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ORIGINAL ARTICLE

How might a collapse in the Atlantic Meridional Overturning Circulation affect rainfall over tropical South America?

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Abstract

The seasonal response of rainfall over tropical South America to a shutdown in the Atlantic Meridional Overturning Circulation (AMOC) is examined, in HadGEM3 model simulations where freshwater is added to the north Atlantic. Potential biases in these simulations are explored by comparing the unperturbed simulation with observations. In this simulation, in years when the latitude of the model Atlantic Intertropical Convergence Zone (ITCZ) is realistic, the model provides a reasonable simulation of the spatial and seasonal variation in regional-scale rainfall over tropical South America. However, some climatological mean rainfall biases over this region are attributed to the climatological southward bias in the Atlantic ITCZ. Under an AMOC shutdown, the rainfall changes over tropical South America are largely associated with a southward shift of the Atlantic ITCZ. The large seasonal variation in rainfall change over tropical South America is linked primarily with the variation in the location of peak rainfall (itself driven largely by variation in the latitude of peak solar insolation and by the lagged variation in Atlantic ITCZ). The simulated rainfall changes appear to be biased in some months by the southward bias in the Atlantic ITCZ, including a possible overestimation of drying in March and June. In addition, the Atlantic ITCZ in HadGEM3 tends to shift too far in both the seasonal cycle (as reported in other models) and in inter-annual variability. Excessive inter-annual variability may arise because the model ITCZ is too close to the equator, combined with an increase in variability near the equator. Further understanding of what drives the variability in ITCZ latitude, and how that relates to ITCZ shifts under an AMOC shutdown, is suggested as a future research priority.

KEYWORDS
geographic/climatic zone, geophysical sphere, physical phenomenon, scale, tools and methods

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1 | INTRODUCTION

A collapse in the Atlantic Meridional Overturning Circulation (AMOC) has long been known as theoretically possible (Stommel, 1961; Srokosz *et al.*, 2012). The AMOC transports large amounts of heat and salt northward (Hall and Bryden, 1982; Srokosz *et al.*, 2012), so any weakening in this circulation would impact surface climate over a large area (Vellinga and Wood, 2002; Sun *et al.*, 2012; Parsons *et al.*, 2014; Jackson *et al.*, 2015). Although a complete collapse is thought unlikely (Castellana *et al.*, 2019), the AMOC has reached its lowest level over the last millennium (Caesar *et al.*, 2021). Tropical South America (including the Amazon) is one key area that might be affected by rainfall changes arising from an AMOC weakening (Parsons *et al.*, 2014). Quantifying and understanding such potential impacts is important for managing the risk associated with a potential collapse or weakening in the AMOC. This includes using observations to understand and reduce climate model biases related to AMOC impacts.

Current information on the potential impacts of a large reduction in the AMOC mostly comes from freshwater hosing experiments using climate models (Vellinga and Wood, 2002; Parsons *et al.*, 2014; Jackson *et al.*, 2015). These involve adding freshwater to parts of the North Atlantic to slow the AMOC.

Some large-scale features of the impacts of an AMOC weakening are understood to be relatively robust. These include a relative cooling of the northern hemisphere compared to the southern hemisphere, and a southward shift of the ITCZ (Vellinga and Wood, 2002; Jackson *et al.*, 2015). The latitude of the zonal-mean ITCZ is thought to be linked to the inter-hemispheric energy transport (Kang and Held, 2012), so an ITCZ shift is naturally expected if the AMOC were to weaken. In particular, a southward shift in the latitude of the Atlantic ITCZ is expected (Chiang et al., 2002; Chiang and Bitz, 2005), associated with a change in the meridional gradient in tropical Atlantic sea surface temperatures (SSTs).

A number of studies have found that an AMOC weakening (Vellinga and Wood, 2002; Parsons *et al.*, 2014; Jackson *et al.*, 2015) tends to reduce annual mean rainfall over the Amazon. The effect on the seasonal cycle can be rather more complex, however. One study using an earth system model (Parsons *et al.*, 2014) found that although annual mean precipitation reduced slightly under an AMOC collapse, Amazon vegetation productivity increased overall, due to a less intense dry season.

A meridional shift in the Atlantic ITCZ has downstream impacts on rainfall over tropical South America, by shifting the patterns of moisture transport and vertical ascent/descent (e.g. Good *et al.*, 2008; Richter and Xie, 2010). The effects of an AMOC weakening on Atlantic and South American rainfall may, therefore, be partly viewed as geographical shifts in rainfall (a simplification, but conceptually useful).

This means that the rainfall impacts of an AMOC weakening would be seasonally varying, as rainbands migrate across the continent. The seasonal migration in peak rainfall over tropical South America is driven by seasonal variations in the latitude of peak solar insolation, and by variations in tropical Atlantic SST patterns (Fu *et al.*, 2001; Biasutti *et al.*, 2003). The latitude of peak solar insolation affects the geographical distribution of solar energy available to balance the energy exported by deep convection (Biasutti *et al.*, 2003). The north-south SST gradient varies with meridional migration of the peak solar heating, driving meridional shifts of the Atlantic ITCZ, and hence shifting rainfall over tropical South America.

Model-simulated rainfall changes associated with an AMOC weakening are subject to uncertainty due to model errors. This includes model biases in the climatological location (and strength) of rainbands, as well as the distance over which rainbands shift as the AMOC weakens. These biases in turn could be affected by errors in the location of the Atlantic ITCZ itself (Biasutti et al., 2006; Breugem et al., 2006; Richter and Xie, 2008; Richter and Tokinaga, 2020), and errors in how the Atlantic ITCZ influences South American rainfall (Bai and Schumacher, 2021).

Here, the rainfall impacts over tropical South America of an AMOC collapse are explored in a hosing experiment with a high-resolution climate model (Jackson *et al.*, 2015). Section 2 describes the model data, observations and the solar and Atlantic indices. Section 3 introduces the seasonal cycles in HadGEM3 and compares them with observations; then presents simulated rainfall changes under an AMOC weakening and discusses how they may be affected by model biases in the Atlantic ITCZ; and finally explores biases in the simulated Atlantic ITCZ latitude. Section 4 summarizes the conclusions.

