

## 1 Overall Response

We would like to thank both Pascale (as the Editor) and the reviewer for their comments on our work. We believe that we have taken them onboard and hopefully the manuscript is more appealing for other reviewers and readers to look at now. We itemize below our thoughts and any edits made in response to the individual comments.

The major changes implemented for this revised version of the manuscript are:

- We have adopted a different definition of the AMM. This was motivated, so that the manuscript conforms with the most recent release of the CVDP software.
- Relationship of modes with rainfall brought earlier in the text when the patterns related to the AMM and ATL3 modes are compared to observations/reanalysis (added new Figure 4).
- Reference to other basins substantially down-weighted in the text, focus only on the Atlantic ocean region.
- Figures were redone:
  1. adjusted to show just the focus of the paper, the Atlantic ocean region.
  2. preindustrial control results were added to Figures 1,2 and 3
  3. new Figure 4 with historical rainfall patterns associated with the ATL3 and AMM modes.
  4. Figures 6,8 and 10 have changes in the precipitation response as well as contour lines showing PI-control patterns.
- Results were recalculated in order to consider just the subset of models that submitted consistent results across all experiments.

## 2 Editor Comments on the manuscript.

The subject is quite ambitious and timely, and the methodology used to discuss the two major Atlantic modes seems appropriate. As far as I know this has not been done yet, and providing systematic diagnoses to assess how the modes of variability are affected by climate change is a valuable task. In its present form however the paper is too descriptive and key aspects on precipitation are lacking. In particular :

- The introduction and first section highlight the fact that AMM and Atl3 modes have fundamental impact on South American and African monsoon, but this linkage is not discussed any further when considering the different climates. This limits the interest of the manuscript and is a major concern.

**We have increased the discussion of the precipitation consequences dramatically and brought this earlier in the text. This is most visible through the inclusion of precipitation patterns in many of the figures. We hope that by stressing that the tropical modes of variability define the SST anomalies that ultimately control ITCZ-related precipitation**

- The discussion on physical and dynamical mechanisms should be enlarged. This concerns both the anomalous circulations associated with the SST modes and the changes in these circulations associated with changes in mode patterns in the different climates

**We have attempted to increase discussion around the physical and dynamical mechanisms. We have created a new section of the manuscript specifically focused on this topic.**

- One of the difficulties with the analyses of paleoclimate simulations is that both the background climate mean state and the variability change. How the pattern of the changes in variability is connected with patterns of the changes in the mean state should be discussed in more depth. A question out of this is does mode patterns only follow the mean state patterns? In other words if there is shift in the mode pattern is it directly reflecting a shift in the mean state pattern or is there other feedback that could explain that new areas become affected by the mode?

**The spatial patterns associated with each of the Tropical modes are very robust and closely related to the SST anomalies. Mode shifts actually reflect changes in intensity/amplitude rather than changes in spatial distribution. Figures 13 and 14 quantify the strength of the modes as a function of the SST distribution showing that for the AMM there is clear distinction between the climatic periods. The LGM and Mid-Holocene show opposite behavior. In the LGM there is an increase in the AMM amplitude while the North-South SST gradient decreases while for the Mid-Holocene there is an increase in the North-South SST gradient accompanied by a decrease in the amplitude of the AMM. The behavior of the AMM for the 1pctCO2 shows an overall weakening of the AMM mode with a decrease in both the AMM amplitude and the associated North-South SST gradient. For the ATL3, the relationship between the amplitude and east-West SST gradient for each climatic period is not as clear cut. In other words, changes in the variability of the AMM mode appear directly related to changes in the mean state. However for the ATL3, the relationship is not that linear**

- The outline of the paper is also a little bit boring. This feeling is due to the fact that the discussion section could include additional analyses to explain

when possible part of the rationale behind model responses (which may be different from one period to the other). The discussion section could thus be enlarged and have a more appealing title and content. It could compare relationships as it is done as well as mechanisms.

**We have introduced another section "TAV amplitude changes as a function of the SST gradient" for the relationship between changes in the AMM and ATL3 relative to changes in the meridional and zonal gradients, respectively. Furthermore, Discussions and Conclusion section were merged**

A few questions when reading the manuscript:

- It is interesting to see that the AMM mode is reduced at mid Holocene. Is it because the seasonal cycle is stronger and that a dipole-like pattern emerges in summer when comparing mid-Holocene with PI?

**We believe that the AMM mode is reduced because the MH is cooler in the Tropical Atlantic compared to PI, even though the seasonal cycle is stronger.**

- Is there a reason why a colder climate would have increased variability?

**We do not think *a priori* that cooling should lead to increased variability. The IPCC suggests that monsoon region variability should increase with temperature (Christensen et al., 2013). Yet Rehfeld et al. (2018) have just shown (similar to our findings here) that variability was substantially higher at the LGM. They suggest this is because of stronger meridional temperature gradients, but we don't find particular evidence for that for the AMM.**

- Could the non-symmetrical differences between LGM and future results from non-symmetrical responses in mean change in Hadley & Walker circulations between these two climates (related for the Hadley circulation to a dynamical or cooling effect induced by the ice-sheet)?

**Yes, they could. The impact of different climates on the Hadley Circulation in the Tropical Atlantic is subject of ongoing research. For example, Jones et al. (2018) show that the Walker circulation responds to thresholds in ice-sheet volume during the deglaciation - causing remote changes in ENSO teleconnections.**

## 2.1 Other comments

- Please, provide error bars on the different bar plots

**We investigated the practicality of providing error bars on these plots. For some models, they could have been readily computed by subsetting the long preindustrial control simulations, but this cannot be done for all models. We have therefore decided to leave off all the models to maintain consistency.**

- Table 1 mentions past1000 simulations, but they are not used in the text.

**Table 1 has been modified to reflect only the simulations used in this study**

- Make sure the color scales are identical for all the plots with the differences. Some of the values are so small that they should not be plotted.

**The color scales have been standardised and small changes removed.**

- Would there be an interest to also show separately the results for models for which the difference is an increase in the index and the models for which it is a decrease? which would require that statistical significance is defined to tell for which models it is different from 0.

**We feel that the manuscript is already long enough. So we would prefer not to include additional figures showing this decomposition. Figures 13 and 14 show the individual standard deviations for the AMM and ATL3 modes for each model. The patterns for all individual models are available online.**

- For the maps of differences you could add isolines showing the pattern for PI to better highlight where the changes are located compared to the reference.

**Isolines have now been incorporated into every plot where relevant.**

- Section 2 should be more informative. Details would be welcome to make sure we understand well how exactly the anomalies are computed for each of the periods, how the regressions are computed to provide the ensemble mean map, and also for each model what is the level of significance for the regression and should non-significant values excluded (or set to 0) when computing the ensemble mean map?

**Efforts were made to better detail the methodology employed.**

- The estimates of the changes in variability are done using the ensemble mean value. Since the sampling is limited given the size of the model ensemble would it make any difference to consider the median valued?

We feel that explicitly providing a mean is the standard practice - the changes for each ensemble member are shown in the bar-charts in both absolute and percentage terms, so the full distribution is there for readers who wish to see that.

- In section 3 tell why the observations look so noisy in figure 2.

This is a feature of the 20<sup>th</sup> Century reanalysis precipitation. It likely occurs as a spectral echo from the sharp topography in the region. We have decided to shift to using the GPCP rainfall product for this particular plot. The subsequent plots still use the 20<sup>th</sup> Century reanalysis, because we feel that the long, consistent nature of this dataset should be better at capturing variability.

- In section 3.1 PI-control should also be considered with historical to show the differences between this two close periods and discuss the limited length of the simulations.

PI-control panels were added to Figures 1-3 in section 3. We had previously assumed that including these would be detrimental to the length of the manuscript. As both reviews request this information, we were wrong in this assumption.

- Some of the Pi Control experiments are long enough to be subsampled for an uncertainty analysis.

Uncertainty analysis for individual PI-control simulations for each of the models is interesting in itself, but we believe it is not essential for the understanding of the ensemble mean changes approached here.

- Make sure the modes are discussed in the same order in all sections and figures.

In the revised manuscript, ATL3 is discussed first followed by the AMM

- Even though the modes are extracted using an index and not EOF you could compute and provide the percentage of variance they represent. Previous studies Jolly et al. 2007 or Zhao et al. 2008 suggested that ENSO dominate variability in most models and thereby the teleconnection with the African monsoon, which is not the case in the observations. Is it valid here?

We have decided to focus the study just on the tropical Atlantic modes of variability excluding teleconnections from the Pacific (i.e. ENSO). A new Figure (Figure 4) was added to show the relationship

of the ATL3 and AMM modes with PPT. This is done through the regression of the respective indices onto the PPT fields. We choose to show these as absolute rainfall variations, rather than percentages, for consistency. However, we acknowledge that this approach can over-emphasize their importance.

- P12 1230. The sentence is incorrect. Pausata et al. 2017 didnt simulate vegetation better they impose a mid-Holocene extreme reconstruction of the vegetation cover. So it should read something like when imposing mid Holocene vegetation reconstruction as boundary condition to the model.

This sentence was changed to “It has been shown that when imposing mid Holocene vegetation reconstruction as boundary condition to the model, inter-annual climate variability can be impacted”.

### 3 Referee 1

This work investigated the change in the leading modes of the Tropical Atlantic Variability, the Atlantic Meridional Mode (AMM) and the Atlantic Nio (ATL3), in different climate scenarios: the historical, the last glacial maximum, the mid-holocene and future simulations in the multi-model ensemble of the PMIP3/CMIP5. Authors used this set of experiments in order to find robust signal of change in the Tropical Atlantic Variability. They found that all models across all experiments are able to represent main characteristics of dominant modes of variability in the Tropical Atlantic in spite of the mean state bias.

The paper addressed a relevant question: how the Tropical Atlantic Variability change under different climates and how the information from mean state and past climates can be used as a constraint for the future. They quantified first the mean state model bias of the tropical temperature and precipitation in the historical simulations against reanalyses. After that, they compared the magnitude of the simulated change of the tropical temperature and precipitation in the mid-holocene, the lgn and the future climate with the mean state bias, concluding that the simulated changes are reasonably represented in these experiments. Hence, the main conclusion is that ATL3 and AMM are well represented among models and experiments considered, although authors found weak correlation with change in temperature gradients, so it is not possible to identify emerging constraints for future projections from this analysis.

- I think this is a good work but sometimes the storyline is hard to follow: I suggest to work more on the structure of the paper and on discussion and conclusions in order to clarify main findings (perhaps merging both sections would be helpful).

**This suggestion is echoed by the editor. We added a new section and "Discussions" and "Conclusions" were merged.**

- About the method, I think that conclusions hold only if same models among experiments are considered, otherwise results might be affected by different model physics and also by the different number of the model used for each experiment (see my comments below).

**We believe this is an overly conservative position. Nonetheless, results have been recomputed with just the subset of models that submitted simulations for all climate periods. These subset figures are appended at the end of this response for your perusal.**

- Furthermore, several typos in the captions (see specific comments below) made the paper difficult to read.

**We have addressed all typos**

- Some recent and important literature is also missing (see the list below).

**We have included all references suggested except Egerer et al. (2016) on dust because the sentence was rephrased (following comment from Reviewer 2 that better vegetation was not a result of simulation but of boundary condition used)**

### **3.1 Minor Comments**

There are some typos in the text. Here, it is a list:

- Ln 39: It is associated with a shift ...". It is not clear what is the subject of the sentence.

**the sentence was re-written as "The AMM is associated with a shift ..."**

- Ln 63: a full stop is missing after the brackets "(c.f. the AMM).

**full stop was added**

- Figure 1: the caption mentioned HadISST for panels a and b, but 20C\_reanalysis is written on the top of both panels.

**Labels on figures corrected**

- Figure 2: replace in precipitation with of the precipitation in the caption.

**replaced**

- Ln 203: You specified already the acronym TAV for Tropical Atlantic Variability in the very beginning of the paper. You can use it throughout the paper.

**We have now used the acronym TAV instead of "Tropical Atlantic Variability" when found throughout the text.**

- Figure 3: Typos in the caption. ATL3 is shown in panel a and c. AMM in panel b and d. In the upper panels observation results and in the lower panels simulation results are shown. Also the standard deviations must be reorder: 0.17 refers to panel a, 0.18 to panel b, 0.05 to panel b and 0.04 to panel d.

**The labels on the figures have now been corrected.**

- Figure 6, 8, 10: It is better to change the color of dark gray bars in light gray bars. You could also replace the letters associated to each model, with a number or a short name.

**We have changed the color from dark gray to light gray**

- Ln 280: repetition: ... is expected to be still be..."

**corrected the sentence**

## **4 Major Comments**

- Ln 36: ...strength of the ITCZ. What do you mean for strength of the ITCZ. Usually, the ITCZ is the latitude of the wind convergence, and or, the latitude of the maximum of the precipitation. Please clarify.

**We have revised in the text to reflect the intensity of the ITCZ-related PPT.**

- Ln 40-42: Add literature about the ITCZ. (e.g. Schneider et al., 2014, Bischoff, T., & Schneider, T. , 2016, Green, B., & Marshall, J., 2017).

**Discussion of this relevant literature on the ITCZ was added.**

- Ln 63: cite Schneider et al., 2014.

**This review paper on the migration/dynamics of ITCZ is cited.**

- Ln 68: You might want to cite also D'Agostino et al., 2017. They linked Hadley Circulation changes also to change of the meridional temperature gradient and interhemispheric thermal contrast.

**D'Agostino et al., 2017 is cited**

- Ln 166-168: What do you mean for: models are unable to get the full intensity of the ITCZ? I would like to clarify again that the ITCZ is a latitude of the maximum of the tropical precipitation not the rainfall intensity itself. Please reword, otherwise add specific analysis on the ITCZ shift, including also how to define the ITCZ in the methods.

**The reviewer is correct. The phrase was reworded. What was meant is that models are unable to realistically represent the distribution of the ITCZ-related rainfall.**

- Ln 335-340: these statements about the ITCZ are not supported by the analysis shown in the paper. How did you quantify the ITCZ shift? Please include further analysis

**We agree that the ITCZ position shift was not quantified, and was sloppy language on our behalf. The change or displacement of rainfall mentioned is in reference to the Tropical Atlantic ITCZ-related precipitation, this was changed in the text.**

- Ln 225, the Mid-Holocene section: the Tropical Atlantic is elsewhere cooler than Pre-Industrial and this is pretty consistent among models. I was wondering if you believe to this result if the magnitude of the change is weaker than the change in the mean state.

