmospheric CO$_2$ concentration is set at 1000 ppm, well within the range of estimates of CO$_2$ concentration at the early Eocene reconstructed from proxy data (Beerling and Royer 2011; Anagnostou et al. 2016), and the Atlantic Ocean is narrowed by removing a 25° longitude strip from the Atlantic Ocean, while the Pacific Ocean is stretched by 25° longitude. The resulting “narrow Atlantic” is close to the Atlantic geometry reconstructed for the early Eocene (Seton et al. 2012). The Q-flux used in the Narrow_1000CO2 experiment is the same as that in the modern-day experiment, except that it is zonally symmetrized in the
Atlantic Basin and uniformly, zonally stretched in the Pacific; a small longitudinally invariant correction is then added to the Q-flux so that the zonally integrated ocean heat flux at each latitude is identical to that in the modern-day experiment (see discussion in section 4d). We also refer to the Narrow_1000CO2 experiment as the “Early Eocene” experiment.

To isolate the impact of a narrower Atlantic basin and the impact of higher atmospheric CO$_2$ on precipitation and temperature, we perform two further experiments: Wide_1000CO2 is the same as the modern-day experiment except that the atmospheric CO$_2$ concentration is set to be 1000 ppm; and Narrow_353CO2 is the same as Narrow_1000CO2 except for a 353 ppm CO$_2$ concentration. Differences between Wide_1000CO2 and Narrow_1000CO2, or between Wide_353CO2 and Narrow_353CO2 isolate the effects of narrowing the Atlantic with atmospheric CO$_2$ of 1000 ppm and 353 ppm, respectively. Differences between Wide_1000CO2 and modern-day experiment, or between Narrow_1000CO2 and Narrow_353CO2 isolate the effect of increasing atmospheric CO$_2$ concentration, given two different geometries. To explore whether the major conclusions are sensitive to the choice of model, all four experiments were repeated using CESM 1.2; the main conclusions are robust to the choice of models. We focus on the results from the ECHAM 4.6 model which has a better modern-day precipitation climatology in tropical South America than does the modern-day CESM 1.2 simulation.

3. Results

a. Modern-day climate

Seasonal and annual mean precipitation and 925-hPa winds in observations (left panels of Fig. 1) are compared with the modern-day control simulation (middle panels of Fig. 1). Three major circulation systems characterize much of the precipitation of tropical South America (see the review
by Garreaud et al. 2009 for more details): the Atlantic intertropical convergence zone (ITCZ), the
SASM (Zhou and Lau 1998; Vera et al. 2006)) over continental South America, and the South
Atlantic convergence zone (SACZ). The Atlantic ITCZ is associated with the convergence of trade
winds over the ocean from both hemispheres. The Atlantic ITCZ migrates north-south seasonally
following the Sun and is responsible for the rainy season of northeastern Brazil in austral autumn
(March - May), when it reaches its southernmost position. South American monsoon-related pre-
cipitation also follows the migration of the Sun: it is centered over northwestern South America
in the austral spring, expands southward and eastward from austral spring to austral summer, and
then retreats to the northwest from austral fall to austral winter. In austral summer, the SASM
brings precipitation to almost all of tropical South America, reaching as far south as 30°S. The
SACZ forms due to the convergence of the mid-latitude westerly flow with northwesterly flow
along the western flank of the South Atlantic anticyclone (Kodama 1993; Lenters and Cook 1995;
Nogués-Paegle and Mo 1997); the passage of extratropical transient frontal systems contributes to
the southern portion of the SACZ (Garreaud and Wallace 1998). The SACZ is present year-round,
but it is most intense during austral summer when it produces the rainy season of southeastern
Brazil.

The major features in the seasonal cycle of the precipitation over tropical South America are
fairly well simulated by ECHAM 4.6 (middle panels of Fig. 1). This encourages us to use this
model as a framework for examining the effects of variable atmospheric CO₂ and variable geom-
etry of the Atlantic basin.

b. Climate of the early Eocene

In the early Eocene experiment the Atlantic ITCZ is almost completely absent, except at the
inner corner of Gulf of Guinea in austral summer and autumn (right panels of Fig. 1). The SASM
still migrates seasonally following the Sun as in modern day, but in general it is weaker and brings precipitation over a smaller region. The SACZ is absent throughout the year. The low-level circulation is largely similar in pattern to modern day, except that the trade winds are predominantly in the southwesterly or northwesterly direction with little to no convergence along the equator, consistent with the disappearance of the ITCZ.