2 | DATA AND METHODS

2.1 | HadGEM3 model and experiments

The HadGEM3 model version and experiments used here are described in detail by Jackson et al. (2015). Briefly, the GC2 version (Williams *et al.*, 2015) of the HadGEM3 coupled ocean-atmosphere general circulation model (Hewitt *et al.*, 2011) was used with an atmospheric horizontal resolution of N216 (approximately 60 km in mid-latitudes) and 85 vertical levels. The ocean model is eddy permitting, with a nominal horizontal resolution of 0.25° with 75 vertical levels. Higher-resolution models have shown some advantages (Small *et al.*, 2014), including AMOC strength and structure (Saba *et al.*, 2016; Roberts *et al.*, 2020).

The AMOC overturning strength at 26N is slightly too weak in the model control experiment (around 14 Sv; Jackson *et al.*, 2015) compared to 16–19 Sv in observations (Smeed *et al.*, 2014, 2018). The vertical structure of overturning at 26N is similar (not shown) to the GC3.1-MM version of the same model, which has the same spatial resolution as in the current study. GC3.1-MM compares well with observations, albeit with a slightly too shallow overturning cell, as seen in most current models (Roberts *et al.*, 2020).

Two experiments were used: a fixed-forcings pre-industrial control experiment and an 'AMOC-off' experiment where the salinity of the upper layers of the North Atlantic is perturbed (Jackson *et al.*, 2015). Salinity perturbations equivalent to a total of 100 Sv Year are made over the first 10 years of AMOC-off. Time series of overturning in this experiment are shown in figure 2 of Jackson et al. (2015). The AMOC-off experiment simulates a near-shutdown of the AMOC, but our results also give an idea of regional precipitation changes at intermediate AMOC states.

Unless stated otherwise, results from AMOC-off are 90-year means over years 54–143 of the simulation (salinity perturbations start at year 0).

2.2 | Observations

Precipitation observations are from version 2 of the Global Precipitation Climatology Project (GPCP) monthly analysis (Adler *et al.*, 2003), over years 1979–1998.

SSTs for the same period are taken from HadISST version 1.1 (Rayner *et al.*, 2003).

2.3 | Atlantic and solar indices

The large-scale meridional SST gradient in the tropical Atlantic (tropical Atlantic SST gradient – TAG) is quantified using a previously defined index (Good *et al.*, 2008). This index quantifies the difference between two regional SST means. The two regions (north and south of the equator) are 20–40° W, 5–25° S and 15–70° W, 5–25° N (land areas must be masked when using these regions).

The latitude of the Atlantic ITCZ is quantified using a precipitation-weighted latitude mean. A weighted mean is used instead of finding the latitude of peak precipitation as the ITCZ is not always in the form of a single peaked rainband. First, precipitation is zonally averaged over longitudes 35–15° W, extracted over the latitude range 15° S–15° N. Each zonal mean is multiplied by the corresponding latitude, and the result divided by the mean precipitation over this latitude range. This gives a weighted mean latitude (where greater weight is given to latitudes with greater precipitation).

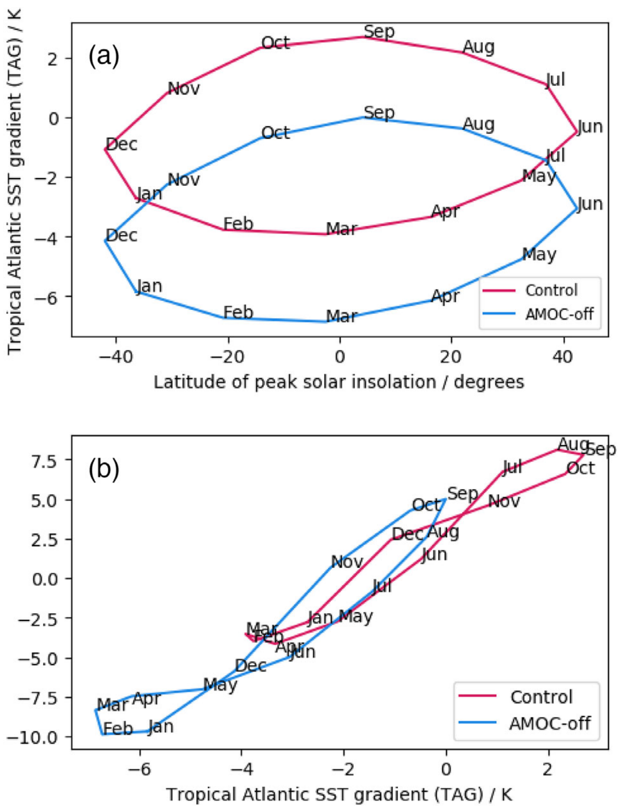


FIGURE 1 Seasonal cycles in climate means of the three indices in the control (red) and AMOC-off (blue) experiments. (a) TAG versus the latitude of peak solar insolation. (b) ITCZ latitude versus TAG

To quantify the meridional progression of solar insolation during the year (to help understand the seasonal migration of precipitation over tropical South America), the latitude band with peak top-of-atmosphere downward short-wave radiative flux is taken for each month of the year. The seasonal cycle of solar insolation does not vary in these model experiments, being fixed at pre-industrial conditions.

3 | RESULTS

Detailed results are presented below for 4 months of the year: March, June, September and December. These mark the extremes of solar and ITCZ latitudes (Figure 1a) and capture the main seasonal patterns. Three study regions are highlighted in Figure 2 (pink rectangles). These are chosen to capture the main features of precipitation change under an AMOC shutdown (Figure 2m–p).