**Yes, this cooling is also noted in other studies that evaluate PMIP data such as Braconnot et al. (2007) and Zhao et al. (2005).**

- Figure 4: I have a question about these panels. How did you perform the difference between the multimodel ensemble mean for each experiment and the multimodel ensemble mean of the Pre-industrial condition? You must use different pre-industrial multimodel ensemble mean for each experiments, because you must account for different model list. I did not find any specification about it in the paper.

We have now increased the explanation of the methodology. We had performed the average of the change in pattern (rather than the change in the ensemble mean patterns). This is the ensemble averaging approach adopted by the IPCC. Whilst this does mean that there is some differences in the pre-industrial multimodel means there are relatively small (you can see their impact through the new isolines added on the figures).

- Furthermore, I have some doubt: I don't think the mean state bias can be used to give credibility to results of the different experiments in this context, because the ensemble mean of the historical experiment accounts for 14 models. The ensemble mean of the pre-industrial for 21. They tell different story then. The difference is much more evident if you compute different pre-industrial ensemble mean for each experiment! Therefore, when you compare the climate change with the mean state bias, you are wrong because the different model list. I suggest to restrict the model list to common models only for all experiments. Unfortunately, the list is very short (only 9 models) but I think that is still possible to reach robust conclusions.

We have added the preindustrial control ensemble mean to Figs 1 to 4. The analysis has been repeated with just the subset of models consistent across all experiments. The versions of these figures are included at the end of this response.

- Ln 235: add also dust and cite Erger et al., 2016.

This has not included, because the sentence was rephrased following comment from Reviewer 2.

- Ln 316: please quantify a little relationship.

”little relationship” was substituted for ”no apparent relationship emerging”

- Ln 330: please quantify again little robust relationship. The text was re-written as: ”A decrease in the AMM amplitude change can be associated with an increase in the meridional SST gradient for the mid-Holocene while the opposite occurs for the 1% per year until quadrupled CO<sub>2</sub> (1pctCO2). The relationship at LGM is more dubious relative to the changes in SST-gradient but suggests an increase in the AMM amplitude. Overall, the relationship between the amplitude change of the AMM and the changes in the meridional SST-gradient depends on the climatic period considered.”

## References

- Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, T., Hewitt, C., et al.: Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum—Part 2: feedbacks with emphasis on the location of the ITCZ and mid-and high latitudes heat budget, *Climate of the Past*, 3, 279–296, 2007.
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- Jones, T. R., Roberts, W. H., Steig, E. J., Cuffey, K., Markle, B., and White, J.: Southern Hemisphere climate variability forced by Northern Hemisphere ice-sheet topography, *Nature*, 554, 351, 2018.
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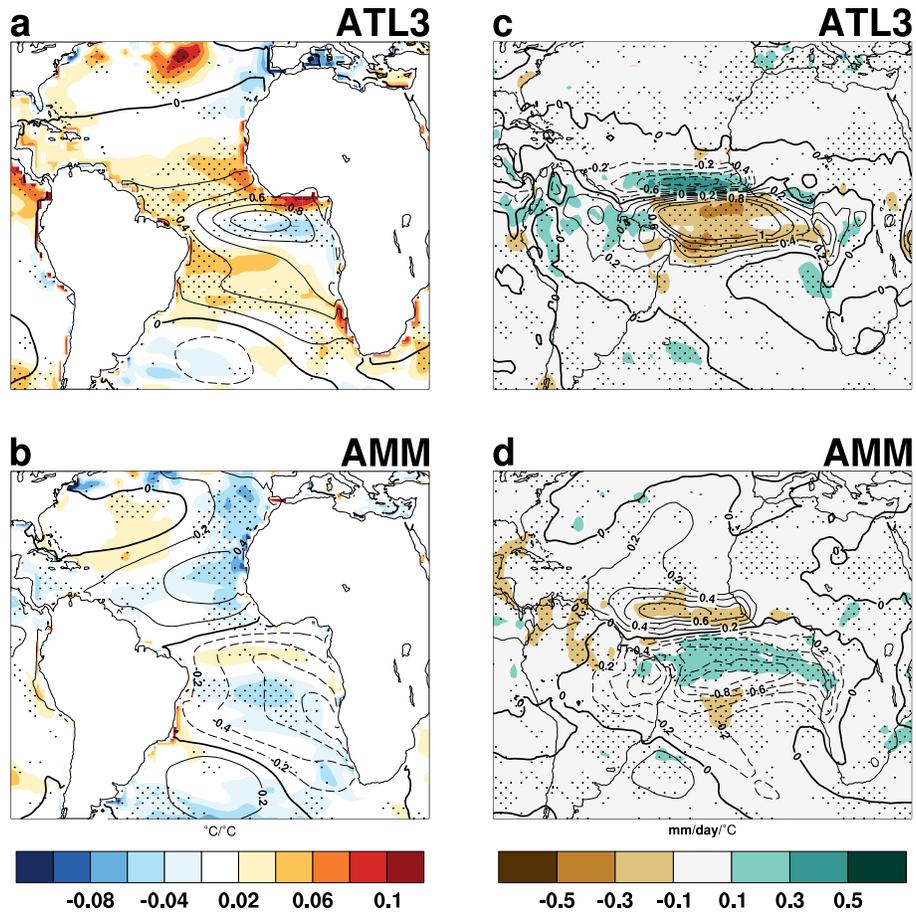


Figure 1: Alternate version of Fig. 8, using only the self-consistent set of models. Mid-Holocene changes relative to preindustrial in the temperature patterns related to (a) the ATL3, (b) AMM indices. The changes are stippled with greater than two-thirds of the ensemble shows the same direction as the ensemble mean change. The contours show the change in regression strength onto the index in question; i.e. the change in local expression of +1 degC index

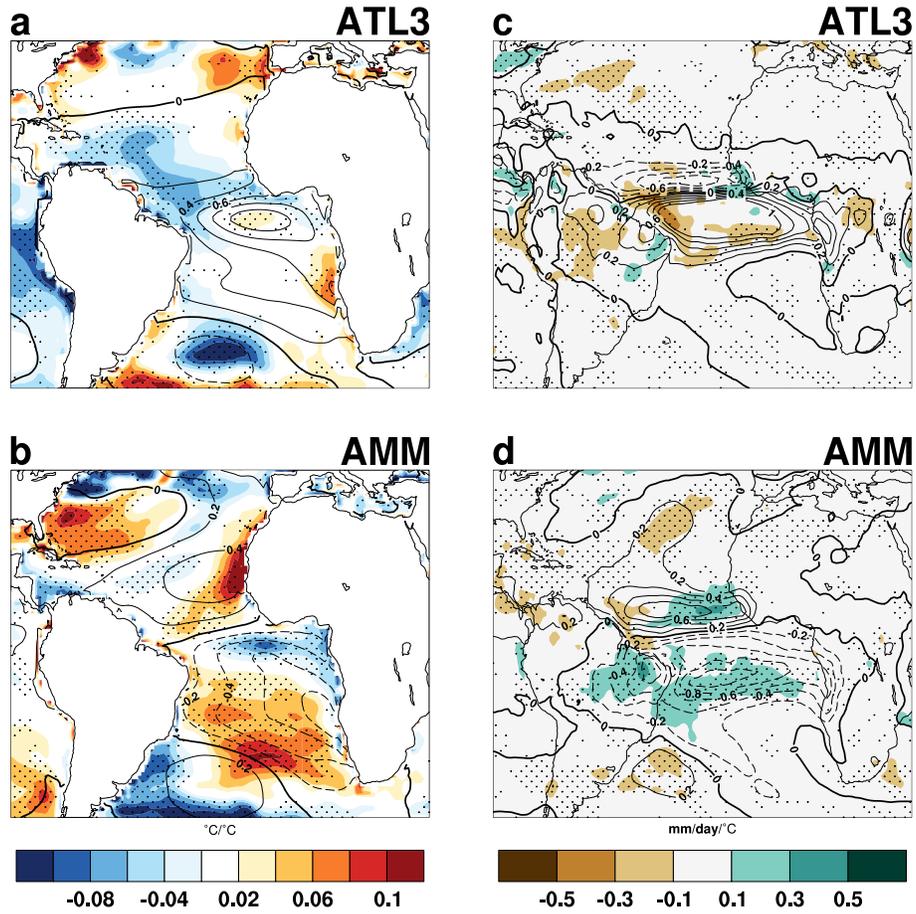


Figure 2: Alternate version of Fig. 10, using only the self-consistent set of models. LGM changes relative to preindustrial in the temperature patterns related to (a) the ATL3, (b) AMM indices. The changes are stippled with greater than two-thirds of the ensemble shows the same direction as the ensemble mean change. The contours show the change in regression strength onto the index in question; i.e. the change in local expression of +1 degC index

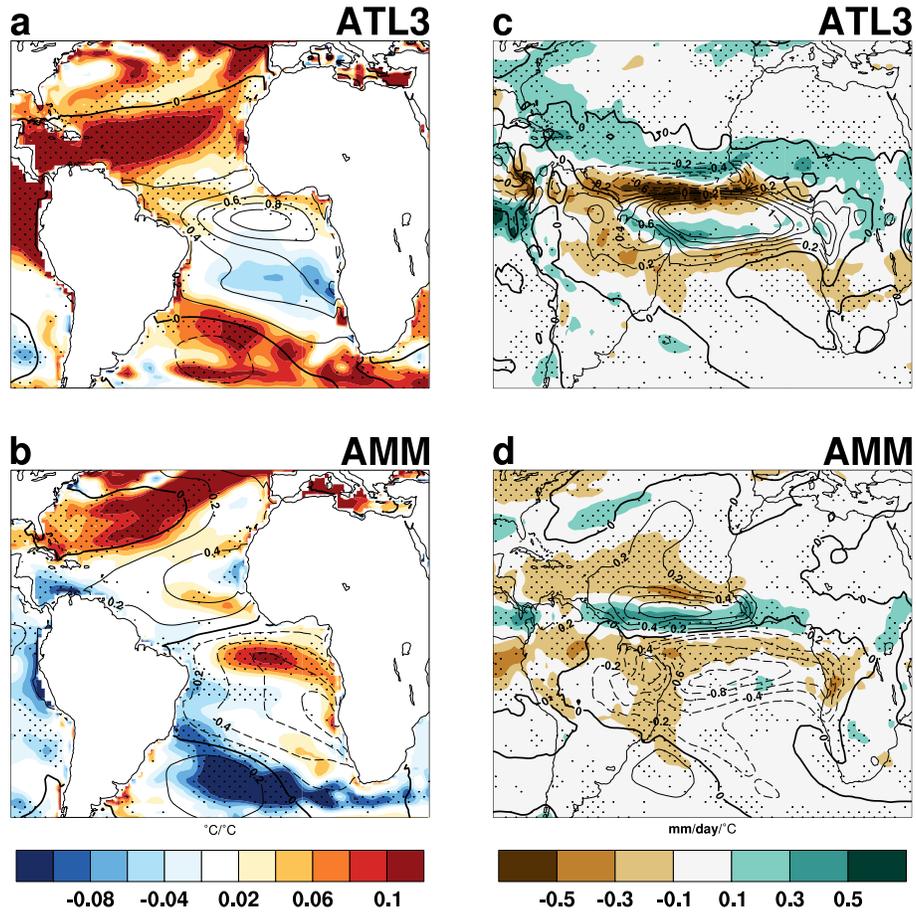


Figure 3: Alternate version of Fig. 12, using only the self-consistent set of models. Future changes relative to preindustrial in the temperature patterns related to (a) the ATL3, (b) AMM indices. The changes are stippled with greater than two-thirds of the ensemble shows the same direction as the ensemble mean change. The contours show the change in regression strength onto the index in question; i.e. the change in local expression of +1 degC index

# Interannual Variability in the Tropical Atlantic from the Last Glacial Maximum into Future Climate Projections simulated by CMIP5/PMIP3.

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## Abstract.

Tropical Atlantic Variability (TAV) plays an important role in driving year-to-year changes in rainfall over Africa and South America. In this study, its response to global climate change is investigated through a series of multi-model experiments. We explore the leading modes of TAV during the historical, last glacial maximum, mid-Holocene and future simulations in the multi-model ensemble known as PMIP3/CMIP5. Despite their known sea surface temperature biases, most of the models are able to capture the Tropical Atlantic's two leading modes of SST-variability patterns - the Atlantic Meridional Mode (AMM) and the Atlantic zonal mode (also called the Atlantic Niño or ATL3). The ensemble suggests that AMM amplitude was less during the mid-Holocene and increased during the last glacial maximum; but is equivocal about future changes. ATL3 appears stronger under both the last glacial maximum and future climate changes, with ~~little~~ no consistent message about the mid-Holocene. The patterns and the regions under the influence of the two modes ~~alters~~ alter a little under climate change - in concert with changes in the mean climate state. ~~Both modes demonstrate a coupling with the equatorial Pacific that depends on the climate period being considered - especially for the ATL3 mode of equatorial Pacific.~~ In the future climate experiment, the equatorial mode weakens, the whole northern hemisphere warms up while the south Atlantic displays an hemisphere-wide weak oscillating pattern. For the LGM, the AMM projects onto a pattern that resembles the Pan-Atlantic Decadal Oscillation. No robust relationships between the amplitude of the zonal and meridional temperature gradients and their respective variability was found.

## 1 Introduction

### 1.1 Tropical Atlantic variability and its importance

Variability in the Tropical Atlantic Ocean occurs at different time scales ranging from seasonal, interannual to decadal and longer (Xie and Carton, 2004; Chang et al., 2006; Wainer et al., 2008; Deser et al., 2010; Muñoz et al., 2012). The dominant frequency for this region is the seasonal cycle, which combined with continental monsoon forcing and air-sea interaction,

regulates the latitudinal displacement of the rain producing Inter-Tropical Convergence Zone (ITCZ). The marine portion of the ITCZ, in its turn, is locked to the Atlantic's sea surface temperature (SST). In the Tropical Atlantic, changes in SST are in phase with the meridional displacement of the ITCZ and associated meridional wind stress (Wainer and Soares, 1997). SST departures from the seasonal cycle are primarily driven by changes in surface winds that result from local air-sea interaction associated with the latitudinal migration of the ITCZ, or remotely forced by external factors (e.g. variability associated with ENSO). There is also significant interannual variability in the Tropical Atlantic that is represented by its two leading SST modes.

