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Influence of the Atlantic Meridional Overturning Circulation on the monsoon rainfall and carbon balance of the American tropics

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[1] We examine the response of the American Tropics to changes in Atlantic Meridional Overturning Circulation (AMOC) strength using a set of water-hosing experiments with an Earth system model that explicitly simulates the global and regional carbon cycle. We find that a moderate weakening (27%) of the AMOC, induced by a 0.1 Sv ($1\,\mathrm{Sv} \equiv 10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$) freshwater addition in the northern North Atlantic, drives small but statistically significant drying in the South American monsoon region. By contrast, a complete shutdown of the AMOC, induced by a 1.0 Sv freshwater addition, acts to considerably shift the ITCZ southward, which changes the seasonal cycle of precipitation over Amazonia. Our results indicate that AMOC weakening can have a significant impact on the terrestrial primary productivity and carbon storage of the American Tropics.

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1. Introduction

[2] Seasonal rainfall in the South American Summer Monsoon (SASM) provides abundant water for hydroelectric power generation [*Stickler et al.*, 2013], agriculture, and natural ecosystems, but this precipitation is susceptible to climatic variability and change [*Marengo et al.*, 2012a]. Variations in precipitation and terrestrial water storage can lead to fires, drought, and flooding, disturb the carbon uptake, and threaten biodiversity over Amazonia, as well as damage infrastructure [*Fernandes et al.*, 2011; *Davidson et al.*, 2012; *Marengo et al.*, 2012b; *Chen et al.*, 2013]. For instance, even small changes in South American rainfall amount in the dry season can alter potential land vegetation and surface albedo over Amazonia [*Zeng et al.*, 2008].

[3] Previous research shows that the Atlantic sea surface temperatures (SSTs) and the Atlantic Meridional Overturning Circulation (AMOC) play an important role in regulating the position of the Intertropical Convergence Zone (ITCZ) and the SASM [*Nobre et al.*, 2012; *Yoon and Zeng*, 2010]. Due to its large northward oceanic heat transport, a weakening of the AMOC can cause cool North Atlantic SSTs and a southward shift of the thermal equator [*Broccoli et al.*, 2006; *Souza and Albuquerque Cavalcanti*, 2009; *Vellinga and Wood*, 2008; *Zhang and Delworth*, 2005]. The climate impact of the AMOC is typically investigated by performing the idealized "water-hosing" experiment [e.g., *Manabe and Stouffer*, 1995; *Stouffer et al.*, 2006]. In these experiments, an external source of freshwater is added to the ocean surface in the northern North Atlantic Ocean. The added freshwater reduces the density of the surface waters in the northern North Atlantic; these density changes in turn cause a reduction in strength of the AMOC. While the global-scale precipitation response to the hosing seems quite robust [*Stouffer et al.*, 2006; *Vellinga and Wood*, 2008], some critical questions about regional and temporal details, especially in Amazonia, remain to be answered: (1) Does a weakening of the AMOC cause significant changes in precipitation in rainforest regions helping to modulate climate, such as eastern Amazonia [*Hutyra et al.*, 2005] and lowland Central America? (2) Are the simulated precipitation responses consistent with available paleoclimatic records in this region? (3) How does a weakening of the AMOC influence the terrestrial carbon storage and sink in the Amazonian rainforest, given the close link between water availability and vegetation growth [*Wang et al.*, 2011]?

[4] To address these questions, we perform a set of water-hosing experiments with the GFDL ESM2M, a state-of-the-art Earth system model [*Dunne et al.*, 2012, 2013]. Our goal is to isolate changes over tropical Central and South America that could occur from variations in AMOC strength, rather than from a greater — and more difficult to diagnose — complexity of climate system changes. We particularly focus on changes in precipitation and carbon storage in Amazonia due to this region's impact on the global carbon budget [*Tian et al.*, 1998].