The above-mentioned difference in precipitation is better shown by the difference map between early Eocene experiment and modern day experiment; we use early Eocene minus modern day experiments (Fig. 2). Note that all the differences we discuss in the paper are statistically significant at a level of $p = 0.05$. The model results show that annual mean precipitation was lower in the early Eocene than today throughout all of tropical South America. The area-and annually-averaged precipitation over the South American continent decreases by about 15%, from 4.1 mm/day in the modern-day experiment to 3.5 mm/day in the early Eocene experiment (Table 2). This drying occurs in every season and is strongest in austral summer (December - February; DJF), the rainy season for most of tropical South America (Table 2). In northern tropical South America (Box A), there is higher-than-modern precipitation in austral spring (September - November; SON) and austral winter (June - August; JJA) and lower-than-modern precipitation in the other seasons; in far eastern Brazil (Box C), precipitation is enhanced during DJF but reduced during the other seasons. The latter finding may be indication of an east-west tropical South America precipitation dipole similar to that previously observed in both model (Liu and Battisti 2015) and proxy observations (Cruz et al. 2009) studies.

Figure 3 shows the seasonal cycles of precipitation area-averaged over the three boxed regions indicated in Fig. 2. These three regions are representative of precipitation in northern South America, central Amazonia, and eastern Brazil, respectively. In northern South America today (Box A), the rainy season spans boreal spring and boreal autumn with peak rainfall in June (black line). This
seasonal cycle is in phase with that of Northern Hemisphere summer monsoon; it is well captured by the modern-day simulation of ECHAM 4.6 except that the precipitation from June to August is weaker than observed. Compared to the modern climate, during the early Eocene, precipitation is greatly reduced throughout much of the year (December to July) and enhanced from August to November.

In the central Amazon (Box B), the observed rainy season lasts from austral spring to early autumn, out of phase with precipitation of northern South America. This feature is roughly captured by the modern-day simulation of ECHAM 4.6. Compared to modern day simulation, precipitation is reduced in the Amazon region in the early Eocene in almost every month except October and November.

Modern-day precipitation in northeastern Brazil (Box C) occurs from austral spring to the end of summer (October to April), with a near-complete absence of precipitation from May to August. This seasonality is well reproduced in the modern-day simulation. Relative to modern, precipitation in the early Eocene increases in the peak rainy season, and the dry season is greatly extended to seven months (April to October), resulting in regionally enhanced seasonality in the early Eocene.

c. Mechanisms for the early Eocene drying

In the remainder of the paper, we focus on discerning the mechanisms responsible for precipitation decrease in the early Eocene. We focus our analysis on DJF because the decrease of DJF precipitation accounts for a major part of the overall drying pattern observed in the early Eocene simulations (Table 2 and Fig. 2). DJF is also the rainy season for most of tropical South America except north of the equator. The unique pattern of early Eocene wetting in SON in northern tropical South America is briefly analyzed and summarized in section 3d.
Fig. 4 shows the difference in DJF precipitation between early Eocene and modern day, i.e., the combined effect of higher atmospheric CO$_2$ and a narrower Atlantic Ocean, as well as the individual effect of each. Note that precipitation difference in Figs. 4b and 4d (also 4c and 4e) add up exactly to the precipitation difference shown in Fig. 4a. Narrowing the Atlantic greatly decreases DJF precipitation, independent of the atmospheric CO$_2$ concentration (cf. Figs. 4b and 4c). Increasing atmospheric CO$_2$ concentration, on the contrary, increases the precipitation, opposing the drying caused by a narrower Atlantic. The decrease in DJF precipitation in the early Eocene relative to modern day (Fig. 4a) is due to the impact of a narrower Atlantic basin (Fig. 4b and Fig. 4c).