~~The first mode is a meridional mode characterized by a north-south inter-hemispheric SST gradient (Atlantic Meridional Mode, hereafter referred to as - AMM), which significantly impacts changes in the position and strength of the ITCZ. Studies have linked this mode to changes in the surface winds and associated evaporation feedbacks (Xie and Carton, 2004; Mahajan et al., 2010; A. These feedbacks are important in defining the spatial and temporal features of the AMM and its impact on rainfall. It is associated with a shift in the distribution of precipitation towards the hemisphere with anomalously warm SST (relative to the other). The inter-hemispheric SST gradient is accompanied by a cross-equatorial atmospheric flow in the same direction (Chiang et al., 2002; Saravanan and Chang, 2004; Xie and Carton, 2004).~~

~~The second mode of Tropical Atlantic Variability is a~~ most well-known mode of TAV is a zonal mode (ATL3; Zebiak, 1993) that is governed by equatorial ocean dynamics in response to surface winds; much like ENSO in the Pacific. It involves changes in the Atlantic equatorial cold tongue and associated displacement of the equatorial thermocline. Although this mode has a weaker impact on the meridional displacement of the ITCZ, it can nonetheless impact South America precipitation (Tokinaga and Xie, 2011). The positive phase of this equatorial mode presents positive SST anomalies in the eastern part of the basin and is associated with increased precipitation over Northeast Brazil and the western Amazon. The negative phase is associated with weakening of the African monsoon.

The leading mode is a meridional mode characterized by a north-south inter-hemispheric SST gradient (Atlantic Meridional Mode, hereafter referred to as - AMM), which significantly impacts changes in the position and intensity of the ITCZ-related rainfall. The inter hemispheric SST-gradient is accompanied by a cross-equatorial atmospheric flow in the same direction (Chiang et al., 2002; Saravanan and Chang, 2004; Xie and Carton, 2004). Furthermore, the AMM mode has been linked to changes in surface winds and associated evaporation feedbacks (Xie and Carton, 2004; Mahajan et al., 2010; Amaya et al., 2016). These feedbacks are important in defining the spatial and temporal features of the AMM and its impact on rainfall. The AMM is associated with a shift in the distribution of ITCZ-related precipitation towards the hemisphere with anomalously warm SST (relative to the other). In other words, the ITCZ tends to follows the warmest hemisphere (Green and Marshall, 2017; Bischoff and Schneider et al. (2014) presents a comprehensive review of the dynamics of the ITCZ and associated meridional shifts.

In both modes, the coupling between SST and the ITCZ is an important driver of rainfall variability both for North-Northeast Brazil and for the Sahel region in Africa. It is regulated by the combined changes in intensity and meridional displacement of the ITCZ driven by the underlying SST gradient associated with a surface wind response (Ruiz-Barradas et al., 2000; Servain et al., 2000; Okumura and Xie, 2004). The reader is referred to Xie and Carton (2004) for a detailed review of the patterns, mechanisms and impacts of ~~Tropical Atlantic Variability-~~ TAV.

## 1.2 What do we know about TAV in past climates?

Several studies of past climates have attempted to understand predominant characteristics of the Last Glacial Maximum (LGM) and mid-Holocene relative to preindustrial controls (PI) (e.g. [Pinot et al. \(1999\)](#); [Wainer et al. \(2005\)](#); [Braconnot et al. \(2007\)](#); [McGee et al. \(2014\)](#); [Pinot et al. \(1999\)](#); [Wainer et al. \(2005\)](#); [Braconnot et al. \(2007\)](#); [McGee et al. \(2014\)](#); [Donohoe et al. \(2013\)](#); [Schneider et al. \(2014\)](#) among others). A common thread among these studies is the idea that in response to the changes in meridional SST-gradient, the mean position of the ITCZ shifts to the hemisphere with warmer temperatures (c.f. the AMM). It is known that during the LGM, the tropics cooled less than extra-tropical latitudes (e.g. Pinot et al., 1999; Braconnot et al., 2007; Wainer et al., 2005). Braconnot et al. (2007) examine and quantify changes in the north-south location of the ITCZ from simulation results from PMIP2 for the Last Glacial Maximum (LGM) and the Mid-Holocene (MH). They establish that changes in the associated meridional SST-gradient in the tropical Atlantic during summer at the MH are in phase with changes in precipitation over West Africa. [D'Agostino et al. \(2017\) linked changes in the meridional SST-gradient with changes in the Hadley circulation and north-south thermal contrast.](#) Wainer et al. (2005) discuss that for the LGM, the marine portion of the ITCZ does not reach the South American continent during DJF contributing to weakened precipitation. McGee et al. (2014) find that for the LGM and mid-Holocene the latitudinal shift in the mean ITCZ is less than 1° latitude. They discuss how the position of the ITCZ is associated with the heat transport between the hemispheres. An important conclusion of their work (also noted by Donohoe et al., 2013) is that tropical SST gradients for past climates can be reconstructed with greater certainty than the ITCZ position, which means that understanding the fluctuations of the anomalous SST variability patterns allows the assessment of past changes in ITCZ position and related rainfall patterns.

Considering the significant impact that ~~Tropical Atlantic Variability (TAV)~~ TAV has on the ~~the~~ positioning of the ITCZ and the distribution of rainfall of the adjacent continental regions, and given that it has been changing with global climate change, we seek to characterize the SST-modes of TAV for different climates. The idea is to identify, if any, changes in TAV for past climates and understand its behavior in future projections using simulations from complex climate models. The present study has the goal to examine the performance of Earth System Models relative to the simulation of TAV in terms of SST for different climates, in the context of the Palaeoclimate Model Intercomparison Project (PMIP). Hopefully by understanding the link between the modes of variability of the Tropical Atlantic for different climates, we can improve our understanding of related monsoon-dynamics and mechanisms in the region.

## 2 Methods

### 2.1 Model simulations

Coupled atmosphere-ocean general circulations models (GCMs) are routinely used for climate research. Simulations of future climate are coordinated by the Coupled Model Intercomparison Project (CMIP) through the use of collectively defined experiments (Taylor et al., 2011). The fifth phase of CMIP was heavily relied upon by the IPCC for their fifth assessment report (IPCC, 2014). Additionally, a series of past climate experiments have been coordinated by PMIP. Three such experiments

formed part of the 3<sup>rd</sup> phase of PMIP: the mid-Holocene, the last glacial maximum and last millennium (although this latter ~~one experiment~~ is not analysed here). A pre-industrial control and an idealized warming scenario were also requested to establish the baseline and forced climate response respectively. Further details of these experiments will be introduced later when relevant.

5 Anomalous SSTs are calculated separately for each individual simulation. The climatology across the all years is used for the preindustrial, midHolocene and LGM experiment; the average of 1971-2000 for the historical simulation; and the final 40 years of idealized warming experiment. For all simulations, the resulting SST anomalies are then linearly detrended to remove any residual drift or aliasing from changes in mean state. Anomalous precipitation is similarly computed with respect to the same climatologies and linearly detrended.

10 Patterns associated with the ATL3 and AMM are calculated as linear regression slopes of the anomalous SST and precipitation to the derived timeseries. No statistical significance testing of this regression is performed. This pragmatic choice is motivated by the challenges posed by averaging pattern changes over an ensemble with each individual field having its own missing data mask.

Not every modeling group within PMIP was able to perform all the requested simulations - although only in the case of  
15 GFDL's last glacial maximum run was this for scientific rather than resourcing reasons. Here we investigate every simulation that has posted the required data on the Earth System Grid Federation's data nodes (Table 1). ~~Two-Three~~ modelling groups provided multiple realisations of the simulations differing only by their initial conditions (Table 1). Every simulation is considered equally likely during the creation of any ensemble averages. The ensemble-mean change patterns shown consist of the average of the difference for each model that has run both simulations (rather than the difference ~~of the ensemble mean in~~  
20 the two ensemble means). The spread within in the ensemble is illustrated throughout this analysis by stippling to indicate consistency. We consider the ensemble's signal to be consistent, if two-thirds or more of the participant models show a change of the same sign as the ensemble mean. Whilst this particular measure is not overly stringent, it does allow ready identification of regions where the signal is more likely to be robust.

## 2.2 Observations

25 This research involves the joint investigation of sea surface temperature ~~, surface air temperature~~ and precipitation. We adopt a combination of the Twentieth Century Reanalysis (Compo et al., 2011) for the atmospheric variables with HadISST1.1 (Rayner et al., 2003) for the SST. HadISST1.1 forms the underlying boundary conditions for the Twentieth Century Reanalysis (Compo et al., 2011), providing internal consistency between the datasets. These datasets exist over the period 1871-2012 C.E., although there is an increased amount of uncertainty in the early portion of the record (e.g. Ilyas et al., 2017). For the mean precipitation  
30 field shown in Fig. 2, we use GPCP (Adler et al., 2003). Despite having only a shorter available record than the reanalysis, it looks to give better rainfall over the elevated topography of South America. We follow Solomon et al. (2007) in using a climatological period of 1971-2000, as the historical simulations only extend until 2005.

	Group
A	NCAR
B	<a href="#">NCAR</a>
<a href="#">C</a>	CNRM-CERFACS
<a href="#">ED</a>	FUB
<a href="#">DE</a>	CSIRO-QCCCE
<a href="#">EF</a>	UNSW
<del>FEC-EARTH-2-2-0-40-G</del>	LASG-CESS
H	LASG-CESS
I	NASA GISS
J	NASA GISS
K	<a href="#">NASA-GISSMOHC</a>
L	<del>NASA-GISSGISS-E2-R*100-MNASA-GISSGISS-E2-R*100-NNASA-GISSGISS-E2-R*156-140OUBrisHadCM</del>
<a href="#">QM</a>	<del>MOHCHadGEM2-CC240145-RIPSL</del>
<a href="#">SN</a>	CAU-GEOMAR
<a href="#">TO</a>	MIROC
<a href="#">UP</a>	MPI-M
<a href="#">VQ</a>	MPI-M
<a href="#">WR</a>	MRI
<a href="#">XS</a>	BCC

**Table 1.** The number of simulated years of monthly output used to calculate the ~~tropical atlantic~~ [tropical Atlantic](#) variability in each model simulation. The models can be identified by their established acronyms from the Earth System Grid Federation database. †The name of this simulation is ‘midHolocene’ on the Earth System Grid Federation. ‡ indicates models that only form part of PMIP3, but not CMIP5. \*~~both~~ [\\*CCSM4](#), GISS-E2-R and MPI-ESM-P deposited multiple ensemble members.

### 2.3 Definition of modes

Climate modes of variability are preferred spatial patterns associated with time variations that have global-to-regional impacts. Both modes of tropical Atlantic variability analysed here have been identified using area-averaged SST anomaly indices. We avoid using definitions based upon Empirical Orthogonal Functions (EOFs) as preliminary analysis indicated they could have alternate ordering in the various models and simulations.

PMIP’s [Paleovariability working group PMIP4](#) is endeavoring to perform routine evaluation of the simulated climate variability (Kageyama et al., 2018) using the ESMValTool software (Eyring et al., 2016). This includes a collection of standardized analyses to look at coupled climate modes (Phillips et al., 2014). [In particular this research was performed using the Climate Variability Diagnostics Package \(CVDP v5.0.0\)](#). We have expanded the software to additionally incorporate analysis of the predominant modes of tropical Atlantic climate variability (TAV) listed below. The main source code is freely available

at [http://www.cesm.ucar.edu/working\\_groups/CVC/cvdp/](http://www.cesm.ucar.edu/working_groups/CVC/cvdp/). The full results of the software on the simulations described here are visible via the PMIP [variability database](#) [Variability Database, currently hosted](#) at <http://www2.geog.ucl.ac.uk/~ucfaccb/PMIPVarData/>.

### 5 2.3.1 [Atlantic zonal mode - ATL3](#)

[The Atlantic zonal mode \(Zebiak, 1993\) is the second mode of tropical Atlantic variability and represents changes in the cold tongue at the eastern part of the basin, just south of the equator. We adopt the ATL3 region of Zebiak \(1993\) as a metric. It is defined to be the area-average of the detrended SST anomaly over the region \[3°N-3°S, 20°W-0°W\]. This index definition is somewhat analogous to that of a Niño region in the Pacific, leading to this mode sometimes being termed the ‘Atlantic Niño’ \(Tokinaga and Xie, 2011; Xie and Carton, 2004\).](#)

### 2.3.2 Atlantic meridional mode - AMM

The AMM is the leading mode of variability in the Atlantic. It represents variations in the north-south SST-gradient that exhibits opposite SST anomalies on either side of the mean position of the ITCZ (Servain et al., 1999). The underlying SST distribution has an influence on the position of the ITCZ which in turn affects the regional rainfall distribution. Here we adapt the SST-based index of [Servain et al. \(1999\)](#) [Doi et al. \(2009\)](#). The AMM state is defined as the basin-wide area-average, detrended SST anomaly difference between the two hemispheres. More precisely is the average of [[2015°N-5°N, 80°W-050°W-20°W](#)] minus the average of [[1015°S-5°N, 60°W-1520°W-10°E](#)].

### 2.3.3 ~~Atlantic zonal mode - ATL3~~

~~[The Atlantic zonal mode \(Zebiak, 1993\) is the second mode of tropical Atlantic variability and represents changes in the cold tongue at the eastern part of the basin, just south of the equator. We adopt the ATL3 region of Zebiak \(1993\) as a metric. It is defined to be the area-average of the detrended SST anomaly over the region 3°N-3°S, 20°W-0°W. This index definition is somewhat analogous to that of a Niño region in the Pacific, leading to this mode sometimes being term the ‘Atlantic Niño’ \(Tokinaga and Xie, 2011; Xie and Carton, 2004\).](#)~~

## 3 Present-day

### 25 3.1 Mean State

Prior to investigating the interannual variability, it will be instructive to look at the representation of the mean climate state. The Atlantic is warmest on the Equator throughout the year (Fig. 1). The West Atlantic warm pool shifts to stay in the summer hemisphere. The Eastern Equatorial Atlantic has a tongue of cold upwelling that peaks in JJA. The warmest SSTs are associated

with the strong precipitation of the ITCZ (Fig. 2). Both South America and West Africa experience heavy monsoonal rainfall in their respective summers.