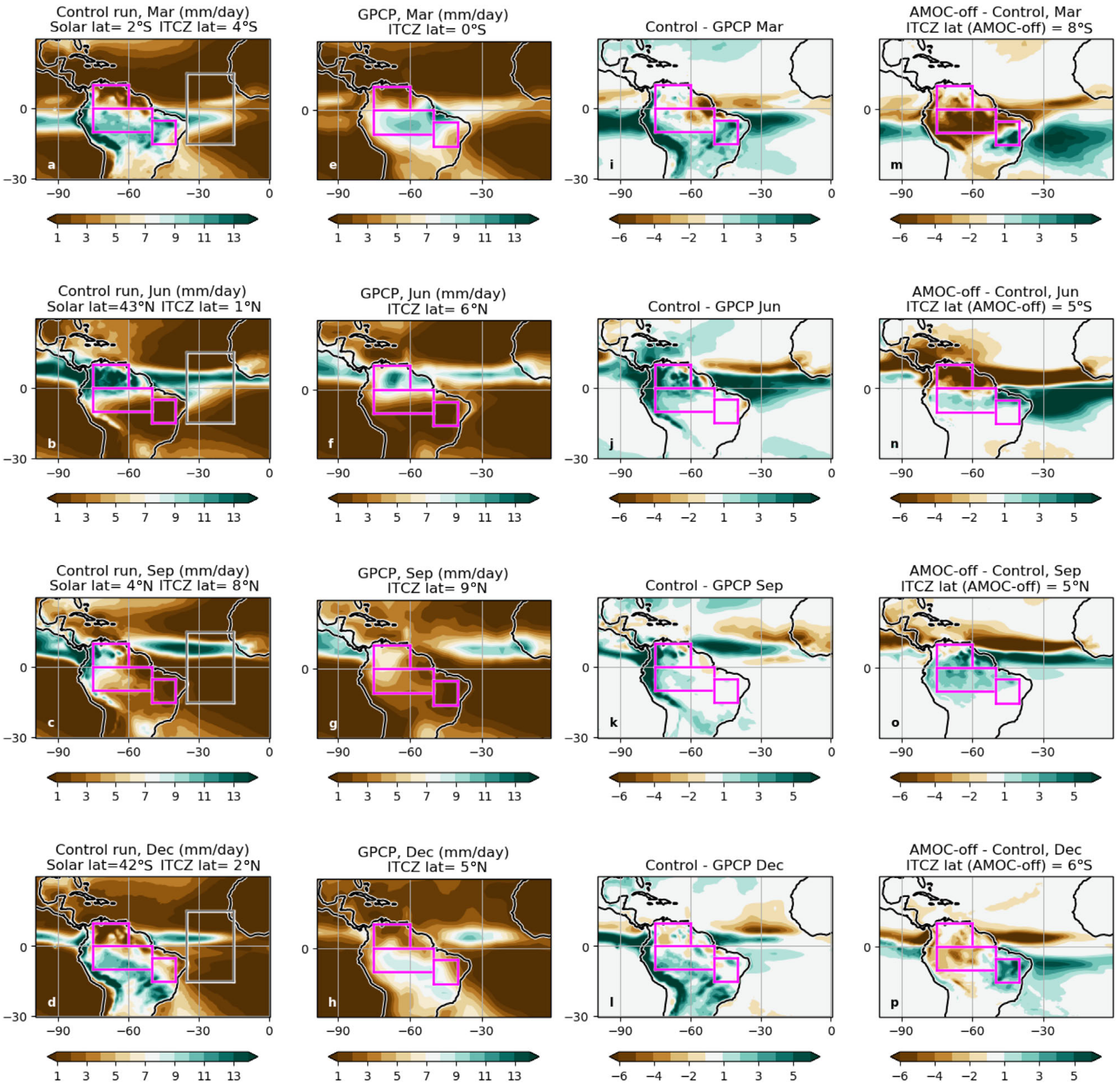


FIGURE 2 (a–d) Mean rainfall in the control run for March, June, September and December. Titles specify the latitude of peak solar insolation and the Atlantic ITCZ latitude. Pink rectangles mark the three regions analysed in Figures 3–6 (region boundaries are stated in titles of Figures 3–6). Grey rectangle marks the region used to calculate the Atlantic ITCZ latitude. (e–h) Mean rainfall observed by GPCP. (i–l) Control run minus GPCP. (m–p) Rainfall change under an AMOC shutdown; title specifies the ITCZ latitude in AMOC-off (the latitude in the control experiment given in panels a–d)

3.1 | Seasonal cycles in the HadGEM3 control run

Seasonal cycles in the HadGEM3 control run are first discussed, to give context to the other results. The qualitative features discussed are also seen in the observations. Differences between model and observations are discussed in the next section.

The seasonal cycle of rainfall over tropical South America can partly be understood as a response to two factors (Hastenrath and Lamb, 1977; Nobre and Shukla, 1996; Biasutti *et al*., 2003): the latitude of peak solar insolation, and the meridional TAG, via its influence on the ITCZ latitude. The seasonal cycles of these two factors are roughly 90° out of phase (Figure 1a), with TAG maxima and minima occurring during the equinoxes. This is due to the well-known

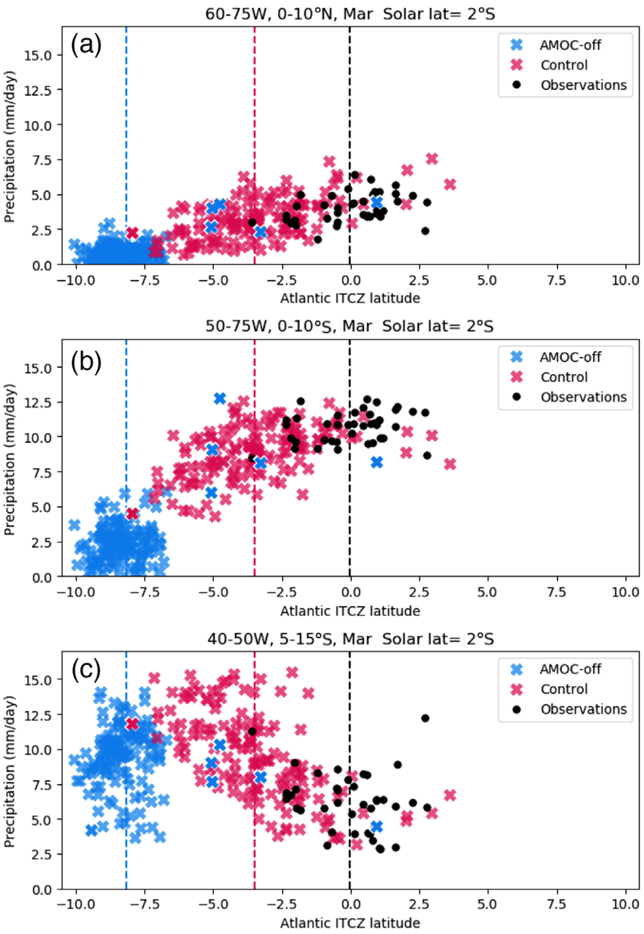


FIGURE 3 Regional mean rainfall against Atlantic ITCZ latitude, for March. *Y*-axes: rainfall averaged over each of the three regions marked in Figure 2, corresponding to (a) the northern region, (b) the central region and (c) the south-eastern region (region boundaries stated in each title). Each symbol represents the March monthly mean for a single year from the AMOC-off experiment (blue), the control run (red) or observations (black). Vertical dashed lines mark the time mean ITCZ latitude for each of the three datasets. For the AMOC-off experiment, all years from 1 to 143 are included

lagged SST response to solar heating (due to thermal inertial of the ocean mixed layer). In the HadGEM3 seasonal cycle, as expected, there is a strong (Pearson $r = 0.96$) relationship between the meridional TAG and the latitude of the Atlantic ITCZ (Figure 1b).