1) IMPACT OF A NARROWER ATLANTIC OCEAN

We study the effect of narrowing the Atlantic by examining the water budget over South America. The equation for the conservation of water can be written as

$$\frac{\partial W}{\partial t} = E - P - \nabla \cdot \int_{0}^{P_s} (qV) dp = E - P - \int_{0}^{P_s} dp \oint qV \cdot d\mathbf{n},$$

(1)

where $W$ is the column-integrated precipitable water vapor, $P$ is precipitation, $E$ is evaporation, $q$ is specific humidity, $V$ is wind velocity, $p$ is pressure, $t$ is time, and $\mathbf{n}$ is the outward pointing unit normal field of $q$. In all of the experiments, the tendency of $W$, $\frac{\partial W}{\partial t}$, is much smaller than the other terms, indicating that $W$ is in steady state, thus the column-integrated vapor flux convergence over South America equals the difference between precipitation and evaporation. We use monthly climatology data to calculate vapor flux convergence; as a result, the water budget is not closed, likely due to the neglect of sub-monthly covarying anomalies associated with eddies. Nonetheless, the change in the calculated vapor flux convergence qualitatively agrees with what is implied by change in precipitation minus evaporation (Table 3).
Comparing the Wide_1000CO2 and Narrow_1000CO2 experiments (Fig. 5a), at a fixed CO$_2$ of 1000 ppm, precipitation (area-averaged over the entire South American continent) is 30% lower with a narrow Atlantic (4.5 mm/day) than with a modern Atlantic (6.4 mm/day). This difference is almost exclusively due to a decrease in water vapor convergence over South America: the water vapor convergence is 1.6 mm/day lower with a narrow ocean than with a wide ocean; changes in evaporation flux account for only 0.1 mm/day. That the decrease in precipitation is primarily due to decrease in vapor transport is in agreement with results from identical experiments using the CESM 1.2 model which includes contributions due to transients (Table 3).

The contribution to the total water vapor converged into South America was calculated across each boundary (Fig. 5b). Note that the x-axis in Fig. 5b starts in the farthest south and goes northward along the eastern boundary of South America. It continues northwestward to the northern tip of tropical South America, Cape Gallinas at 12$^\circ$N, and then returns southward along the western boundary to Cape Horn. The lower water vapor flux into South America in the narrow Atlantic simulation is mostly due to reduction in water vapor advection across the tropical eastern$^1$(B to C) and, especially, the northeastern (C to D) coasts of tropical South America, accounting for 85% of the total decrease in water vapor delivered to South America in the early Eocene compared to modern climate (Fig. 5c). The smaller changes in water flux across the western (D to A) and subtropical eastern (A to B) boundaries are model dependent – the same pair of experiments using CESM 1.2 feature the opposite changes as those in ECHAM 4.6 (Table 3).

Decrease in water flux across the northeastern boundary is predominantly due to a decrease in water vapor in the air crossing the boundaries, not due to a decrease in mass flux associated with atmospheric circulation change: when assuming no change in $q$ (light red bars in Fig. 5c)$^2$,  

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$^1$Note that the definition of “tropical” eastern is arbitrary here. It is defined as the part of eastern boundary where water fluxes into South America; the rest of eastern boundary is defined as “subtropical eastern” boundary.

$^2$The value of $q$ around the South American continent in Wide_1000CO2 experiment is used for both Wide_1000CO2 and Narrow_1000CO2.
change in $V$ alone accounts for only 12\% of the total decrease in water flux across the northeastern boundary.

Water vapor that crosses the boundaries of South America and eventually condenses inland is sourced from evaporation of surface seawater into air parcels. To determine why there is less water vapor in the air parcels across the northeastern boundary when the Atlantic is narrower, we calculate the amount of water vapor accumulated by an air parcel, following its trajectory from eastern Atlantic to South America (Fig. 6). That is, we calculate the total water vapor that can be evaporated into the boundary layer on its passage from the eastern Atlantic to South America:

$$q(x_f) = q(x_0) + \int_{t_0}^{t_f} E(s, t) ds,$$

where $E(s, t)$ is evaporation, $q(x_0)$ is the amount of water vapor in the air parcel when it leaves Africa and South Atlantic Ocean, $s$ is the location of the air parcel at time $t$, which is a function of its initial location $x_0$ and the wind velocity $v$:

$$s = x_0 + \int_{t_0}^{t} v dt.$$

The solution to this equation represents the upper limit of the total water vapor in the air column, assuming zero initial moisture content, i.e. $q(x_0) = 0$. We take $v$ to be the wind velocity at 925 hPa which is representative of flow in the boundary layer.