2. Model and Experimental Design

[5] The physical component of the GFDL ESM2M is the GFDL CM2.1 climate model. The horizontal resolution of the atmospheric model is 2° latitude by 2.5° longitude. The oceanic component employs MOM4 with 50 vertical levels and 1° horizontal resolution that is enhanced to 1/3° in the tropics. In addition, ESM2M incorporates land/ocean ecology

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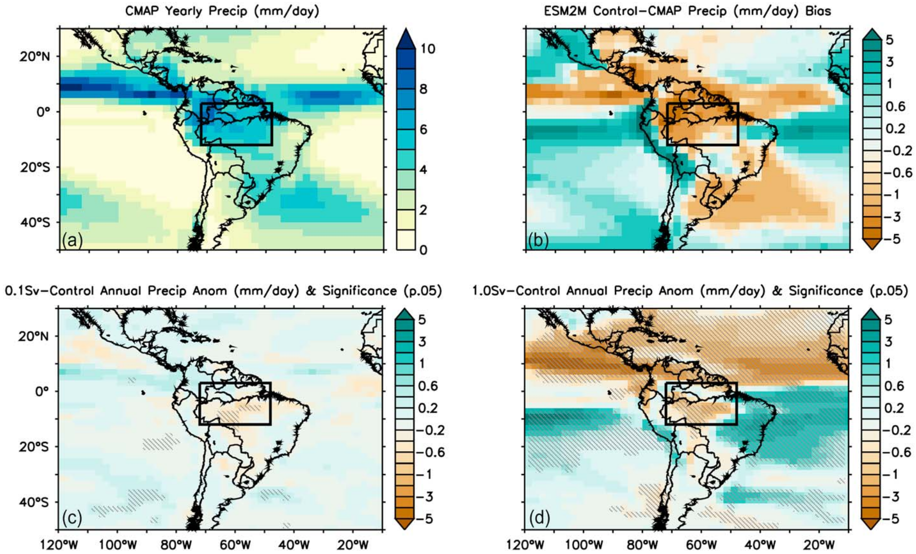

Figure 1. Climatological annual mean precipitation rate, precipitation bias, and precipitation anomalies (color shading in mm d^{-1}) with hatching indicating statistically significant precipitation changes ($p < 0.05$). The black box delineates Amazonia (12°S to 3°N and 72°W to 48°W). (a) Annual mean CMAP precipitation, (b) model biases (ESM2M control-CMAP), (c) precipitation anomalies in the 0.1 Sv hosing experiment, (d) precipitation anomalies in the 1.0 Sv hosing experiment. Notice the nonlinear scales in the anomaly figures. Significance levels were calculated using the Gaussian approximation methods described in *Katz* [1982].

and biogeochemistry models to study carbon/climate feedbacks on global and regional scales.

[6] With ESM2M, we perform a control run and two hosing experiments. In all three runs, the radiative conditions, including the atmospheric CO_2 concentration, are fixed at the pre-industrial (PI) level (we note that there has been ~0.7°C global warming since 1860 [*Trenberth et al.*, 2007]) and no human impact on land vegetation is prescribed. In each of the two hosing experiments, we impose a perturbation freshwater flux of 0.1 or 1.0 Sv ($1\,\mathrm{Sv} \equiv 10^6\,\mathrm{m}^3\,\mathrm{s}^{-1}$) in 50°N–70°N of the North Atlantic for 100 years, which is switched off subsequently [*Yin and Stouffer*, 2007]. This freshwater flux reduces the surface water density of the North Atlantic and reduces the AMOC strength. The perturbation freshwater flux is not compensated by removing freshwater elsewhere. All of these runs are branched from a long (>2000 years) model spin-up to a near-equilibrium PI state for heat and carbon.

[7] The mean strength of the AMOC in the control run is 24 Sv. Here the AMOC strength is defined as the maximum values of the meridional overturning streamfunction in 30°S–90°N, 500–3000 m depth [*Yin and Stouffer*, 2007]. The AMOC is slowed down 27% by 0.1 Sv hosing over the 100 year period, whereas 1.0 Sv hosing completely shuts down the AMOC. Recent observations show that the AMOC varies relative to the mean on interannual and longer time scales [*McCarthy et al.*, 2012]. Significant changes in AMOC strength since the last deglaciation have been inferred from paleoclimatic records [e.g., *McManus et al.*, 2004]. A weakening of the AMOC has also been projected in the future under continued greenhouse gas (GHG) emissions [*Wood et al.*, 2003; *Weaver et al.*, 2012]. However, there is still uncertainty about the magnitude and rate of past and future AMOC changes. Our idealized experiments focus on the possible range of impacts associated with AMOC change alone. In reality, past and future AMOC changes were and will be convolved with changes in GHG concentrations. The hosing runs here represent sensitivity experiments and do not consider the combined effect of GHG and AMOC.