Comparing the months of March and September, peak solar insolation is, of course, near the equator in both months (Figure 1a). However, the TAG is about 6K more negative in March than in September, with the Atlantic ITCZ about 10° further south in March (Figure 1b). Consistent with this difference in ITCZ latitude, in March, peak rainfall over tropical South America falls south of the equator (Figure 2a; red symbols lower in Figure 3a than in 3b), whereas in September (Figure 2c), peak rainfall is positioned to the extreme north of the continent (red symbols higher in Figure 4a than in 4b).

In December and June, on the other hand, TAG is similar in both months, with the ITCZ just north of the equator (Figure 1b), whereas the peak solar latitude is, of course, very different between these 2 months. Consistent with this difference in latitude of peak solar insolation, rainfall over South America is positioned much further north in June than in December (Figures 2b,d, 5a,b and 6a,b).

3.2 | Comparison of HadGEM3 control run with observations

Here, we compare precipitation patterns and the TAG seasonal cycle in the HadGEM3 control run, with observations. Differences can arise both from model errors, and from the fact that the control run is forced by pre-industrial conditions.

Over the ocean, HadGEM3 shows two main precipitation biases compared to GPCP (Figure 2a–l): a southward bias in the Atlantic ITCZ (Biasutti, Sobel and Kushnir, 2006; Richter *et al.*, 2014; Richter and Tokinaga, 2020) in all months (see titles of Figure 2a–h), and excessive precipitation over the Eastern equatorial Pacific, peaking in March (Figure 2i–l). A southward bias of the Atlantic ITCZ is typical in models (Biasutti, Sobel and Kushnir, 2006; Richter *et al.*, 2014; Richter and Tokinaga, 2020). This appears as a dipole pattern in the difference between model and observations (Figure 2i–l). Consistent with this, TAG shows a negative bias in all months (Figure 7a), but although the TAG bias is similar in all months (around 1K), the ITCZ latitude bias is largest in the first half of the year (Figure 7b). This is discussed in Section 3.5.

Over land east of 60W, in March, peak rainfall is too far south in the model (Figure 2a,e). Figure 3b,c shows rainfall averaged over the central and south-eastern rectangular regions marked on Figure 2, as a function of Atlantic ITCZ latitude. These show that the southward bias in peak rainfall over land can partly be attributed to the southward bias in the Atlantic ITCZ. In Figure 3, the southward Atlantic ITCZ bias is seen: the control run mean (red vertical line) lies to the left of the observed mean (black line). In some years of the control run, however, the model-simulated ITCZ latitude (red symbols) falls within the range of observed values (black symbols, mostly between 2.5°S and 2.5°N). For these years with realistic ITCZ latitude, in both Figures 3b and 3c, the model rainfall is similar to that observed (the clusters of red and black symbols overlap). In years when the model ITCZ is further south, outside the observed range (the red symbols to the left of the black symbols), rainfall over the continent also shifts further south (decreasing in Figure 3a,b and increasing in