In the wide Atlantic experiment, it takes air parcels, on average, over six days (Fig. 6a) to transit the Atlantic. In the narrow Atlantic experiment, this transit time is reduced to just over two days (Fig. 6b). Despite a higher evaporation rate in the narrow Atlantic experiment (Figs. 6c, d), air parcels contain much less water vapor when arriving at South America. This implies that it is the shorter residence time over the ocean that accounts for the reduction in water vapor content and hence water flux into South America across the northeastern boundary.
The decrease in water flux across the tropical eastern boundary, however, is mainly due to a decrease in mass flux across the boundaries (cf. dark and light red bars in Fig. 5c). Compared with the wide Atlantic geometry, the southeasterly trades in a narrow Atlantic are weaker and located more southward (cf. Figs. 6c and 6d). As a result, a part of water vapor is transported back to over the ocean following the South Atlantic subtropical anticyclone, rather than across the eastern boundary into South America as in the case of a wide Atlantic (cf. trajectories in Figs. 6a and 6b).

2) IMPACT OF HIGHER ATMOSPHERIC CO\textsubscript{2} CONCENTRATION

In a fixed modern geometry, increasing atmospheric CO\textsubscript{2} concentration from 353 ppm to 1000 ppm increases the precipitation in the interior of the South American continent (Fig. 4d), enhancing the mean precipitation during DJF (cf. middle panels of Fig. 1). This enhancement due to increased CO\textsubscript{2} is largely independent of Atlantic geometry (cf. Figs. 4d and 4e; Table 2). We note that the precipitation increase over subtropical South Atlantic due to increased CO\textsubscript{2} is in accord with the influence of future atmospheric increases simulated by the IPCC AR5 models — in fact, subtropical South America is the only place on Earth where over 90% of climate models agree on the sign of the future change in precipitation (Stocker 2014).

We diagnose the impact of increasing atmospheric CO\textsubscript{2} in the same way as for narrowing the Atlantic (figures not shown). The precipitation enhancement over the Amazon is from both enhancement of local evaporation and increase of moisture transport into Amazon, both of which are related to the warming caused by higher atmospheric CO\textsubscript{2} (Fig. 7): higher atmospheric CO\textsubscript{2} warms the South American continent and hence local evaporation; higher atmospheric CO\textsubscript{2} also warms the surface of tropical Atlantic Ocean, which increases the evaporation of seawater and hence moisture transport into South America. The increase in local evaporation and moisture
transport into South America increases moisture content in the boundary layer, reduces the gross moist stability and enhances convection (Fu et al. 1999; Chou and Neelin 2004).

d. Precipitation change during SON

Unlike the case for DJF, SON precipitation is enhanced in the early Eocene experiment in northern South America (and reduced in the eastern coast) (Fig. 8a). This precipitation change is caused by both narrowing the Atlantic and increasing atmospheric CO$_2$ (cf. Figs. 8b, d and c, e with Fig. 8a), with a possible contribution from potential changes in ocean circulation (see section 4b). Nonlinearity also seems to play a role: the impact of narrowing the Atlantic depends on CO$_2$ concentration and the impact of increasing CO$_2$ depends on the Atlantic width. Reasons for the precipitation change in SON are complex and beyond the scope of this paper.

4. Discussion

a. Comparison with proxy record

Paleotemperature estimates using oxygen isotope composition and Mg/Ca from planktonic foraminiferal calcite shells and TEX$_{86}$ from the tropical deep ocean drilling sites show that the tropical ocean was warmer in the Eocene than it is today (Zachos et al. 1994; Pearson et al. 2001; Tripati et al. 2003; Lunt et al. 2012). However, the uncertainty range is large regarding how much warmer the tropical ocean was. Depending on the assumptions made and the calibration method used, the Eocene tropical sea surface temperature estimates range between 28°C and 40°C (Huber 2008), making it 0 - 12°C warmer than modern day. In our simulations, tropical sea surface temperature in the early Eocene are up to 4°C higher than in modern day (Fig. 7). This is within the range of paleotemperature estimates.
Over continental South America, the Eocene was warmer than modern day in our model in every season. This is expected because of the higher-than-modern concentrations of atmospheric CO₂. However, there are no proxy paleotemperature records from South America to verify whether the magnitude of warming in our model is reasonable.