[8] We first evaluate the ESM2M performance by showing the biases in the control simulation against observations and then present simulated anomalies from the hosing experiments. For precipitation, we compare the control simulation with the CMAP data for 1979–2008 [*Xie and Arkin*, 1997]. ESM2M captures the observed maximum rainfall belt in the Amazonian basin (Figures 1a and 1b), but the model shows a double ITCZ problem over the Pacific, simulates too much orographic precipitation west of the Andes Mountains, and underestimates the magnitude of precipitation in the lowlands of Central and South America between 10°N and 10°S (Figure 1b). Whereas ESM2M captures the strong seasonal cycle of the monsoon precipitation and the rapid transition between dry and wet seasons, it shows an overall underestimation of Amazonian monthly rainfall (Figure 2a). This annual precipitation bias could affect terrestrial ecosystems, fire occurrence, and therefore the modeled carbon cycle in this region. Additionally, the overestimation of the severity of the dry season could affect the modeled sensitivity of land vegetation to changes in total precipitation and its seasonality in the hosing experiments.

[9] We also evaluate changes in terrestrial carbon storage resulting from a slowing AMOC. In terms of terrestrial carbon storage, *Dunne et al.* [2013] find that the ESM2M simulation compares well to observational estimates of ecotype distributions, but ESM2M overextends the coverage of the tropical forest, while under-representing savannah. The land ecological model of ESM2M is based on LM3V [*Shevliakova et al.*, 2009], with improved soil moisture, vegetation water uptake, and river routing scheme. *Shevliakova et al.* [2009] assess the ability of the stand-alone land model (LM3V) to simulate the carbon cycle by comparing the model output to observational estimates of terrestrial carbon storage. LM3V generally does a good job capturing the range of biomass in Amazonia, but

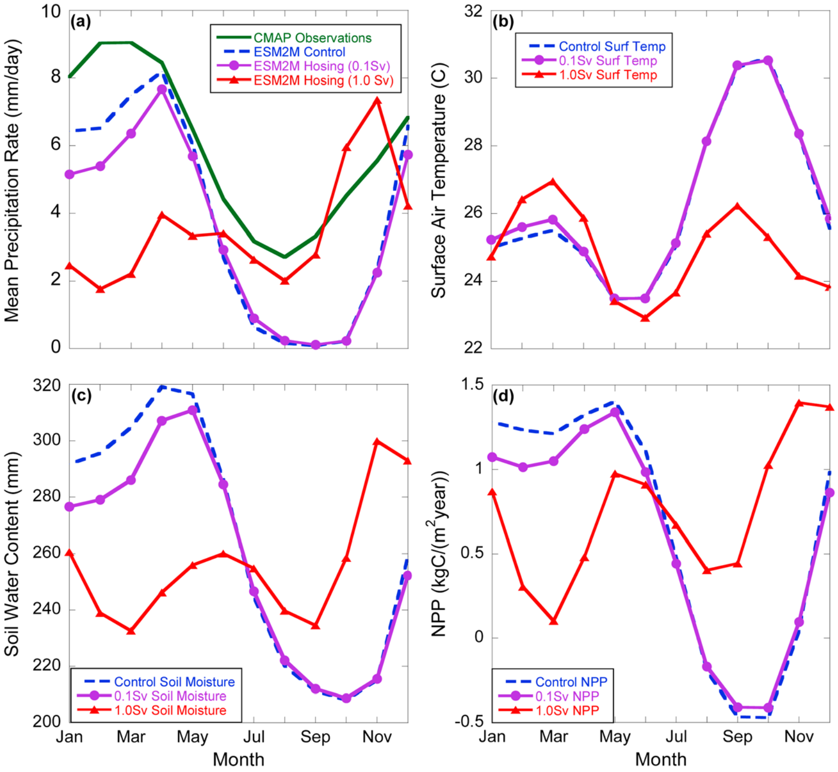

Figure 2. (a) Monthly mean precipitation rate (mm d^{-1}), (b) surface air temperature (°C), (c) soil water content (mm of soil water, integrated 0–0.9 m depth), and (d) net primary productivity (kg C m^{-2} $year^{-1}$) over Amazonia (12°S to 3°N and 72°W to 48°W). Monthly averages of CMAP observations (green), ESM2M control simulation (dashed blue, mean of years 1–100), 0.1 Sv hosing (purple, mean of years 81–100), and 1.0 Sv hosing (red, mean of years 81–100).

the relatively coarse model resolution, precipitation biases, and imperfect representation of subgrid scale processes lead to uncertainties in the LM3V's carbon simulation in the tropics. Unlike the study by *Shevliakova et al.* [2009] with LM3V forced by land use scenarios, the ESM2M integrations in the present study do not incorporate any land use scenario. The vegetation type and amount are solely predicted as a response to the climate variables and CO_2 concentration in the atmosphere.