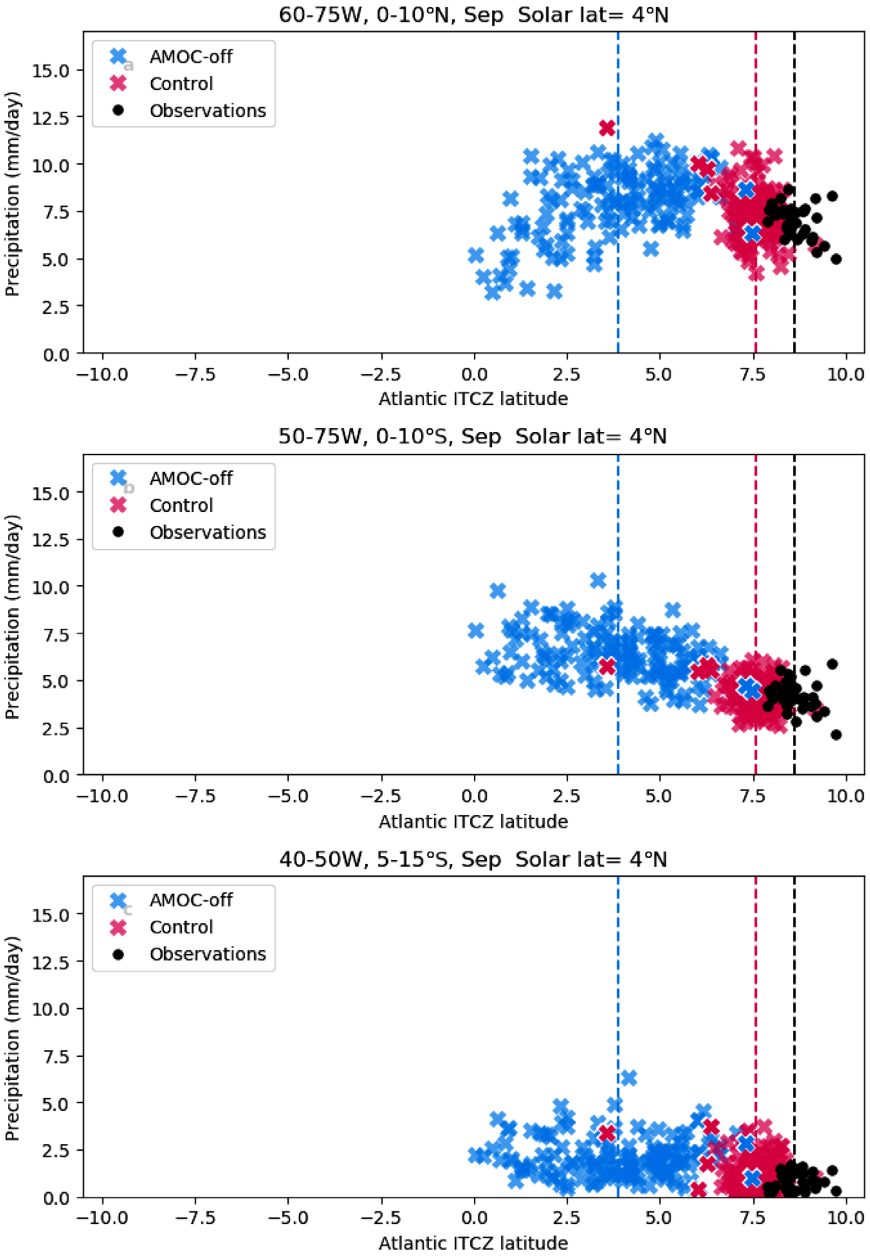


FIGURE 4 As Figure 3, but for September

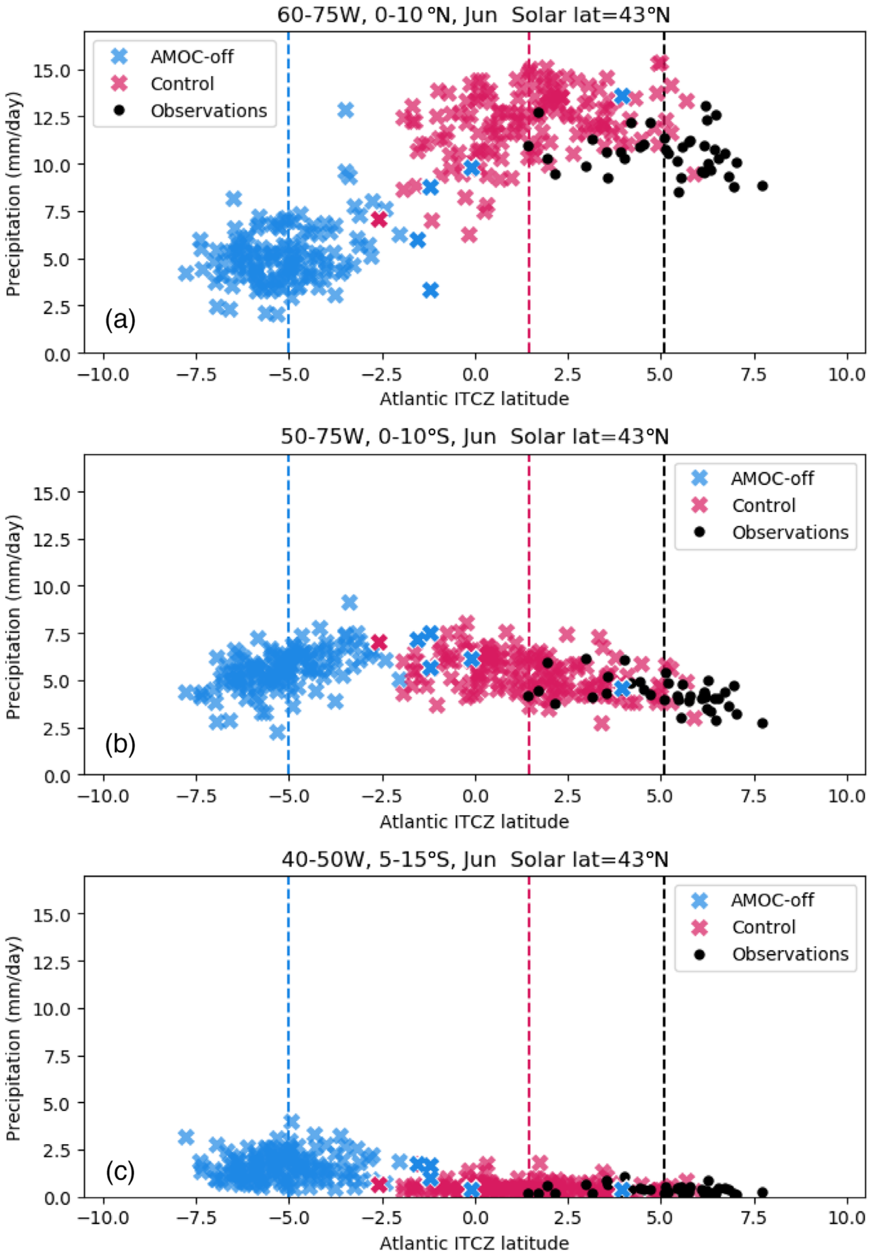
Figure 3c). This suggests that if the model had the correct climatological mean ITCZ latitude in March, rainfall in these land regions (Figure 3) would also be realistic.

In June, there is also some sign of a small rainfall excess in the central region (Figure 5b) associated with the southward ITCZ bias: in this month, southward movement of the ITCZ increases rainfall slightly in the central region.

Overall, Figures 3–6 show that the model performs well in simulating the spatial and seasonal variations in rainfall averaged over these three regions, for years when the Atlantic ITCZ latitude is realistic: in most panels of Figures 3–6, the red and black clusters of symbols overlap, suggesting that biases tend to be small compared to interannual variability.

There are some biases in rainfall that cannot be attributed to the Atlantic ITCZ bias. In June, in the northern region (Figure 5a), the model symbols cluster above the observations, suggesting a wet bias that cannot be fully explained by the ITCZ bias. In December, a dry bias is seen in the northern and central regions (Figure 6a,b). The model shows excessive precipitation near the Andes in all months (Figure 2i–l). This is a problem shared by most model-derived rainfall data sets for South America, including reanalysis products (Boers *et al*., 2015), probably due in part to difficulty resolving processes near orography. Also, the dry bias near the east coast in March (Figure 2i) cannot be fully explained by the ITCZ bias (not shown). This could be influenced by the excessive rainfall over the

FIGURE 5 As Figure 3, but for June



equatorial Pacific: the elevated precipitation that occurs over the equatorial Pacific during El Niño is known to cause drying in a similar part of tropical South America (Saravanan and Chang, 2000; Chiang, Kushnir and Giannini, 2002; Münnich and Neelin, 2005; Rodrigues *et al.*, 2011).

3.3 | Rainfall impacts of an AMOC collapse

In the AMOC-off experiment, the change in meridional SST gradient (TAG) is similar for each month: about 2–3K (Figure 1a, compare red and blue curves). The corresponding southward shift in the Atlantic ITCZ is more variable, ranging from 2.5° to 8°, suggesting that TAG is not the only factor affecting the magnitude of the ITCZ shift (Figure 1b). In both AMOC-off and control experiments, however, the seasonal cycles of ITCZ latitude and TAG are strongly correlated (Pearson correlation coefficient > 0.95 in both experiments), and the results from the two experiments overlap (Figure 1b).