Eocene precipitation proxies from South America are very scarce. Pollen and spore records from central Colombia and western Venezuela show a peak of flora diversity occurring in the early Eocene (Jaramillo et al. 2006). This, however, does not necessarily suggest a wetter climate in the early Eocene given that biodiversity is related to climate in a more complicated way.

Note that although proxy records exist for the midlatitude Eocene climate, we must refrain from comparing these data to our model results in these regions because there are additional differences between the Eocene and modern climate that are likely to impact the mid- and high latitude climate; these include changes in Drake passage and the existence of the Isthmus of Panama, which have been shown to affect the ocean overturning circulation and thus greatly impact the high-latitude climate in both hemispheres (see, e.g., Ferreira et al. 2018 and references therein).

b. Impact of ocean circulation change

By using ECHAM 4.6 coupled to a slab ocean, this study does not allow for changes in ocean circulation that might arise in a narrower Atlantic. To explore whether such changes might be important for changes in precipitation, we performed a sensitivity experiment in which we re-ran the Narrow_1000CO2 experiment but set the slab-ocean Q-flux in the tropical (20°S to 20°N) Atlantic to zero. Although setting Q-flux to zero is arbitrary, it is such a significant perturbation that it likely provides a reasonable test of the influence of Atlantic Ocean circulation on the magnitude of precipitation change. With "ocean circulation change" considered, the difference in precipitation in tropical South America between the early Eocene and modern day is almost identical to that
when ocean circulation change is neglected (cf. Fig. 9 and Fig. 2). This suggests that changes in ocean circulation have a negligible effect on precipitation in tropical South America compared to that of increasing CO\(_2\) and narrowing the Atlantic basin.

c. Dependence on CO\(_2\) concentration

In this study we use 1000 ppm for atmospheric CO\(_2\) concentration in the early Eocene, although estimates for this time vary between 500 and 1500 ppm. Due to the compensation we find between the narrow Atlantic and increased CO\(_2\), the amplitude of drying over South America may depend on the value of CO\(_2\) concentration; however, Table 2 shows that, during DJF, the precipitation increase from CO\(_2\) would need to be twice as large as in our simulations to completely cancel the precipitation reduction from the narrowed Atlantic.

The competing effects of drying from Atlantic narrowing, and wetting from increased CO\(_2\), may help explain why models disagree on the sign of the change in this region (e.g. CCSM3 in Huber and Caballero (2011) vs. ECHAM 5 in Heinemann et al. (2009); also cf. Figs. 1 and 7 of Carmichael et al. (2016)): models in which precipitation is more sensitive to CO\(_2\) or use a much higher atmospheric CO\(_2\) concentration are more likely to show wetting overall.

To explore whether the primary results are model dependent, we repeated all the experiments with CESM 1.2 and found qualitatively similar results: a drier early Eocene compared to the modern climate, with the drying effects of narrowing the Atlantic overwhelming the wetting effects of increasing the atmospheric CO\(_2\). Both ECHAM 4.6 and CESM 1.2 show that narrowing the Atlantic dries tropical South America, and that the drying is primarily due to a decrease in water vapor flux into South America across the northeast boundary (Table 3) which is due to a decrease in the distance over which the air travels across the ocean before reaching the coastline.
5. Conclusion

Proxy records show that global climate during the early Eocene was very different from modern climate, but we know very little about South American climate from the same period. In this study, we examined the impact of changes in the two boundary conditions that are likely to have been most important for tropical South American climate during the early Eocene: a higher atmospheric CO$_2$ concentration and a narrower Atlantic basin. Both the ECHAM 4.6 and CESM 1.2 models, coupled to a slab ocean, produce the same qualitative results. Narrowing the Atlantic on its own decreases the precipitation of South America and increasing atmospheric CO$_2$ on its own increases South American precipitation. Combining both factors, the effect of geometry is greater than the effect of CO$_2$, producing a significantly drier climate in tropical South America for early Eocene conditions than for modern in both models. We anticipate being able to test this result in the upcoming Trans-Amazon Drilling Project that intends to recover Eocene sediments from depositional basins across the Amazon region (Baker et al. 2015).