3. Results

[10] Here we present the results from the hosing experiments in Central and South America (50°S–30°N, 120°W–5°W), with a focus on monthly and annual changes in Amazonia (12°S–3°N, 72°W–48°W) [*Malhi et al.*, 2009]. As shown by earlier hosing studies [e.g., *Manabe and Stouffer*, 1995], a slowing AMOC leads to cooler equatorial North Atlantic surface waters and warmer waters in the South Atlantic, moving the ITCZ toward the south in the Atlantic region [*Broccoli et al.*, 2006; *Yin and Stouffer*, 2007; *Vellinga and Wood*, 2008]. These AMOC and ITCZ changes in turn cause significant shifts in amount and timing of precipitation in Central America and northern South America, with larger forcing yielding larger response. A weakening of the AMOC in the 0.1 Sv experiment causes a statistically significant decrease in Amazonian precipitation near 5°S (Figure 1c). By contrast, a complete AMOC shutdown causes much greater changes in annual mean precipitation over Central America and far northern South America (Figure 1d). Due to the strong forcing, most of these changes are statistically significant.

[11] Although AMOC slowdown leads to minor decreases in the monthly precipitation during the Amazonian rainy season (December–April), a complete AMOC shutdown can significantly suppress this seasonal rainfall, whereas the dry season (July–November) receives more precipitation (Figure 2a). AMOC shutdown prevents the northward migration of the ITCZ over Central America and forces the ITCZ to remain centered over northern South America year-round, causing a more even distribution of Amazonian precipitation throughout the year.

[12] Changes in AMOC strength also lead to shifts in terrestrial carbon storage and soil water content (Figures 3b, 3c, 3e, and 3f). A shutdown of the AMOC causes a net gain in vegetation and soil carbon storage in South America, with Amazonian carbon storage increasing by ~47% (from 55 PgC in the control to 81 PgC in the 1.0 Sv experiment). By contrast, the decrease of annual mean precipitation in Central America and far northern South America causes a loss of carbon to the atmosphere of ~53% in Central America (from 20 PgC in the control to 9 PgC in the 1.0 Sv experiment). In Amazonia, the reduced seasonality of precipitation could enhance biomass production in the tropical forest by minimizing moisture stress due to a less severe, cooler dry season; indeed, *Zeng et al.* [2008] find that the severity of the dry season plays an important role in Amazonian ecosystems. AMOC shutdown causes less extreme seasonal swings in surface-air temperature and smaller seasonal decreases in soil moisture in Amazonia (Figures 2b and 2c), resulting in increased average net primary productivity throughout the year (Figure 2d). AMOC weakening also changes terrestrial water storage: regions receiving less annual