Figure 2m–p shows that in all months, the rainfall response over the tropical Atlantic takes the form of a dipole, consistent with southward ITCZ shifts. This broad dipole character extends over tropical South America. However, as discussed in Section 1, the location and shape of this dipole are strongly seasonally dependent, following

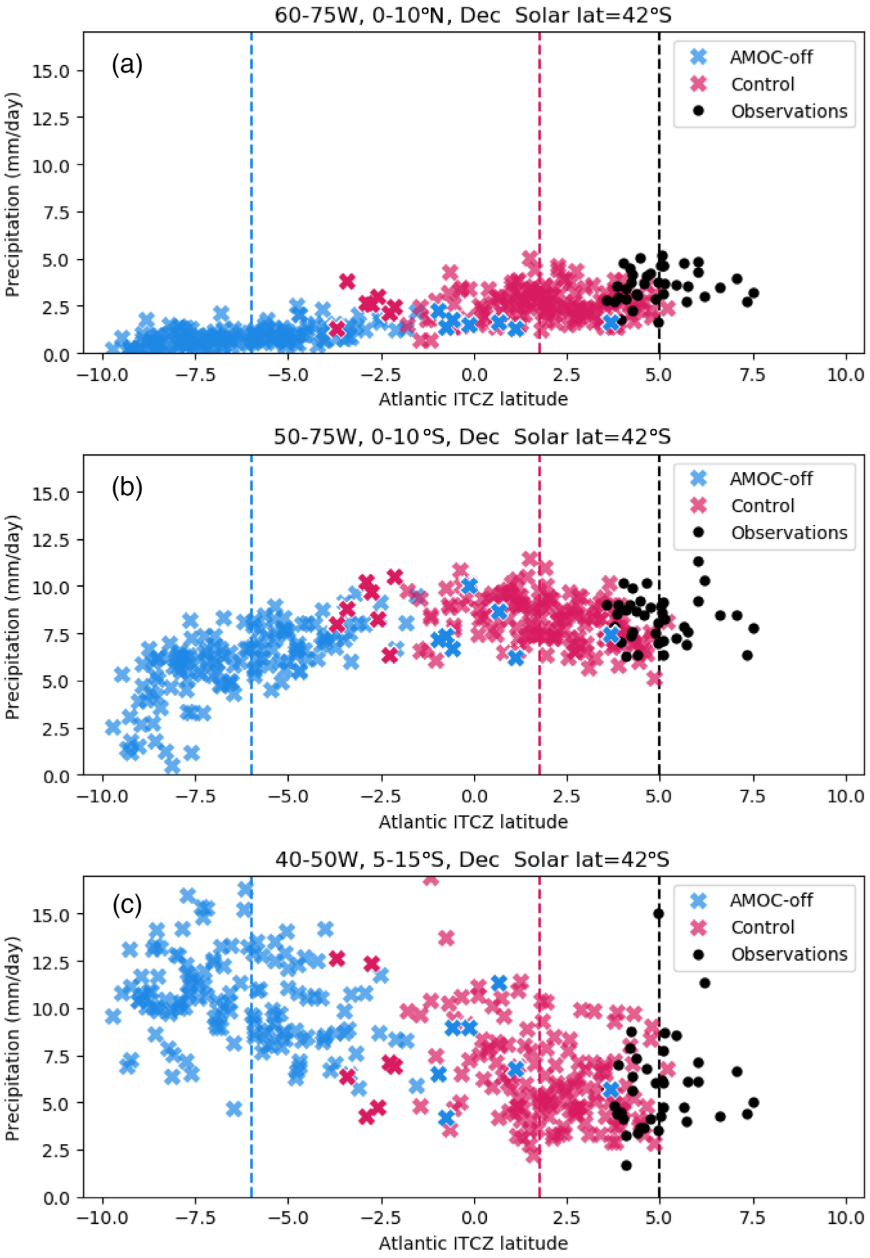


FIGURE 6 As Figure 3, but for December

the seasonal migration of peak rainfall in the control state.

The month of March shows a band of strong drying extending from the north-east through the south-western part of tropical South America (Figure 2m). Large areas see drying of over 5 mm/day. This is consistent with a southward shift of rainfall associated with the southward Atlantic ITCZ shift. In the control experiment in March, peak rainfall over the continent is located around 10°S (Figure 2a), so shifting rainfall even further south tends to cause drying over the northern and central regions (Figure 2m; in Figure 3a,b, rainfall declines as the ITCZ shifts south). The south-eastern region (Figure 3c) sees an increase (for ITCZ latitudes down to about 6°S) followed by a decrease, as the rainfall peak shifts through it.

In contrast, the opposite phase of the seasonal cycle, September, sees rainfall increases in the central region as the ITCZ shifts south (Figures 2o and 4b), with a small area of drying at the extreme north of the continent. In September, peak rainfall in the control is positioned at the north of the continent (Figure 2c), so southward shifts of this rainband cause rainfall increases in the central region (Figure 4b). Broadly, this picture is comparable with the results of Parsons et al. (2014), who found similarly large changes in the seasonal cycle, with rainfall increases and decreases at similar times of the year.