General circulation models provide our best tool for modeling the climate and generally provide a fair representation. However, all models have some biases in their mean climate state. On the ensemble mean, models are unable to simulate the correct magnitude of equatorial upwelling (Fig. 1c, d). Furthermore, the West Atlantic warm pool extent is underestimated. Both of these biases are also seen for the PI-control ensemble mean simulations (Fig. 1e, f) and persist throughout the year. There are precipitation biases as well (Fig. 2). In general, the models are unable to get the full intensity of the ITCZ, which is also associated with realistically represent the distribution of the ITCZ-related rainfall - they have too much rain falling south of the ITCZ. The West African monsoon is biased dry, whilst the models simulate too much convection over N.E. Brazil. The ensemble mean biases discussed are relatively consistent within the ensemble (the majority of the biases demonstrated in Figs 1 and 2 are stippled - meaning that two-thirds or more of the models have the same sign bias as plotted). These biases have been reported by other studies that looked at Tropical Atlantic Variability (TAV) in CMIP models (Breugem et al., 2006; Siongco et al., 2015; Richter et al., 2014; Deppenmeier et al., 2016; Wang et al., 2017). Consistently, the bias is related, The bias in many of the models is related to either a weak eastern equatorial cold tongue or failure to reproduce it. Breugem et al. (2006) examines 20th Century simulations in nine GCMs and identify strong interactions between the Atlantic zonal and the meridional modes that are not realistic. They discuss that the models that seem to best represent the meridional mode show its weakening in future climate conditions. Siongco et al. (2015) examined precipitation from 22 atmosphere-only models and identify an annual mean east-west bias associated with the ITCZ. They find that models with the East Atlantic bias tend to be high resolution models which rain excessively over the Gulf of Guinea. Richter et al. (2014) analyzes-analyze the simulation results of 33 models, of which 29 display biases relative to the mean state that can include an annual mean zonal equatorial SST gradient whose sign is opposite to observations. Deppenmeier et al. (2016) compare the pre-industrial simulation results of 36 different models and show that although there are errors in the annual cycles of SST, wind-stress and heat content, the relationship between them is well simulated. More recently, Wang et al. (2017) consider the validity of eastern equatorial Atlantic upwelling in the CMIP5 models when discussing their ability to predict the cold tongue SST development. Despite the mean state biases reported, the models are able to reproduce the dominant modes of climate variability of the Tropical Atlantic.

### 3.2 Representation of Tropical Atlantic Variability and its relationship to Precipitation

To address the question of how AMM and ATL3 are simulated, we present a comparison between the ensemble mean pattern seen in the historical and PI-control simulations (Table 1) and-together-with the HadISST temperature observations (Fig. 3). The time-series for both modes are determined through area-averaged, detrended SST anomalies for both the AMM (sect. 2.3.2) and ATL3 (sect. 2.3.1). The standard deviation of the resulting monthly time-series are calculated and shown in each panel (Fig. 3). The amplitude variations of the ATL3 region are 0.18 °C, which is approximately identical to the ensemble mean amplitude of 0.17 °C and 0.16 °C (given the ensemble spread) for the historical and PI-control simulations, respectively. The standard deviation of the anomalous-SST gradient used as a metric for the AMM is-substantially-weaker-than-the-variations of the ATL3 box alone. Nonetheless the observed amplitude of 0.05 °C compares favorably the ensemble mean value of 0.04

°C has stronger amplitude in the observations (0.28 °C) than the models suggest (0.18 and 0.19 °C in the historical and preindustrial respectively). It should be noted that one should expect the GCMs to sample different phases of the low frequency natural variability, so a direct comparison of the time-series is not appropriate. Additionally, there are uncertainties in the observational record, which may be considerable in the early portion of the record (Rayner et al., 2003; Compo et al., 2011; Ilyas et al., 2017).

The spatial patterns associated with the tropical Atlantic variability are demonstrated through simple linear regression of the area-averaged indices onto the monthly sea surface temperatures (Fig. 3 anomalies (sect. 2)). This regression is extended across the globe, which highlights correlations with other modes of internal variability. This does not imply that a causal relationship extending out of the Atlantic to other ocean basins exists.

~~The SST pattern associated with the AMM in the GCM ensemble appears to be well represented in the Atlantic when compared to the HadISST data set (Fig. 3). There is some smoothing of the dipole structure in the South Atlantic, which is perhaps to be expected given the ensemble-mean biases in the mean state of the region (Fig. 1). The most visually striking difference between the ensemble mean AMM pattern and the observations occurs over the Pacific. Here the observations show a structure reminiscent of the Interdecadal Pacific Oscillation (Power et al., 1999), which leads to regression strengths as strong in the Central Pacific as in the Atlantic. It is unclear if this arises from a missing connection in the GCMs or a deficient sampling of low frequency variability in the observations. Nonetheless the ensemble clearly demonstrates some coupling between the equatorial Pacific (ENSO) and the AMM (Saravanan and Chang, 2000; Keenlyside and Latif, 2007; Rodríguez-Fonseca et al., 2009) -The relationship with ENSO differs between models, which is interesting. However given this model dependence, we leave analysis of this feature for future work.~~

The spatial extent of the ATL3 does not extend far beyond the tropical Atlantic (Fig. 3). In fact, in both observations and models it has little effect on the North Atlantic. The projection of the ATL3 in models is predominantly onto the Equator itself and there is a muted effect on the upwelling region. This is likely due to an under-representation of the upwelling in the model as demonstrated by the substantial warm biases in the mean state (Fig. 1).

The SST pattern associated with the AMM in the GCM ensembles appears to be generally well represented in the Atlantic when compared to the HadISST data set (Fig. 3). There is too much extension of the negative SSTs across the South Atlantic however.

To evaluate the relationship of the TAV modes with tropical rainfall across the region, the ATL3 and AMM indices are regressed on to precipitation for the ensemble mean historical and PI-control simulations and compared to the equivalent regressions with from the reanalysis. The resulting patterns are shown for two ensembles of simulations and the reanalysis (Fig. 4). It is clear from Fig. 4 that the AMM and ATL3 regressed PPT patterns for the simulations resemble closely that of the reanalysis. Differences are seen mostly over the continents where the relationship with the TAV modes are stronger (towards the west for South America and east-southeast for Africa). The weaker regression relationships in West Africa in the model happen to correspond the low bias in the mean precipitation.

## 4 Past Climates

### 4.1 Mid-Holocene

Around 6,000 years ago was the warmest portion of the Holocene (Marcott et al., 2013) - although there are suggestions this may only represent the summer rather than annual average temperatures (Liu et al., 2014). The magnitude of the simulated temperature changes relative to preindustrial conditions were comparatively small (Fig. 5a, b), with several areas of cooling on the Equator (Braconnot et al., 2007). The climate change was caused by differences in the orbital precession that drove movement of the ITCZ's seasonal cycle to favour the Northern Hemisphere (Braconnot et al., 2007). Most notably, this increased the precipitation over Northern Africa and supported green vegetation in the Sahara (Hély et al., 2014). The ensemble simulates a noticeable northward shift in precipitation over Africa (Fig. 6b). This is however significantly less than observed in the region for the mid-Holocene (Perez-Sanz et al., 2014). It has been shown that ~~a more accurate simulation of mid-Holocene vegetation changes in the Sahara can influence the interannual climate variability~~, when imposing mid Holocene vegetation reconstruction as boundary condition to the model, inter-annual climate variability can be impacted (Pausata et al., 2017). Over N.E. Brazil, the monsoon rainfall reductions are relatively moderate (Fig. 6b), although there is a general decrease in summer rainfall across South America (Fig. 6a).

The precession-related changes in the mid-Holocene led to changes in the amplitude of ~~Tropical Atlantic variability-TAV~~ in many of the ensemble members (Fig. 7). These changes rarely exceeded a 20% ~~reduction or increase change~~ in amplitude. ~~More than two-thirds of the simulations show a reduction in amplitude of the AMM (Fig. 7c), with a mean reduction of 8.6%~~. The ensemble is ~~less confident~~ equivocal about the response of the ATL3 during the mid-Holocene. The ensemble mean change of ~~0.25~~ 1.3% is heavily influenced by the dramatic changes seen in KCM1-2-2 (Fig. 7). More than two-thirds of the simulations show a reduction in amplitude of the AMM (Fig. 7c), with a mean reduction of 7.5%.

~~The~~ There are some small local spatial patterns associated with ~~Tropical Atlantic Variability-TAV~~ shift at the mid-Holocene (Fig. 8), ~~although the remote relationships appear visually more striking~~. The ATL3 shows hints of a Northward shift in its spatial pattern (Fig. 8a). A mid-Holocene weakening of the El Niño-Southern Oscillation has been seen in observations and models (Clement et al., 2000; Chiang, 2009; Cobb et al., 2013). Despite this, there ~~is a greater~~ are of a stronger relationship seen in the ensemble between the AMM and this ~~region mode~~ (Fig. 8b). This ~~leads to an AMM pattern in the mid-Holocene that is a better fit to the historical observations (Fig. 3)~~ feature is model dependent (sect. 2). The mid-Holocene AMM sees a poleward shift in its pattern over the North Atlantic, which is likely related to the shift in the ITCZ location in the mean-state of the ITCZ (Fig. 6a,b). ~~The ATL3 similarly shows signs of a Northward shift in its spatial pattern~~ There appears to be little change in the precipitation patterns associated with TAV over the continents (Fig. 8a). ~~The mid-Holocene is simulated as having an increasingly inverse relationship between the Atlantic and Pacific Niños~~. c,d.

### 4.2 Last Glacial Maximum

21,000 years ago saw the maximum extent of the ice-sheets during the last glacial. The orbital configuration then differed only slightly from the preindustrial. The large ice-sheets were accompanied by substantial cooling across the globe (Broccoli and

Manabe, 1987; Clark et al., 2009; Annan and Hargreaves, 2013). Tropical sea surface temperatures cooled by roughly 2 °C (Fig. 5), predominantly controlled by ~~the roughly 100 ppm~~ a drop in CO<sub>2</sub> of around 100 ppm (Broccoli, 2000; Marcott et al., 2014; Annan and Hargreaves, 2015).

The patterns of SST change are approximately uniform, although there is a slight weakening of the north-south gradient in the Tropical Atlantic (Fig. 5). The ensemble is equivocal about changes in the equatorial zonal SST gradient. The intensity of the tropical rainfall was generally reduced and the position of the ITCZ moved marginally southward (Fig. 6). The ensemble shows a strong propensity for increased climate variability in the Tropical Atlantic (Fig. 9). The average increase in the ATL3 amplitude is 25.5% - with only one dissenter suggesting a decrease. All but two models show an increasing amplitude of the AMM, with the ensemble mean increase being 22.4%. ~~There is even more confidence in the increasing amplitude of the ATL3~~  
10 ~~31.3%~~ (Fig. 9) ~~-with only one dissenter. The average increase in the ATL3 amplitude is 32.8%.~~

These increases in amplitude are associated with small, but robust changes in the spatial pattern of the modes (Fig. 10). The last glacial maximum sees a slight reduction in influence of the ATL3 in the Equatorial Atlantic (Fig. 10). We interpret that to represent the ATL3 further constricting onto the Equator as the ITCZ moves slightly southward (Fig. 6). The AMM sees an increasing influence over the South Atlantic (Fig. 10b). The North Atlantic has something similar, but likely overlaid with changes caused by the imposition of large ice-sheets over North America impacting the atmospheric dynamics (Pausata et al.,  
15 2011). The ~~last glacial maximum sees a slight reduction in influence of the ATL3 in the Equatorial Atlantic~~ impact of TAV on rainfall in South America reduces - in places by 50% (Fig. 10). ~~We interpret that to represent the ATL3 further constricting onto the Equator as the ITCZ moves slightly southward c,d).~~ These TAV-related reductions are proportionally much larger than the LGM change in mean precipitation (Fig. 6). ~~Further afield, ATL3 loses what connection it had to the equatorial Pacific~~  
20 ~~Therefore PMIP3 potentially suggests a rainfall over N.E. Brazil that was simultaneously weaker, but less variable. There are little changes in the TAV patterns over Africa (Fig. 10c,d).~~

### 4.3 Future changes

The climate simulated for both mid-Holocene (sect. 4.1) and last glacial maximum (sect. 4.2) represent equilibrated conditions between the climate and its forcing. The climate is expected to ~~be still be~~ still be in a transient state throughout the coming  
25 century. Rather than selecting a particular plausible future scenario, we analyze the idealised simulations where the atmospheric CO<sub>2</sub> concentrations are increased by 1% per year until it is quadrupled (Taylor et al., 2011). The mean climate during the final forty years of these simulations is substantially warmer (Fig. 5) with an intensified hydrological cycle (Fig. 6). To have sufficient years to assemble robust SST patterns of climate variability, we consider the full length of these transient simulations having first removed a linear trend from each model grid point (after Phillips et al., 2014).

The mean SST and rainfall patterns are very similar to ~~an opposite a reverse~~ of those for the cold LGM (Fig. 5,6). However, the changes in Tropical Atlantic variability are not. There is an indication that there will be an increase in amplitude of ATL3 (Fig. 11a), with an average increase of ~~12.0~~ 13.8%. However, the ensemble is split evenly as to whether the AMM (Fig. 11b) will increase in amplitude as well (mean change of +2.85.1%). Despite that, there is a robust poleward expansion of the AMM's influence in the Atlantic (Fig. 12b). The influence of ATL3 also expands polewards, but only in the Northern Hemisphere

(Fig 12a). ~~There is a weakening of the connection between the AMM and Pacific El Niño, although the ATL3 becomes more tightly connected (Fig. 12a). The relationship between the equatorial Atlantic cold-tongue and the tropical Pacific is relatively understudied and a consensus has yet to be reached upon it.~~ Kucharski et al. (2011) demonstrate that the Pacific ocean response to Atlantic warming is a La Niña-like cooling response, much like the AMM-related future changes in Fig. 12b. Interestingly the precipitation response to the ATL3 is weaker in the future scenarios (Fig. 12c), with a slight contraction onto the Equator. This does not bear a strong relationship to the changes in the mean state (Fig. 6). The AMM shows a similar contraction in related rainfall, but the amplitude of the changes are generally small (Fig. 12d).

## 5 Discussion

~~The study of past climate change to place future changes in context is itself worthwhile (Pancost, 2017). The advantage of using models is that they can be equally applied to the past and future (as shown here). Ideally one could use observations of past climates to constrain future projections (Hargreaves et al., 2012). Unfortunately there are currently no reconstructions of past Tropical Atlantic variability to form that constraint. An alternate approach would be to detect an emergent relationship between the mean state and the climate variability. Reconstructions of changes in the mean state could then be used as emergent constraints on the future behaviour (Hall and Qu, 2006).~~

### 5 TAV amplitude changes as a function of the SST gradient

Changes in the amplitude of the ATL3 mode have previously been linked to changes in the zonal SST gradient since 1950 (Tokinaga and Xie, 2011). In Fig. 13, we investigate whether this link holds across the ensemble and multiple climates. We use the difference in the area-averaged SST between [3°N-3°S, 45°W-25°W] and [3°N-3°S, 20°W-0°W] to characterize the west-east SST gradient (after Tokinaga and Xie, 2011), and only consider the climate change signal to prevent the model biases hiding any relationship. The gradient changes in the future simulations are only analyzed over the final forty years ~~(once the main climate change signal is dominant)~~ (unlike in) unlike the TAV calculations which detrend and use the full timeseries (sect. 4.3).