Analysis of the water budget shows that the drying of tropical South America under a narrower Atlantic geometry is primarily due to a reduction in the water vapor transported into South America across the northeastern and eastern boundaries, and secondarily due to changes in the atmospheric circulation. For both narrow and wide Atlantic basins, the water vapor that flows into and condenses over South America is accumulated in the lower atmosphere as air parcels transit across the tropical Atlantic Ocean. When the Atlantic is narrower, air parcels traveling across the ocean have less time to pick up water from the ocean below; as a result, they contain much less vapor when crossing the coastline of South America.

Despite the dependence on CO$_2$ concentrations, our results support the likelihood of a new view of the early Eocene climate of the Amazon with very warm and relatively dry conditions. Together,
these would suggest lower effective moisture, lower soil moisture, and lower runoff, all conditions that would seem inimical to forest biota. If validated by forthcoming drilling expeditions, this result begs the question: were early Eocene forests present in the Amazon or was the region occupied by savanna? If the latter, then phylogenetic analyses of Amazon biota will have to be interpreted in a very different context from present understanding.

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<table>
<thead>
<tr>
<th>Experiments</th>
<th>Wide$_{353}$CO$_2$ (&quot;modern day&quot;)</th>
<th>Narrow$_{1000}$CO$_2$ (&quot;early Eocene&quot;)</th>
<th>Wide$_{1000}$CO$_2$</th>
<th>Narrow$_{353}$CO$_2$</th>
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<td>continental geometry</td>
<td>Modern</td>
<td>Narrow Atlantic</td>
<td>Modern</td>
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<td>1000 ppm</td>
<td>1000 ppm</td>
<td>353 ppm</td>
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<tr>
<td>other boundary conditions</td>
<td>pre-industrial</td>
<td>pre-industrial</td>
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<td>pre-industrial</td>
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TABLE 2. Precipitation or change in precipitation area-averaged over South American continent; units: mm day$^{-1}$.

<table>
<thead>
<tr>
<th></th>
<th>DJF</th>
<th>MAM</th>
<th>JJA</th>
<th>SON</th>
<th>Annual</th>
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<tr>
<td>Today</td>
<td>5.5</td>
<td>4.5</td>
<td>2.1</td>
<td>4.3</td>
<td>4.1</td>
</tr>
<tr>
<td>Early Eocene</td>
<td>4.5</td>
<td>3.5</td>
<td>1.7</td>
<td>4.0</td>
<td>3.5</td>
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<tr>
<td>Early Eocene minus Today</td>
<td>-1.0</td>
<td>-1.0</td>
<td>-0.4</td>
<td>-0.3</td>
<td>-0.6</td>
</tr>
<tr>
<td>Impact of geometry at 1000 ppm (353 ppm)</td>
<td>-1.9 (-1.8)</td>
<td>-1.5 (-1.0)</td>
<td>-0.6 (0.25)</td>
<td>-0.5 (0.0)</td>
<td>-1.1 (-0.6)</td>
</tr>
<tr>
<td>Impact of CO$_2$ at modern (narrow) Atlantic</td>
<td>0.9 (0.8)</td>
<td>0.6 (0.1)</td>
<td>0.2 (-0.7)</td>
<td>0.2 (-0.3)</td>
<td>0.5 (0.0)</td>
</tr>
</tbody>
</table>
TABLE 3. Changes in DJF precipitation, evaporation, precipitation minus evaporation, and water vapor flux between Narrow_1000CO2 and Wide_1000CO2. All quantities are area-averaged over South America; units: mm day$^{-1}$.

<table>
<thead>
<tr>
<th></th>
<th>ECHAM 4.6</th>
<th>CESM 1.2</th>
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<tr>
<td>Precipitation</td>
<td>-1.76</td>
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<td>-0.10</td>
<td>-0.19</td>
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<td>Precipitation minus Evaporation</td>
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<td>Water vapor convergence</td>
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<td>Water flux across subtropical eastern boundary</td>
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<td>Water flux across tropical eastern boundary</td>
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<td>Water flux across northeastern boundary</td>
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<tr>
<td>Water flux across western boundary</td>
<td>-0.46</td>
<td>0.61</td>
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Fig. 1. The seasonal and annual mean climatological precipitation (shading; mm day\(^{-1}\)) and 850-hPa winds (vectors; m/s) for (left) observation, (right) from the modern-day (Wide\(_{353}\)CO\(_2\)) experiment, and (right) early Eocene (Narrow\(_{1000}\)CO\(_2\)) experiment. Observed precipitation data are from monthly Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP; Xie and Arkin 1997) from January 1979 to December 2010, available online at [http://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html](http://www.esrl.noaa.gov/psd/data/gridded/data.cmap.html). Observed 850-mb winds are from NCEP2 covering the same period.