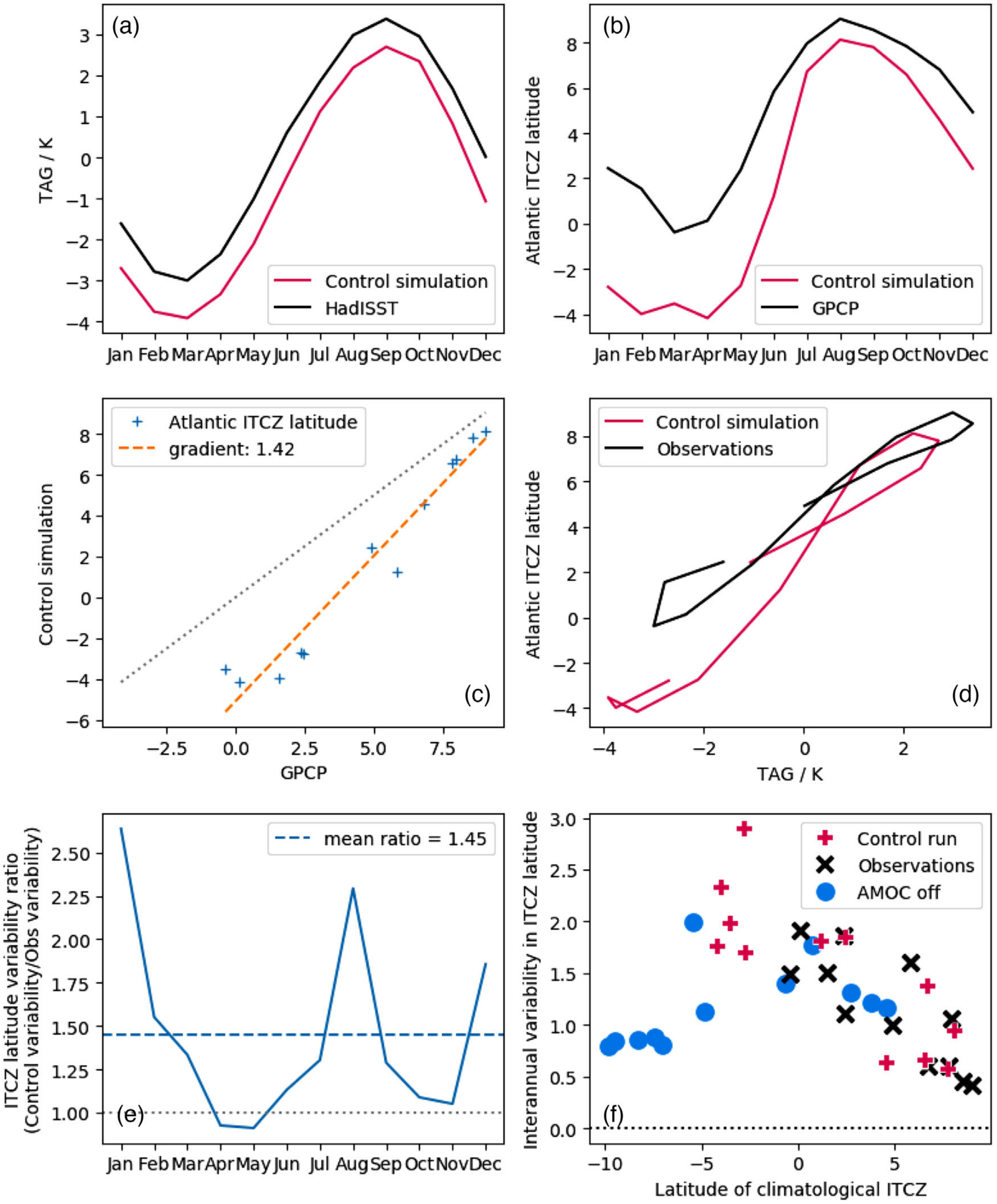


FIGURE 7 (a) Climatological mean seasonal cycle of TAG for the control (red) and HadISST observations (black). (b) As panel a, but for Atlantic ITCZ latitude. (c) Climatological Atlantic ITCZ latitude for each month in the control simulation plotted against the same for GPCP observations (each symbol represents one month). (d) as Figure 1b, but for control run and observations. (e) Inter-annual variability of ITCZ latitude in the control run for each month divided by the same from GPCP observations (inter-annual variability is calculated for each month as the standard deviation in ITCZ latitude for that month). (f) Inter-annual variability in ITCZ latitude for a given month plotted against climatological mean ITCZ latitude for the same month (each symbol represents 1 month for either control run, AMOC-off run or observations)

These results are consistent with the idea that rainfall changes simulated over tropical South America, as the AMOC weakens, are largely associated with a southward shift of the Atlantic ITCZ. This is clearest in Figures 3–6. In each panel of Figures 3–6, the results from the control and AMOC-off experiments both appear to fall on the same curved relationship between rainfall and ITCZ latitude. Years in the AMOC-off experiment (red) with a more northerly ITCZ overlap the results from the control experiment (blue), and vice versa. This also suggests that Atlantic

ITCZ shifts have roughly the same effect on rainfall over these regional scales, whether they arise from internal variability or from an AMOC weakening.

3.4 | Influence of Atlantic ITCZ bias on simulated impacts of an AMOC collapse

Section 3.2 showed that regional rainfall in the HadGEM3 control is reasonable for years with a realistic Atlantic ITCZ latitude, but the climatological southward bias in the Atlantic ITCZ (Figure 7b) affects the location of continental rainfall. Here, we discuss how this southward ITCZ bias might affect the simulated impacts of an AMOC weakening. This can happen because the relationships between precipitation and ITCZ latitude (Figures 3–6) are curved: the change in regional rainfall per degree of ITCZ latitude change varies, depending on the starting ITCZ latitude. The curvature can occur as a rainband shifts through a region: rainfall in the region starts low, increases as the rainband moves into the region and then decreases again as the rainband moves away.

In HadGEM3, the largest impacts of an AMOC shutdown on precipitation are seen in March (Figure 2m). In the central region (Figure 3b), precipitation declines sharply as the model ITCZ shifts by 4.5°, from about 3.5°S (the control climate mean, red vertical dashed line) to 8°S (the mean of the AMOC-off experiment, blue dashed line). The relationship between regional precipitation and ITCZ latitude (Figure 3b) is curved, however, as would be expected from a rainband shifting through a region. In the real world, the ITCZ is positioned further north, near the equator (Figure 3b, black dashed line). This corresponds to a flatter part of the curve. This means that if the control run had the Atlantic ITCZ correctly positioned near the equator, the same southward ITCZ shift (about 4.5°) would cause a smaller rainfall decline than that seen in the current model.

The model also simulates large drying in June in the northern region (Figures 2n and 5a). Again, the observed ITCZ latitude in June (Figure 5a, black line) is next to a flatter part of the curve than in the control run (red line). That is, if the control ITCZ was correctly positioned for June in this region, a southward ITCZ shift of a few degrees would cause less drying than that seen in the current model. Similar comments apply to the central region in December.

Some regions and months are less sensitive to the ITCZ bias, because their relationship between rainfall and ITCZ latitude is more linear. This includes the northern region in March (Figure 3a) and the central region in September (Figure 4b).

These results show that correct simulation of the historical ITCZ latitude is important to simulate the rainfall impacts of an AMOC shutdown. A key uncertainty remains, however: how far the Atlantic ITCZ would shift as the AMOC weakens. Some initial findings are presented in the next section.

3.5 | Biases in how far the Atlantic ITCZ shifts

The results above explored how rainfall over tropical South America responds to variation in Atlantic ITCZ latitude. Here, we provide some initial validation of the behaviour of the Atlantic ITCZ latitude itself.