Despite the ensemble showing robust changes in mean state and often robust changes in variability, there is ~~little~~ no apparent relationship emerging between the ~~two pairs of changes~~ change in the standard deviation of the ATL3 and changes in the zonal SST gradient (Fig. 13). This perhaps questions the previous conclusions of Tokinaga and Xie (2011). In fact, extending their time series of ATL3 earlier within the instrumental period indicates little persistence of the trends they find between 1950-2000 (not shown). ~~However,~~ Tokinaga and Xie (2011) highlight aerosols as the cause of their trends ~~. Yet aerosols and their associated forcing are not properly~~ something which is not really explored across these simulations ~~,~~ leading us to conclude that further work is required to understand the future of the ATL3.

The AMM is defined as variations in the inter-hemispheric tropical SST gradient (sect. 2.3.2). It would seem logical to think that as ~~that the~~ inter-hemispheric gradient changes the interannual variability of that gradient would also change. Recently

Rehfeld et al. (2018) have suggested there was an increased climate variability during the last glacial, which is well supported by Fig. 9. They propose that the increased meridional temperature gradients are the underlying cause of the greater variability. We explore this suggestion to search for an emergent constraint of the future AMM response. When looking at changes in the standard deviation of the AMM amplitude as a function of the meridional gradient, there seems to be a disconnect from the mean state gradient. There appears to be no robust relationship between the AMM amplitude and the mean meridional gradient (Fig. 14). A decrease in the AMM amplitude change can be associated with an increase in the meridional SST gradient for the mid-Holocene while the opposite occurs for the LGM. The 1% per year until quadrupled CO<sub>2</sub> experiment shows that the amplitude of the meridional mode decreases with decreasing gradient. Therefore there is little robust relationship overall. (1pctCO<sub>2</sub>). Overall, the relationship between the amplitude change of the AMM and the changes in the meridional SST gradient depends on the climatic period considered.

## 6 Conclusions

This study has used the multi-model CMIP5/PMIP3 ensemble to investigate changes in Tropical Atlantic variability across several climate states. All models are able to represent the main characteristics of the dominant modes of variability, with similar mean state bias, for all climate periods analyzed. These biases are consistent among all models (Fig. 1) especially in the equatorial cold tongue. They are also consistent in showing precipitation biases over South America and Africa with associated biases in the ITCZ location. Africa and over the tropical Atlantic. Despite their mean state biases, the simulation results show reasonable representation of the observed patterns of Tropical Atlantic variability. Overall, the ensemble analysis shows that SST anomalies patterns associated with cooling north of the equator can be associated with a southward shift of the Intertropical Convergence Zone (ITCZ) which is accompanied by a weakening of rainfall and increasing dryness over both continents.

Across the climate periods, the relationship between equatorial Atlantic and Pacific variability is not robust. The ensemble shows that this coupling changes substantially for all climate periods: For the LGM, the ATL3-related equatorial cold tongue intensifies near the equator and weakens off the coast of Namibia while the Pacific equatorial response significantly strengthens. The mid-Holocene shows a stronger intensification of the cold tongue system. It also displays the increase of the Pacific equatorial mode, but its less than for the LGM. The warm climate of the 1% per year until quadrupled CO<sub>2</sub> experiment, shows opposite results: the equatorial Atlantic cold tongue weakens and there is an associated increase of the Pacific equatorial mode. The region along the coast of South Africa and Namibia shows cooling. In fact, Lübbecke and McPhaden (2012) discuss how the relationship between SST anomalies in the equatorial Atlantic and Pacific may vary with time. ENSO events can be associated with both warm or cold SST anomalies in the equatorial Atlantic cold tongue region. More recently, Li et al. (2016) show, the importance of Atlantic SST anomalies for the tropical Pacific over the past three decades.

Regarding the Meridional Mode (AMM), we also find a coupling with the equatorial Pacific for all periods. The AMM for the LGM (Fig. 10b) projects onto a basin-wide meridional oscillating pattern from Antarctica to Greenland with alternating signs, much like the Pan-Atlantic Decadal Oscillation pattern (PADO) described by Xie and Tanimoto (1998). The AMM coupling

~~with the equatorial Pacific for the mid-holocene is strong and shows intensification. In the Atlantic, there are small changes in the Tropics. A warming of the North Atlantic subtropics and cooling of the South Atlantic except at the Brazil-Malvinas confluence region in the Southwest Atlantic. In the future climate experiment, the equatorial mode weakens, the whole northern hemisphere warms up while the south Atlantic displays an hemisphere-wide weak oscillating pattern.~~

5 ~~This study has used the multi-model CMIP5/PMIP3 ensemble to investigate changes in Tropical Atlantic variability across several climate states.~~ Analysis of the idealised warming scenarios alone suggest a spectrum of future climate change responses. The additional analysis of the palaeoclimate simulations provides some valuable context for those responses. For example, the simulated future ATL3 (Atlantic Niño) amplitude increase is not simply a response to the warmer temperatures - as a similar increase is seen during the last glacial maximum. ~~The particular relationships between the mean state and variability changes that were tested here did not transpire to be robust.~~

10 The spatial patterns associated with each of the Tropical modes are very robust and closely related to the SST anomalies. Mode shifts actually reflect changes in intensity/amplitude rather than changes in spatial distribution. Results have shown that for the AMM behavior in particular, the distinction between climatic periods is clear. The LGM and Mid-Holocene AMM mode show opposite behavior: at the LGM there is an increase in the AMM amplitude while the North-South SST gradient decreases while at the Mid-Holocene there is an increase in the North-South SST gradient accompanied by a decrease in the amplitude of the AMM. The behavior of the AMM for the 1pctCO2 shows an overall weakening of the AMM mode with a decrease in both the AMM amplitude and the associated North-South SST gradient.

15 The study of past climate change to place future changes in context is itself worthwhile (Pancost, 2017). The advantage of using models is that they can be equally applied to the past and future (as shown here). Ideally one could use observations of past climates to constrain future projections (Hargreaves et al., 2012). Unfortunately there are currently no reconstructions of past Tropical Atlantic variability to form that constraint. An alternate approach would be to detect an emergent relationship between the mean state and the climate variability. Reconstructions of changes in the mean state could then be used as emergent constraints on the future behaviour (Hall and Qu, 2006). We investigate whether there are such quantifiable links between TAV and the mean state in CMIP5/PMIP3: no significant relationships emerge. Nonetheless, we feel the approach of analysing  
20 several different multi-model climate experiments, some with direct or proxy observations available, promises to constrain the uncertainty in future projections.

*Code and data availability.* The software is freely available at <http://www2.cesm.ucar.edu/working-groups/cvcwg/cvdp>, with the modifications plotting scripts for this paper to be found at <https://bitbucket.org/cbrierley/cvdp-pmip>. The results for individual models are freely available for inspection and download from the PMIP variability database at <http://www2.geog.ucl.ac.uk/~ucfacb/PMIPVarData/>, along  
30 with results for many other modes of climate variability.

*Author contributions.* Both authors contributed equally to devising the study and writing the manuscript. C.B. performed the data analysis.

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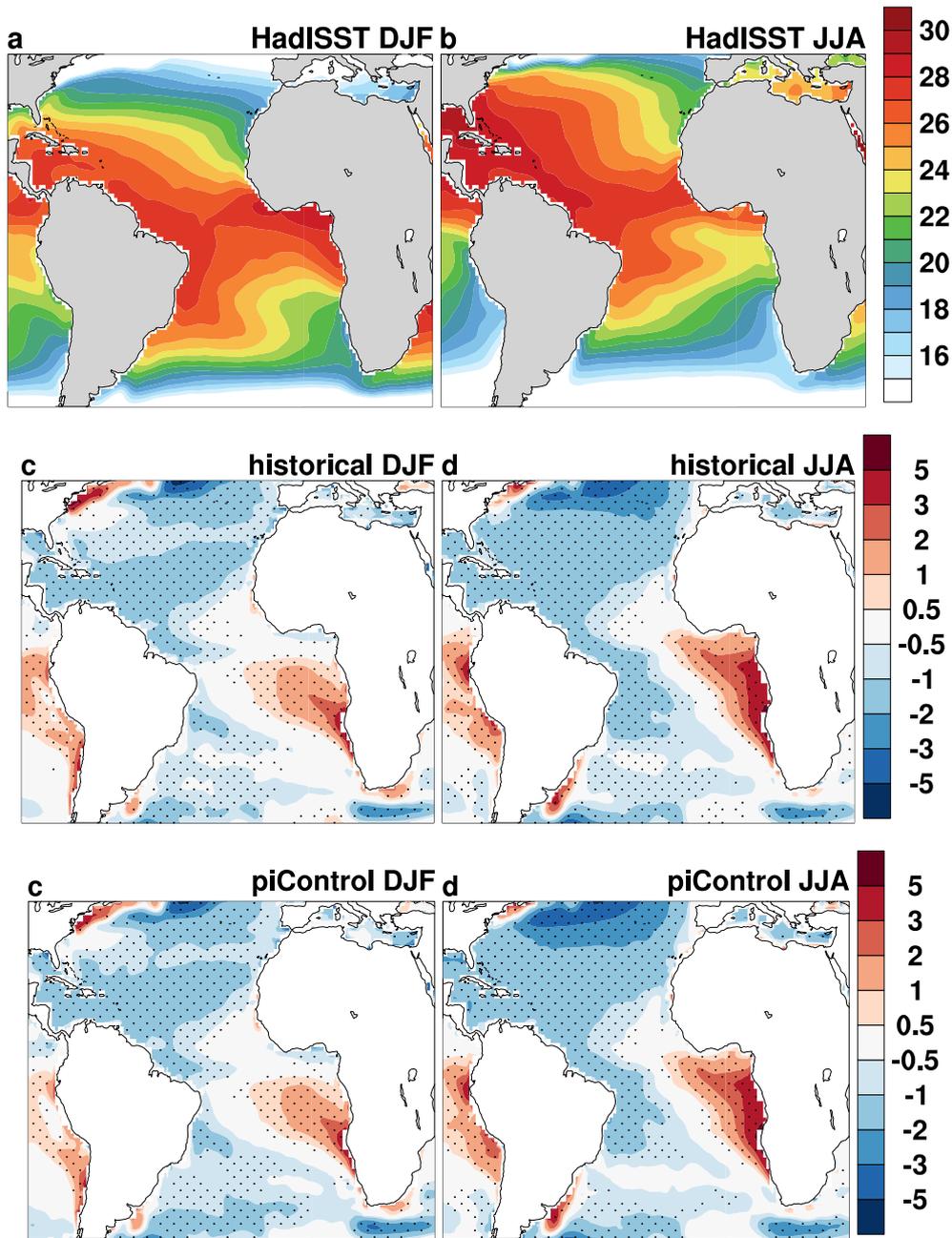
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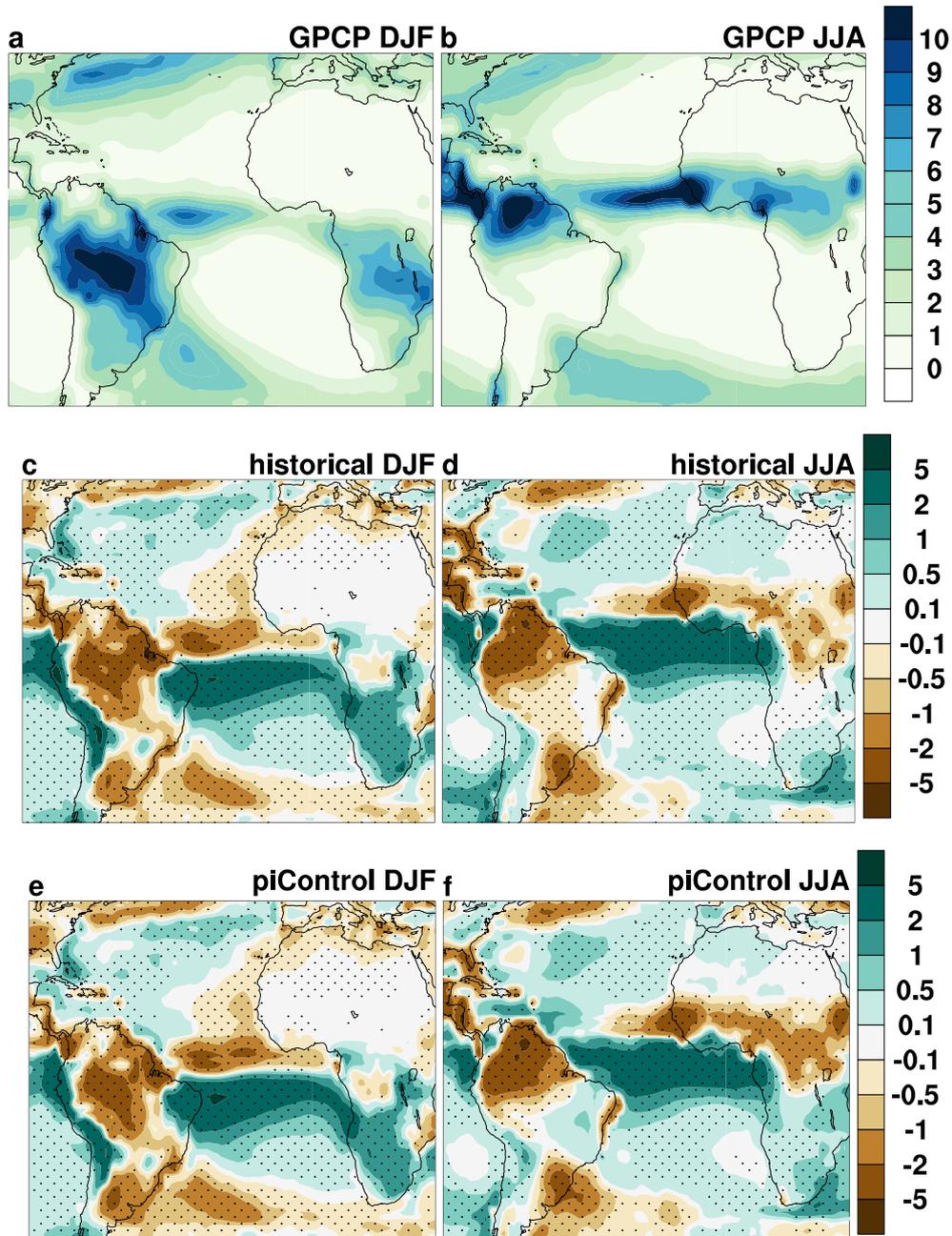
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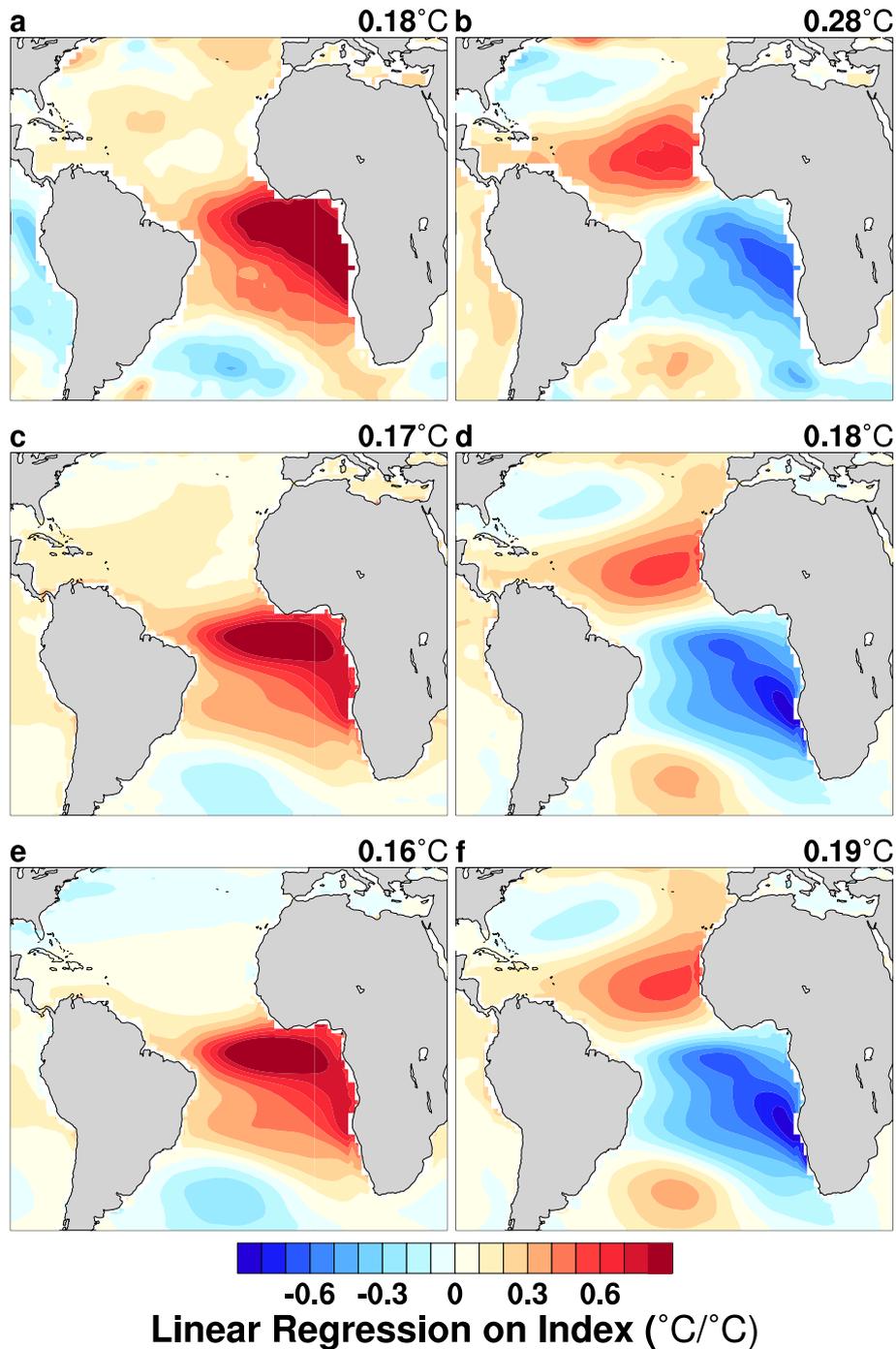
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**Figure 1.** The sea surface temperature representation and changes in the ensemble. The climatological (1971-2000) sea surface temperature seen in HadISST (Rayner et al., 2003) in-for DJF (a) and JJA (b). Even on the ensemble mean, there are model biases in the seasonal temperatures in-of the historical simulation for DJF (c) and JJA (d). The ensemble mean biases in the seasonal temperatures in the PI-control simulations for DJF (e) and JJA (f) are very similar to those of the historical simulations. Stippling indicates regions where two-thirds or more of the models agree with the sign of the ensemble mean bias (sect. 2).