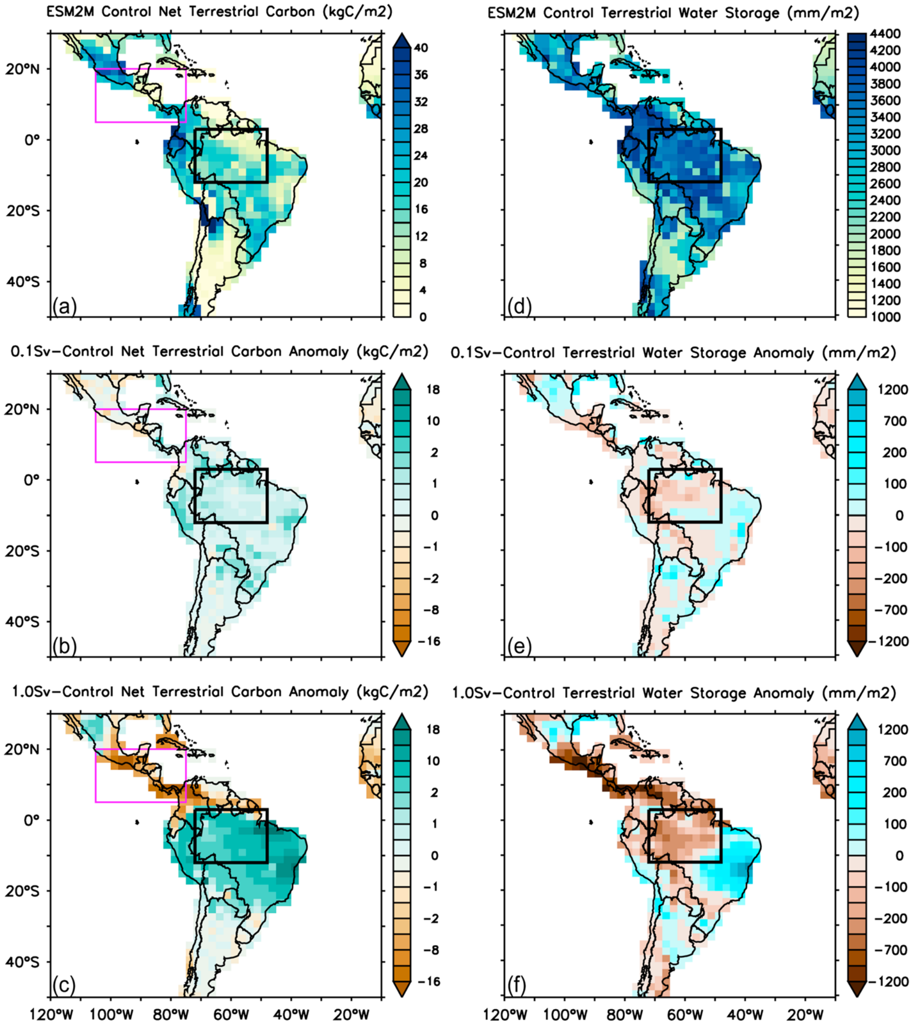

Figure 3. Climatological annual mean net terrestrial carbon storage and net terrestrial carbon storage anomalies (color shading in kg C m^{-2} of soil) and annual mean terrestrial water storage and terrestrial water storage anomalies (shading in mm of water m^{-2} of soil). (a) ESM2M control net terrestrial carbon storage, (b) 0.1 Sv-Control carbon anomalies, (c) 1.0 Sv-Control carbon anomalies, (d) ESM2M control water storage, (e) 0.1 Sv-Control water storage anomalies, and (f) 1.0 Sv-Control water storage anomalies. The black box delineates Amazonia (12°S to 3°N and 72°W to 48°W), and the pink box delineates the Central American region used to calculate carbon storage. Terrestrial carbon storage is defined as the sum of carbon in soil and vegetation components, and water storage is defined as the sum of liquid and frozen water components. Notice the nonlinear scales in the anomaly figures.

mean precipitation in the hosing experiments (Figures 1c and 1d) show a consistent decrease in annual mean terrestrial water storage (Figures 3e and 3f), and vice versa. Whereas the changes in seasonality promote growth in Amazonia, the severe drying in Central America reduces carbon storage (Figures 3c and 3f). Zonally averaged (90°W–35°W) precipitation and soil water anomalies in the American Tropics illustrate the seasonal effects of the southward shift of the ITCZ, which no longer returns north of ~5°N in the AMOC shutdown experiment (Figure S1d). When the ITCZ is forced to the south, the region between ~10°S and 5°N experiences a large soil water content deficit in January through April. Precipitation and soil water content decrease north of 5°N from July to November, while the region between ~15°S and 5°N receives increased moisture during this time (Figure S1). Changes in seasonality and water storage could have important implications for fire season severity, as water storage deficits in southern Amazonia precede abnormally severe fire seasons [*Chen et al.*, 2013]. Fire season activity could increase or decrease due to AMOC shutdown depending on if decreased mean annual soil water content combined with more vegetation dominates or if a less severe dry season dominates. Thus, the results suggest that the AMOC weakening could lead to changes in fire activity in tropical rainforest regions such as Amazonia (note that the ESM2M simple fire module is not capable of providing seasonal information). Changes in vegetation and soil water storage also lead to changes in carbon storage (Figure S2). These changes in vegetation could be caused by changes in the seasonal cycle of precipitation, soil moisture, and temperature that cause shifts in species composition, biomass pools, and soil decomposition rates. Additionally, it should be noted again that the ESM2M annual and dry-season precipitation biases could affect the accurate simulation of the carbon cycle and potential changes in carbon storage in the experiments.