Fig. 2. The difference in seasonal and annual mean precipitation (units: mm day\(^{-1}\)) between early Eocene and modern day experiment, that is, differences due to enhanced CO\(_2\) and a narrower Atlantic (Narrow\(_{1000}\)CO\(_2\)) compared to that with modern-day geometry and 353 ppm CO\(_2\) (Wide\(_{353}\)CO\(_2\)). Precipitation differences over land are calculated as the grid-to-grid difference between Narrow\(_{1000}\)CO\(_2\) and Wide\(_{353}\)CO\(_2\). Differences over ocean are not shown. The lower right panel shows the percent change of annual-mean precipitation ((Narrow\(_{1000}\)CO\(_2\)/Wide\(_{353}\)CO\(_2\) - 1) *100). Red boxes represent the regions over which domain averages are examined in Fig. 3.

Fig. 3. Seasonal cycle of precipitation (units: mm day\(^{-1}\)) area-averaged over the box regions indicated in Fig. 2: observations (black line), from the modern-day simulation today (Wide\(_{353}\)CO\(_2\) experiment, gray line), and from the early Eocene simulation (Narrow\(_{1000}\)CO\(_2\) experiment, red line).

Fig. 4. Changes in precipitation (units: mm day\(^{-1}\)) during DJF. (a) early Eocene minus modern day (repeated from Fig. 2), (b) The impact of geometry at 1000 ppm CO\(_2\) concentration (i.e. Narrow\(_{1000}\)CO\(_2\) minus Wide\(_{1000}\)CO\(_2\)), (c) impact of geometry at 353 ppm (i.e. Narrow\(_{353}\)CO\(_2\) minus Wide\(_{353}\)CO\(_2\)), (d) impact of CO\(_2\) concentration at modern Atlantic geometry (i.e. Wide\(_{1000}\)CO\(_2\) minus Wide\(_{353}\)CO\(_2\)), and (e) impact of CO\(_2\) concentration at narrow Atlantic geometry (i.e. Narrow\(_{1000}\)CO\(_2\) minus Narrow\(_{353}\)CO\(_2\)).

Fig. 5. Water budget for DJF in the Wide\(_{1000}\)CO\(_2\) (gray) and the Narrow\(_{1000}\)CO\(_2\) (red) experiments. (a) Precipitation, evaporation, and precipitation minus evaporation, all area-averaged over the entire South American continent. All quantities are converted to be in the units of mm day\(^{-1}\). Convergence of water flux is calculated as the sum of water flux into South America across all boundaries shown in panel (b). (b) Vertically integrated water vapor flux into South America across each boundary (units: kg m\(^{-2}\) s\(^{-1}\)) as a function of latitude. Locations of the boundary points are shown in the upper left map. (c) Total water flux into South America across each boundary. In (b) and (c) water vapor flux is converted to be in the units of mm day\(^{-1}\) by dividing the sum by the area of South America.

Fig. 6. Upper panels: the integrated evaporative flux from seawater into the atmosphere (units: kg m\(^{-2}\)) along the trajectory of climatological DJF 925-hPa winds for (a) Wide\(_{1000}\)CO\(_2\) experiment and (b) Narrow\(_{1000}\)CO\(_2\) experiment. Trajectories are terminated after reaching South America. Lower panels: DJF evaporation (shadings; units: mm day\(^{-1}\)) and winds at 925-hPa (vectors; units: m s\(^{-1}\)) for (c) Wide\(_{1000}\)CO\(_2\) experiment and (d) Narrow\(_{1000}\)CO\(_2\) experiment.

Fig. 7. The annual mean surface temperature (units: °C) for (a) modern day experiment and (b) early Eocene experiment. And (c) is the difference of (b) minus (a).

Fig. 8. As in Fig. 4, but for SON.
Fig. 9. Differences in seasonal precipitation (units: mm day$^{-1}$) between early Eocene and modern day experiment, same as Fig. 2, except that a draconian change in “ocean circulation” (see the text) is included in the early Eocene experiment. Changes over ocean are not shown.
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