**Figure 2.** The seasonal cycle in of precipitation and its changes across the ensemble. The climatological (1971-2000/1979-1999) precipitation seen in the Twentieth-Century-Reanalysis (Compo et al., 2011)-Global Precipitation Climatology Project (Adler et al., 2003) in DJF (a) and JJA (b). The ensemble mean biases in of the seasonal precipitation in the historical simulation for DJF (c) and JJA (d). The ensemble mean biases of the seasonal precipitation in the PI-control simulation for DJF (e) and JJA (f). Stippling indicates regions where two-thirds or more of the models agree with the sign of the ensemble mean bias.



**Figure 3.** Sea surface temperature patterns related to ATL3 (a,e:left) and AMM (b,d:right) indices in observations (left-panels a,b) and CMIP5/PMIP3 (right). The model panels show the ensemble mean patterns average for the historical simulations (c,d) and the preindustrial control (e,f). The standard deviations of the SST indices are also shown.

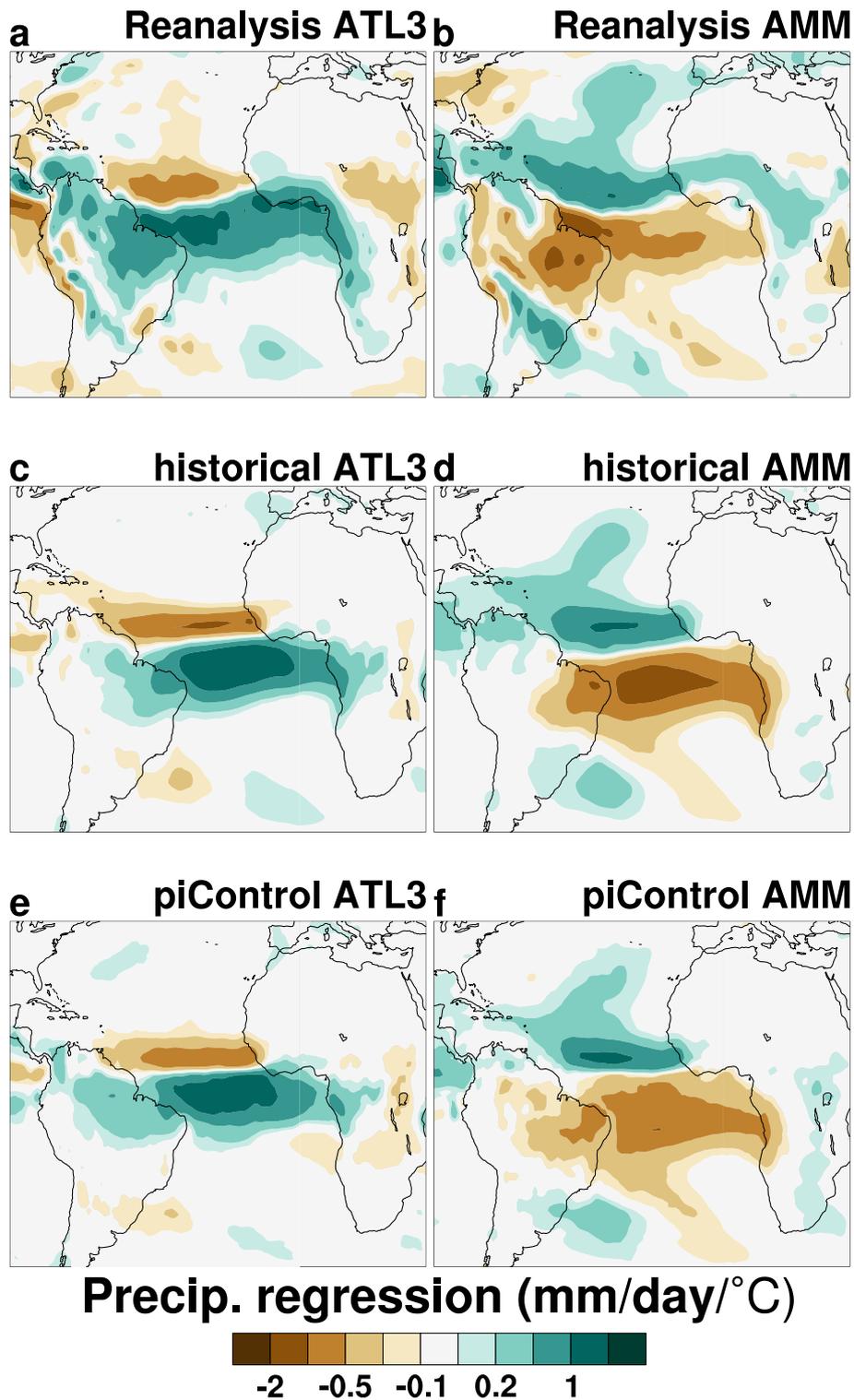
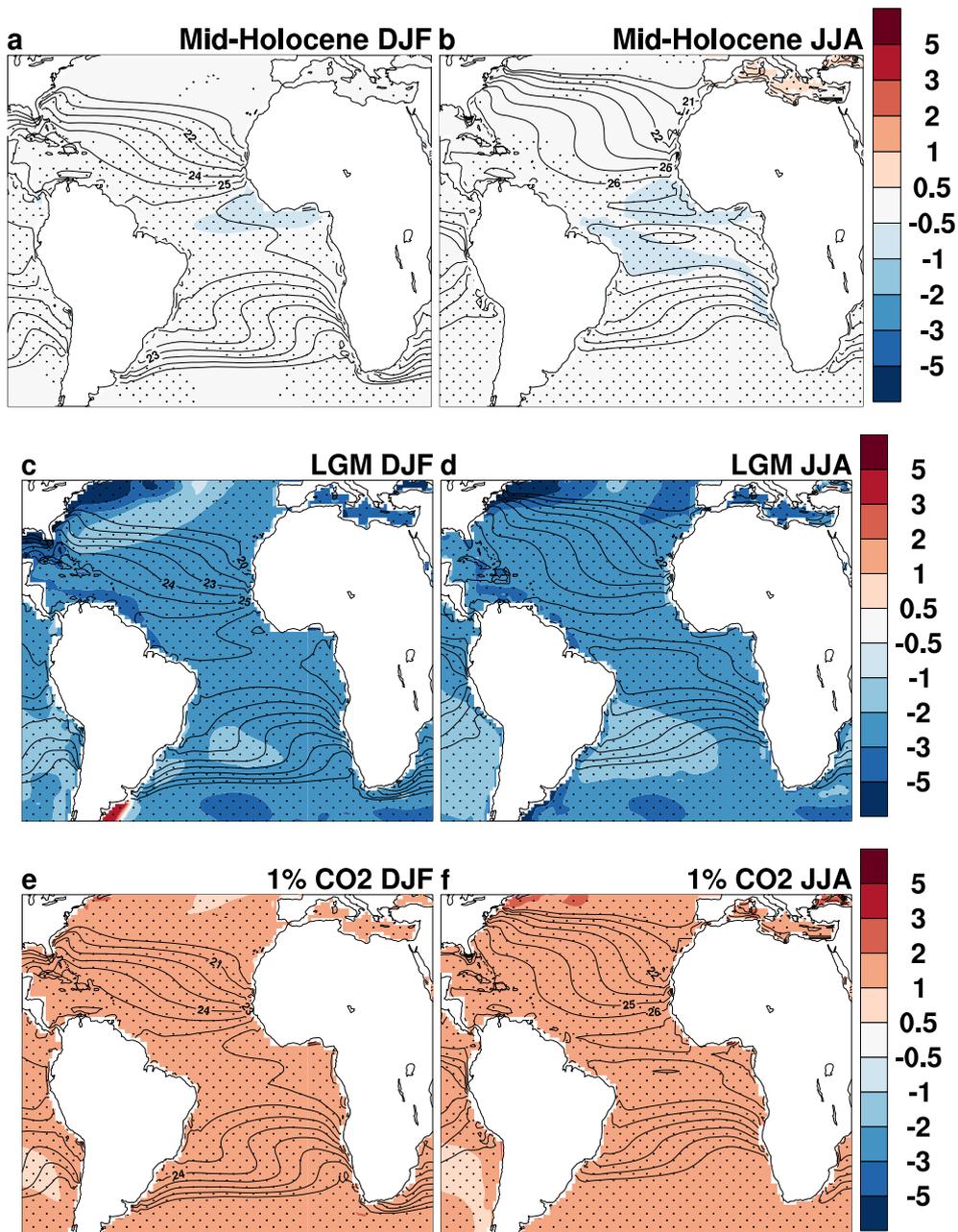
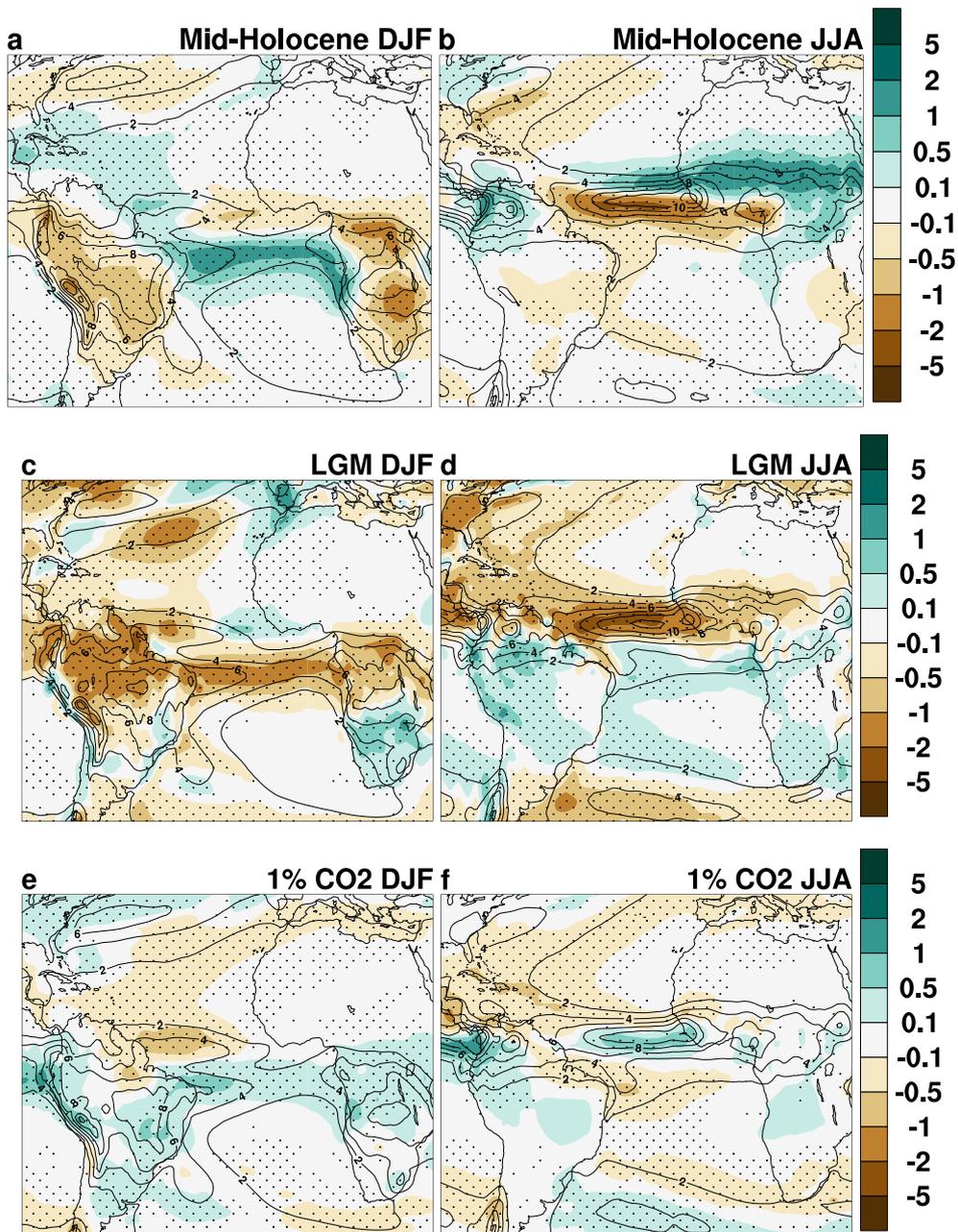