4. Discussion and Conclusions

[13] By performing a set of hosing experiments with the GFDL ESM2M, we examine the range of precipitation and ecosystem impacts in the American Tropics resulting from changes in AMOC strength. Our 1.0 Sv hosing experiment indicates that a complete shutdown of AMOC would cause the ITCZ to shift toward the south, thereby leading to changes in seasonality of northern South American precipitation and large decreases in Central American precipitation. A smaller AMOC reduction causes anomalies with similar patterns but smaller magnitudes. The significant response of South American precipitation to the AMOC change is also evident in other modeling studies [*Harris et al.*, 2008; *Good et al.*, 2008, 2011; *Vellinga and Wood*, 2008; *Wood et al.*, 2003]. In addition, many paleoclimatic records support our modeling results: cooling events in the North Atlantic such as the "8.2 ka event" and the Younger Dryas caused a southward displacement of the ITCZ over tropical Central and South America [e.g., *Strikis et al.*, 2011; *Cheng et al.*, 2009; *Correa-Metrio et al.*, 2012; *Peterson et al.*, 2000; *Morrill et al.*, 2013; *Arbuszewski et al.*, 2013; *Overpeck and Cole*, 2006], although isolated paleoclimatic records indicate that the effect of the North Atlantic SSTs may be less important [*Novello et al.*, 2012; *Reuter et al.*, 2009]. *Vuille et al.* [2012] also find that centennial timescale anomalies in precipitation over northern South America are linked to temperature and circulation changes in the North Atlantic; when the Northern Hemisphere is warm, the South American summer monsoon weakens, and vice versa.

[14] Our results suggest that changes in the amount and timing of Central and South American precipitation depend on the magnitude of the AMOC weakening. Importantly, our ESM2M experiments indicate that changes in the AMOC have the potential to alter terrestrial water storage and regional carbon storage both in Central and South America. The changes in the timing of precipitation in the AMOC shutdown experiment cause a net increase in Amazonian terrestrial carbon storage despite annual mean precipitation decreases, whereas more severe precipitation decreases in Central America cause net carbon storage loss. Thus, land managers and policymakers concerned with the long-term integrity of the region's ecosystems and the ability of American tropical forests to act as a carbon sink and resist fire during the dry season need to factor in future changes in the AMOC and other climatic responses to increasing GHGs in addition to direct human impacts on the forests. Both types of change could be rapid on human time scales.

[15] A direct comparison of the GHG increase and the AMOC weakening, in terms of their effects on precipitation shifts and carbon storage, is beyond the scope of this paper; changing CO_2 concentrations in future projection runs will alter fertilization of CO_2 of land plants [*Taub*, 2010], whereas in our hosing experiments the CO_2 concentration remains fixed. Under projected GHG-induced warming, the Northern Hemisphere warms more than the Southern Hemisphere and the ITCZ moves north [*Vellinga and Wood*, 2008], whereas in hosing experiments the Northern Hemisphere cools relative to the Southern Hemisphere, and the thermal equator and ITCZ in the Atlantic sector move south [*Stouffer et al.*, 2006; *Vellinga and Wood*, 2008]. The RCP scenarios include decreases in AMOC strength over the 21st century: AMOC weakening in RCP4.5 ranges from 23% to 35%, and AMOC weakening in RCP8.5 ranges from 36% to 44% (with a possibility of shutdown in RCP8.5 in two models) [*Weaver et al.*, 2012]. The weakening of the AMOC would likely reduce the effects of GHG-induced warming in the Northern Hemisphere. Although the AMOC weakening generally causes changes in precipitation in the opposite sign to those caused by rising GHG concentrations, *Vellinga and Wood* [2008] find that AMOC shutdown enhances precipitation decreases in Central America and far northern South America. In the long run, the GHG-induced warming likely dominates over the AMOC-induced cooling (Figure S3) [*Collins et al.*, 2013]. However, the AMOC shutdown in the hosing experiment has a greater effect on the hydroclimate of the American Tropics than either RCP scenario (Figure S3). Additionally, nonlinear responses could occur when combining the effects of GHG-induced warming and AMOC-induced cooling (e.g., sea ice).

[16] According to our modeling results, possible future changes in AMOC strength alone will not be sufficient to drive a large-scale dieback of the Amazonian forest. Other recent Earth System Model results of tropical forest projections also indicate that climate change causes minimal dieback of Amazonian forest, but Amazonia is still sensitive to dry-season length [*Good et al.*, 2013]. Additionally, new studies reveal that tropical ecosystems are likely more resilient to drought than previously thought [*Campos et al.*, 2013] and that Amazonia may be at much lower risk of forest dieback if CO_2 fertilization is taken into account [*Cox et al.*, 2013]. However, future work is needed with more sophisticated and refined resolution Earth System Models to examine the extent to which climate change and AMOC weakening could result in future changes in Amazonian ecosystems and their ability to store carbon.

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