The Atlantic ITCZ latitude shows greater seasonal variation in the HadGEM3 control (Figure 7b, red, varies from 4°S to 8°N) than in observations (black, varies from 0°N to 8.5°N), consistent with previous results with other models (Richter *et al.*, 2014). The climatological seasonal variation of the ITCZ latitude in the HadGEM3 control is about a factor of 1.4 too large (Figure 7c). This excessive shiftiness of the ITCZ cannot be attributed to excessive seasonal variation in TAG (although it could be linked to other SST variation): seasonal variation in TAG in the model is close to that observed, with almost the same bias in all months (Figure 7a). Correspondingly, the relationship between ITCZ latitude and TAG is steeper in the model than in observations (Figure 7d). Inter-annual variability in ITCZ latitude for each month is also larger in the model than observed, for most months (Figure 7e). The annual mean of the ratio between modelled and observed variability is 1.45 (Figure 7e), similar to the seasonal cycle ratio of 1.4 (Figure 7c). That is, in the current climate state, the Atlantic ITCZ in HadGEM3 tends to shift too far in both seasonal cycle and internal variability.

This raises the question as to whether the model-simulated Atlantic ITCZ also shifts too far in response to an AMOC shutdown. We first briefly explore why the ITCZ latitude is too variable in the model, then discuss whether this could apply to the size of ITCZ shifts as the AMOC weakens.

Figure 7f suggests that a combination of two factors may be causing the inter-annual variability in ITCZ latitude to be too high in the model (Figure 7e). First, inter-annual variability in ITCZ latitude tends to be larger for months when the mean ITCZ latitude is closer to the equator; and second, the mean ITCZ latitude is closer to the equator in the model than in the observations. The increase of variability nearer to the equator is seen in both the observations (Figure 7f, black symbols) and in the control run (red symbols). This could occur due to ocean-atmosphere feedbacks becoming stronger as the ITCZ approaches the equator (Richter *et al.*, 2014), or due to the behaviour of atmospheric circulation nearer the equator (Chao and Chen, 2004). The observed relationship between variability and mean state in Figure 7f is accurately reproduced by the model (the red and black clouds of symbols overlap). This suggests that if the model had the correct climatological mean ITCZ latitude for each month, it would also show realistic interannual variability in ITCZ latitude. That is, the southward bias in ITCZ latitude may cause the variability in ITCZ latitude to be too high.

In the AMOC-off experiment, the relationship between variability and mean state is the same as in the control run and observations, for months when the mean ITCZ is at or north of the equator (blue symbols overlap the red and black clusters, between about 0°N and 5°N). That is, the AMOC shutdown does not alter this relationship between ITCZ variability and mean state.

South of about 4°S, the relationship reverses: variability decreases as the mean ITCZ moves further south (Figure 7f). This suggests that south of the equator, a southward bias in mean ITCZ latitude could cause the ITCZ variability to be too low (the opposite of what happens north of the equator). Therefore, the excessive model ITCZ shifts seen in Figure 7b–e do not necessarily mean that the model overestimates ITCZ shifts under an AMOC shutdown (the opposite may be true for some months).

A different form of bias could occur because the AMOC overturning strength at 26N is slightly too weak in the model control experiment (around 14 Sv; Jackson *et al.*, 2015) compared to 16–19 Sv in observations (Smeed *et al.*, 2014, 2018). This could mean that a full AMOC shutdown in the real world may have the potential to cause a slightly larger southward shift in the Atlantic ITCZ than seen in the model.

4 | CONCLUSIONS

This work extends previous studies (Vellinga and Wood, 2002; Parsons *et al.*, 2014; Jackson *et al.*, 2015), with results from higher resolution model simulations (Jackson *et al.*, 2015), and a more detailed examination of the large seasonal variation in rainfall response to an AMOC weakening over tropical South America. The rainfall response in HadGEM3 is similar to that in Parsons et al. (2014), who found increases in vegetation carbon over much of the Amazon. The actual forest response could be hard to predict: the results of Parsons et al. (2014) show several months of the year with rainfall just above the dry season threshold when the AMOC shuts down (so a small additional rainfall decrease could cause extensive vegetation loss).

Our results also explore how observable model biases could translate to error in simulated rainfall changes under a weakening of the AMOC. For the HadGEM3 model, the most likely source of error appears to lie in the latitude of the Atlantic ITCZ. This includes both the unperturbed ITCZ latitude (a well-known bias in model simulations, e.g. Biasutti, Sobel and Kushnir, 2006; Richter *et al.*, 2014; Richter and Tokinaga, 2020), and how far the ITCZ latitude could change as the AMOC weakens.

The response of regional-scale rainfall over tropical South America to seasonal changes in ITCZ latitude and solar insolation appears to be reasonably well-simulated in HadGEM3. The performance of the model is generally better when only model years with realistic ITCZ latitude are compared with observations. This applies over the scale of the relatively large regions studied (Figure 2); localized biases may be seen over smaller spatial scales. The variation in the Atlantic ITCZ latitude during the seasonal cycle is over twice as large as the latitude change under an AMOC shutdown (Figure 1a). The fact that the model can capture the response to such large changes gives confidence in its ability to simulate the response to an AMOC shutdown, but only if the distance by which the Atlantic ITCZ would shift can be quantified.

The model-simulated response of rainfall over tropical South America to a given shift in the Atlantic ITCZ appears broadly similar in both inter-annual variability and in the response to an AMOC shutdown. This suggests that some of these results also apply to validation of seasonal forecasting methodologies. This also means that results like Figures 3–6 could be used to estimate regional rainfall for different latitudes of the Atlantic ITCZ, corresponding to partial weaking of the AMOC.

The southward bias in Atlantic ITCZ in the control run is expected to cause some bias in the estimated rainfall change under an AMOC shutdown. This is because the relationship between regional rainfall and the ITCZ location is nonlinear (Figures 3–6), as the effect of rainfall shifts depends on the unperturbed state (Levy *et al.*, 2013). An initial analysis suggests that this bias may cause an overestimation of the large drying signal in March and June, but has less effect on other parts of the year. This could be important in determining the net response of the Amazon rainforest (e.g. Parsons *et al.*, 2014) under an AMOC weakening.

Although it is well-known that the ITCZ tends to shift too far in models during the seasonal cycle (e.g. Richter *et al.*, 2014), biases in inter-annual variability of the ITCZ latitude (Figure 7e,f) have not, as far as the authors are aware, been reported before, although potentially relevant feedbacks have been discussed (e.g. Richter *et al.*, 2014). The bias in variability may be a further consequence of the climatological mean southward bias in ITCZ latitude. This is because variability in ITCZ latitude depends on the mean ITCZ latitude, in a similar way in both the model and in observations (Figure 7f).

These results again highlight the potential importance of correctly simulating the unperturbed mean latitude of the Atlantic ITCZ. This also suggests a further research priority: to understand what affects the interannual variability of the Atlantic ITCZ latitude (Figure 7f), and how this behaviour may relate to how far the ITCZ could shift under an AMOC shutdown.

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