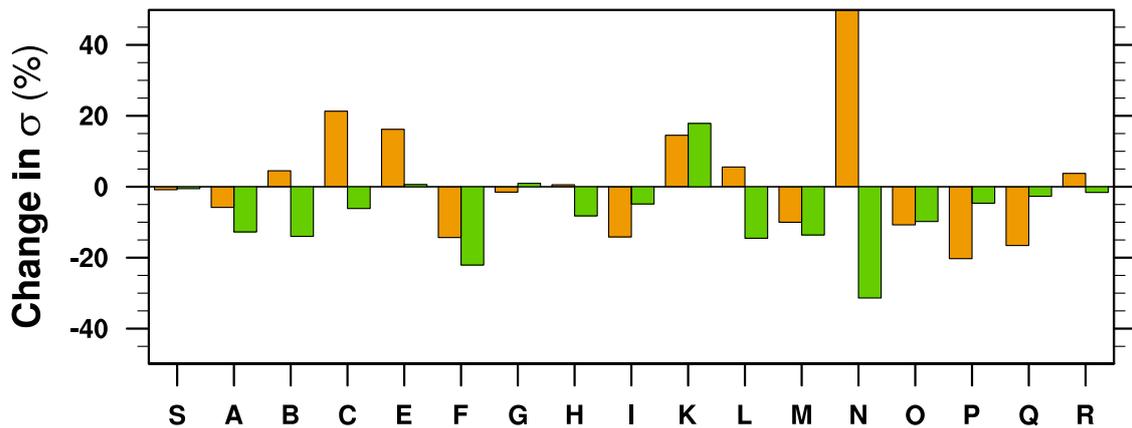
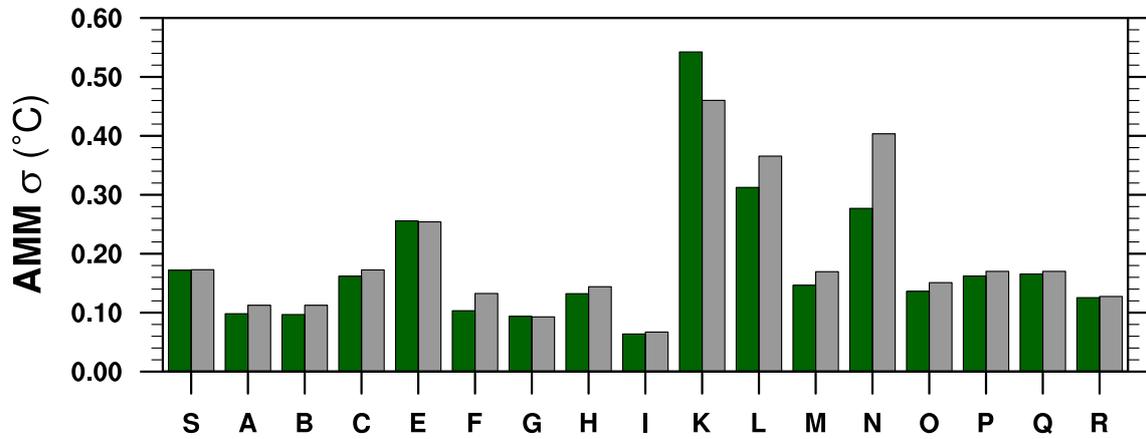
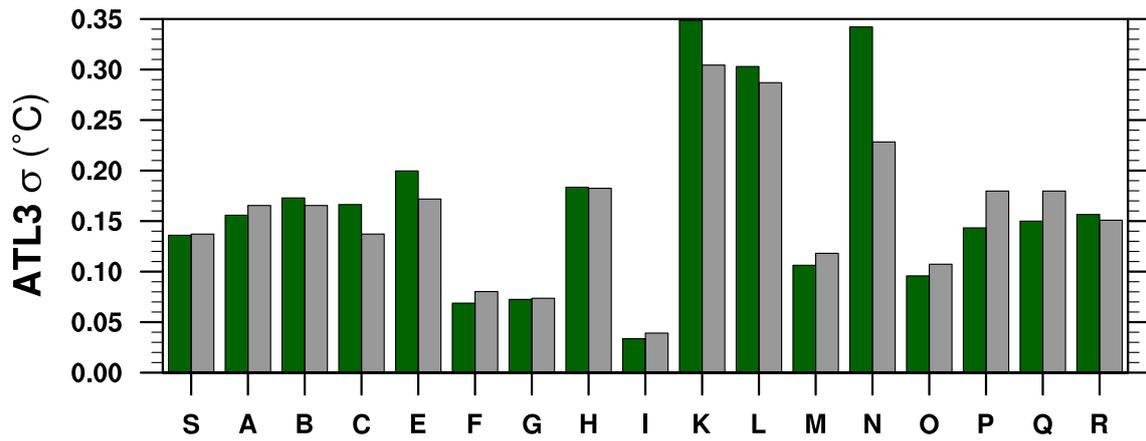
Figure 4. [Precipitation patterns related to ATL3 \(left\) and AMM \(right\) indices in reanalysis \(top\) and CMIP5/PMIP3. The patterns across the historical simulations \(c,d\) and preindustrial simulations \(e,f\) are an ensemble mean across the available models \(Table 1\).](#)



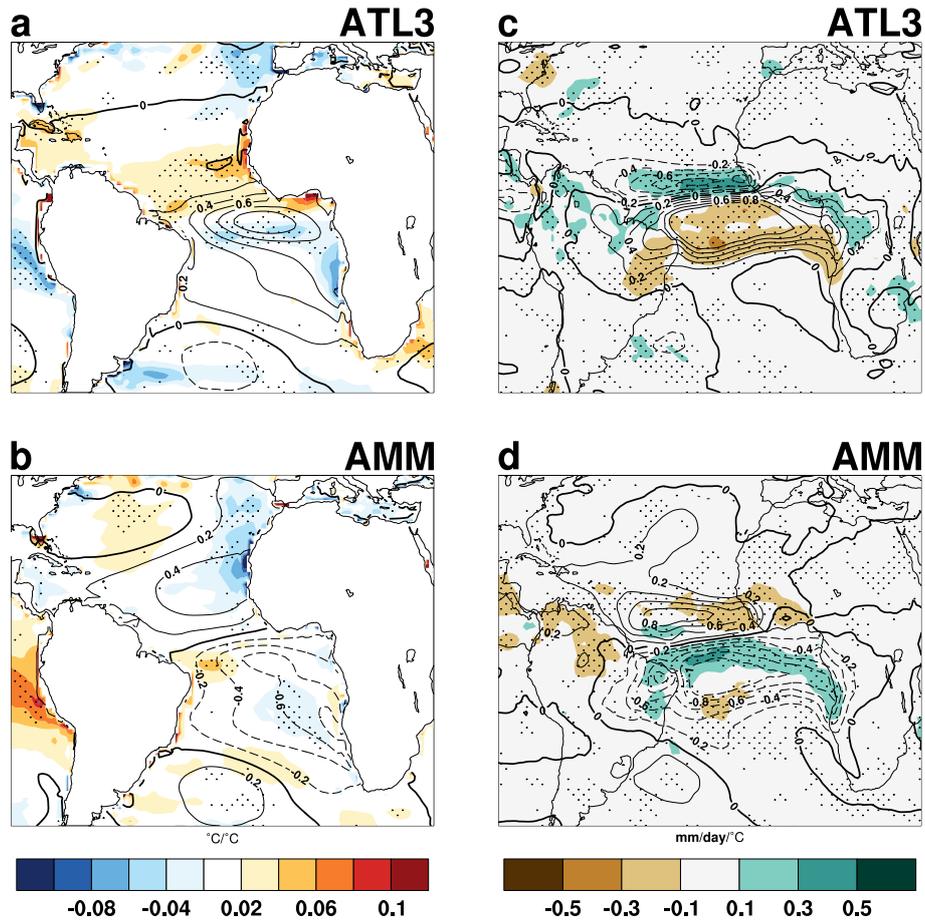
**Figure 5.** The [climatological](#) sea surface temperature changes shown by the ensemble. The ensemble mean difference between the mid-Holocene and preindustrial simulations demonstrates the temperature impacts in DJF (a) and JJA (b). The last glacial maximum is simulated as being substantially colder than the preindustrial in both DJF (c) and JJA (d). In contrast, the ensemble mean average of the final forty years of the 1% per year increasing carbon dioxide concentration run is warmer than preindustrial in both DJF (e) and JJA (f). Stippling indicates regions where two-thirds or more of the models agree with the sign of the ensemble mean change. [Overlaid contour lines represent the mean state in the ensemble mean of the preindustrial control simulations.](#)



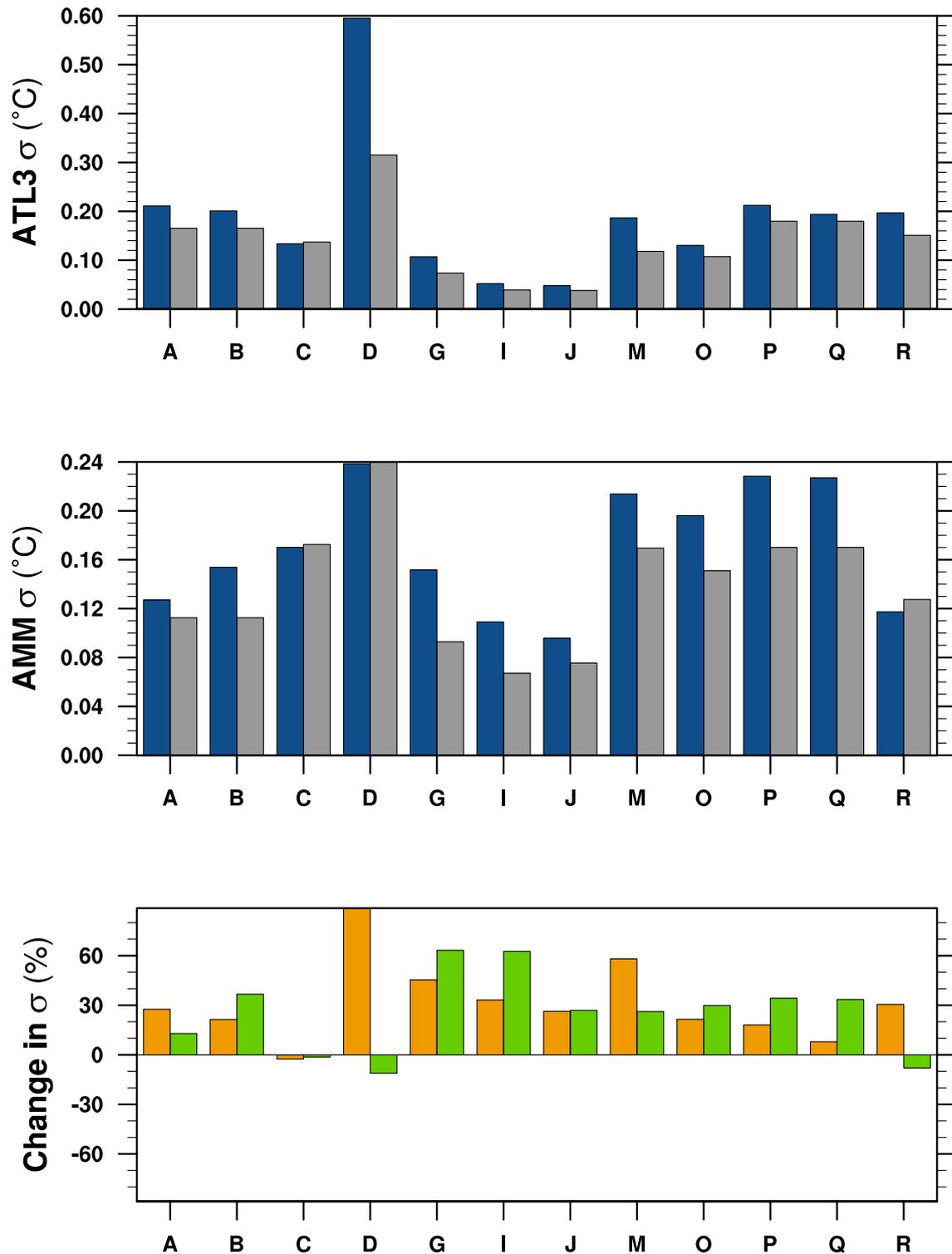
**Figure 6.** The changes in seasonal cycle in precipitation across the ensemble. The ensemble mean difference between the mid-Holocene and preindustrial simulations shows the movement of the ITCZ in DJF (a) and JJA (b). The last glacial maximum is simulated as having less intense rain bands than the preindustrial in both DJF (g) and JJA (h). In contrast, the ensemble mean average of the final forty years of the 1% per year increasing carbon dioxide concentration run demonstrates enhanced activity over the ITCZ than in preindustrial for both DJF (i) and JJA (j). Stippling indicates regions where two-thirds or more of the models agree with the sign of the ensemble mean change. [Overlaid contour lines represent the ensemble mean of the preindustrial control simulations.](#)



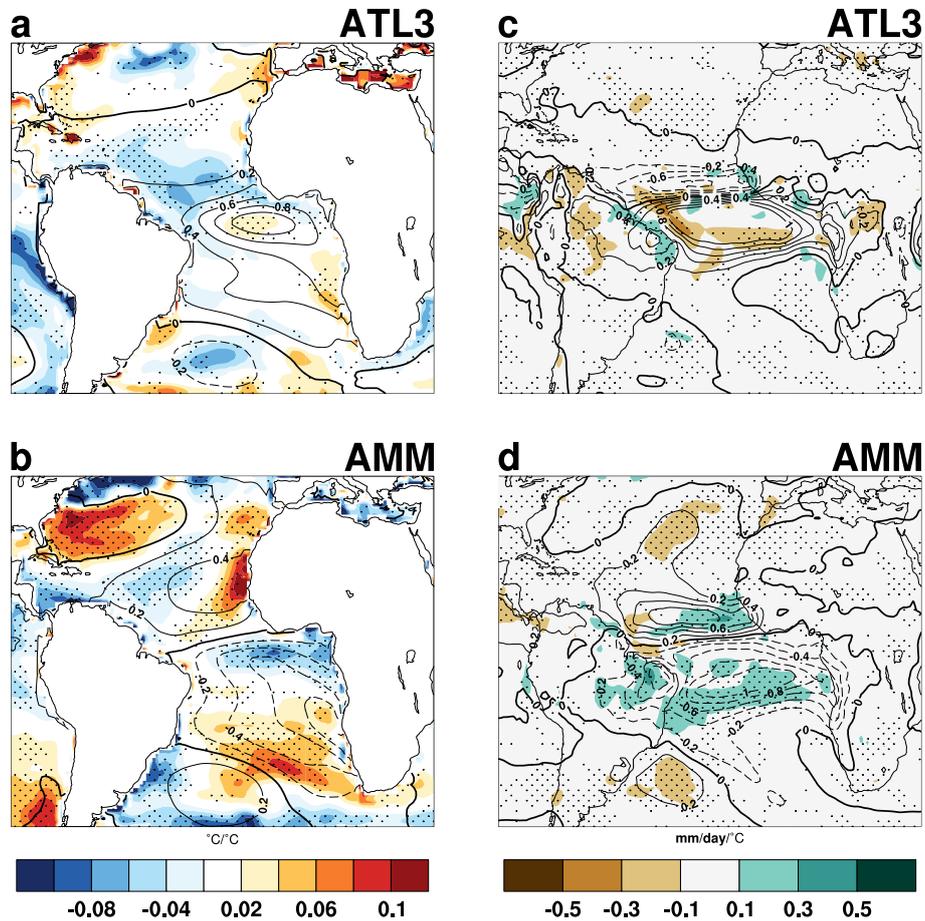
**Figure 7.** The standard deviations of the (atop) ATL3 and (bmiddle) AMM indices in the mid-Holocene (green) and preindustrial results (grey); (ebottom) changes expressed as a percentage across the ensemble for both ATL3 (yellow) and AMM (light green).



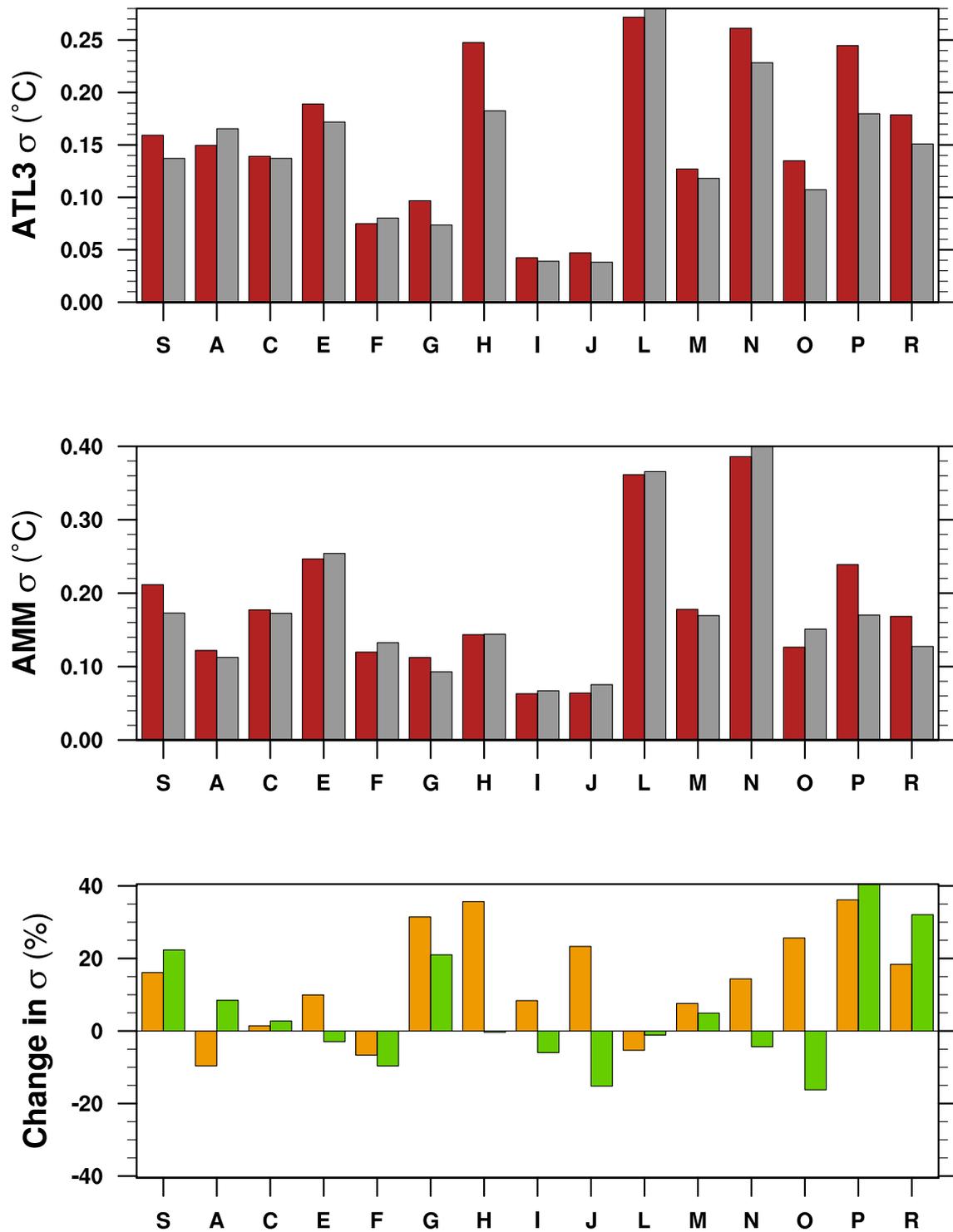
**Figure 8.** Mid-Holocene changes relative to preindustrial in the temperature patterns related to (a) the ATL3, (b) AMM indices. The changes in precipitation patterns are also shown for the ATL3 (c) and AMM (d). The changes are stippled with greater than two-thirds of the ensemble shows the same direction as the ensemble mean change. The contours show the change in regression strength onto the index in question; i.e. the change in local expression of +1°C index. The overlaid contours show the ensemble mean strength of the relationship in the preindustrial control.



**Figure 9.** The standard deviations of (a) the ATL3 and (b) AMM indices in the last glacial maximum simulations (blue), shown alongside the values from their respective preindustrial control simulation (grey); (c) changes expressed as a percentage across the ensemble for both ATL3 (yellow) and AMM (light green).

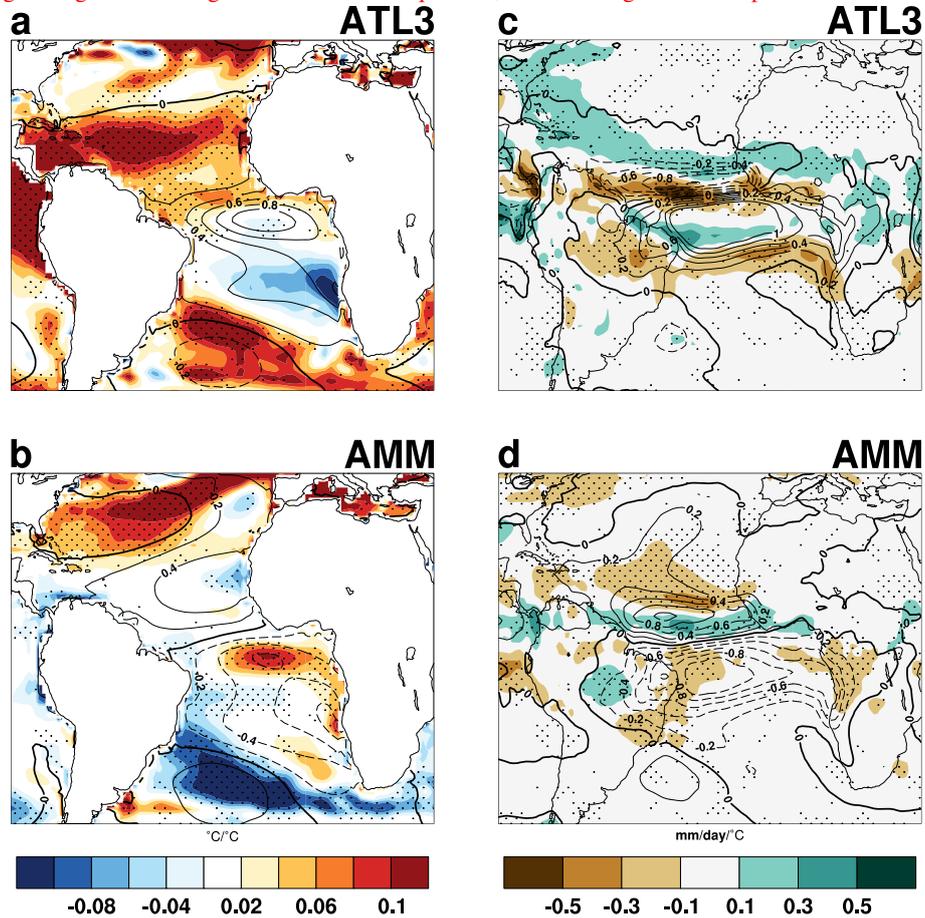


**Figure 10.** Last ~~Glacial-Maximum~~ glacial maximum changes relative to preindustrial in the temperature patterns related to (a) the ATL3 ~~and~~, (b) AMM indices. The changes in precipitation patterns are also shown for the ATL3 (c) and AMM (b). The changes are stippled ~~where with~~ where with greater than two-thirds of the ensemble showing shows the same direction as the ensemble mean change. The contours show the change in regression strength onto the index in question; i.e. the change in local expression of +1°C index. The overlaid contours show the ensemble mean strength of the relationship in the preindustrial control.



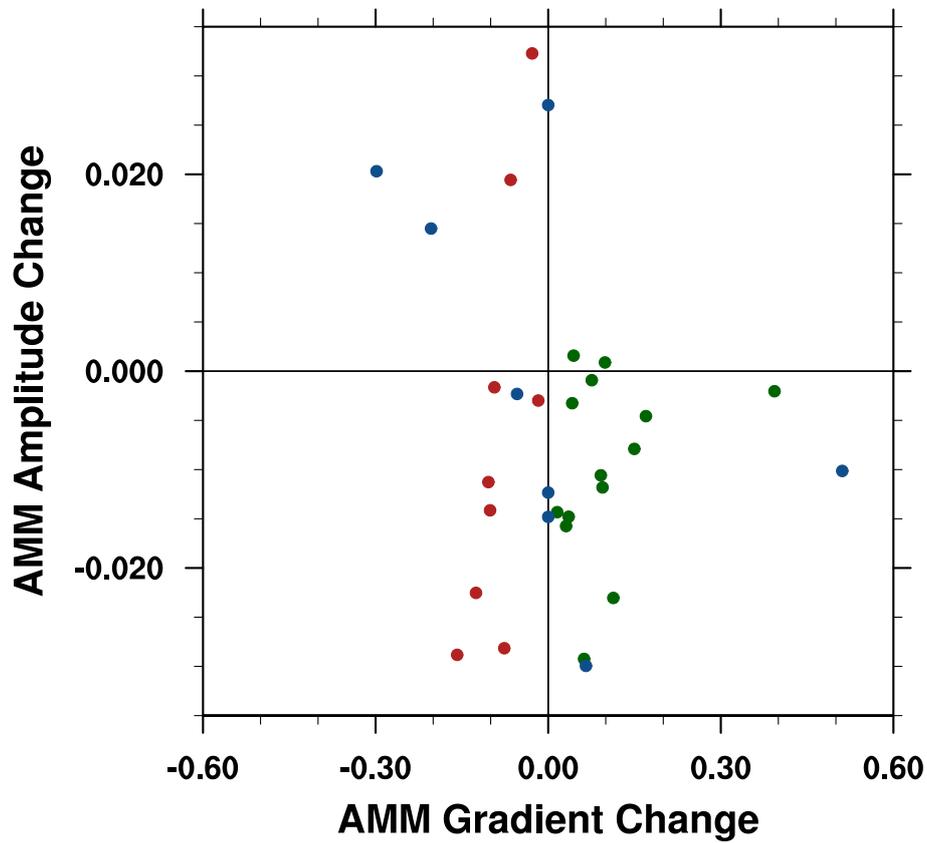
**Figure 11.** The standard deviations of (a) the ATL3 and (b) AMM indices in the 1% per year until quadrupled CO<sub>2</sub> experiment (red), shown alongside the values from their respective preindustrial control simulation (grey); (c) changes expressed as a percentage across the ensemble for both ATL3 (yellow) and AMM (light green).

1% per year until quadrupled CO<sub>2</sub> forced changes in the temperature patterns related to (a) the ATL3 and (b) AMM indices. The changes are stippled where greater than two-thirds of the ensemble shows the same direction as the ensemble mean change. The contours show the change in regression strength onto the index in question; i.e. the change in local expression of +1°C index



**Figure 12.** 1% per year until quadrupled CO<sub>2</sub> forced changes relative to preindustrial in the temperature patterns related to (a) the ATL3, (b) AMM indices. The changes in precipitation patterns are also shown for the ATL3 (c) and AMM (b). The changes are stippled with greater than two-thirds of the ensemble shows the same direction as the ensemble mean change. The contours show the change in regression strength onto the index in question; i.e. the change in local expression of +1°C index. The overlaid contours show the ensemble mean strength of the relationship in the preindustrial control.





**Figure 14.** The change in standard deviation of the meridional mode (AMM) as a function of the change in meridional SST gradient. The gradient is calculated using the same regions as for the AMM index itself (sect. 2.3.2). The colors indicate the different experiments: 1pctCO2 (red), mid-Holocene (green) and last glacial maximum (blue).