Dear Editor,

Concerning the revision of “**The South American Monsoon Variability over the Last Millennium in CMIP5/PMIP3 simulations”** *by* M. Rojas, P. A. Arias, V. Flores-Aqueveque, A. Seth, and M. Vuille.

Please find below our responses the two anonymous reviewers of our manuscript. First of all, we are grateful for the reviewer’s insightful comments and the time and effort they spent reviewing our manuscript. We feel that their comments have helped us to significantly improve our paper.

In response to the editor’s comments, we have included the following paragraph to clarify the hypothesis behind our methodology (lines 259-262):

The hypothesis that guides the methodology used to asses the SAMS variability in models, is that both periods resulted substantially from internal (non-forced) variability. In addition, given that not all GCM simulations used the exact same forcing, we cannot expect the models to exactly reproduce the temporal variability as indicated by the reconstructions.

Reviewer 1:

Summary

The study analyses the South American Monsoon System (SAMS) variability in the PMIP3 simulations spanning the period from 850 to 1850 AD. The models’ ability is assessed by comparing the results to proxy data. The study focuses on the difference between the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). The authors argue that the simulations show a stronger Monsoon during the LIA, resembling proxy data. Still, simulated precipitation in the SAMS region seems not to be consistent with proxy records.

General comment

Although the scientific relevance of using past information from models and proxy reconstructions to better understand variations in the SAMS is given, the study lacks of severe shortcomings (see below) which renders its usefulness. Therefore, I recommend to reject the manuscript.

Major comments

I. Certainly, the manuscript needs to be proofread by a native speaking person – there are numerous strange formulations (only a few are listed in the specific comments).

We have asked our two native speaker co-authors to thoroughly revise the English in the manuscript. We hope that it is now significantly improved.

II: The selection procedure presented on page 5656 seems to be awkward. The comparison MCA LIA implies that the authors focus on a forcing signal. As the forcing is very similar for all model simulations a definition according to the cumulative forcing is thus appropriate. If the authors would hypothesize that the changes are more due to internal variability they shall use a classical composite analysis, i.e., using a fixed length of a period (say 100 yrs) which defines the timescale of interest and assess all periods with exceed or fall below one standard deviation of an index (e.g. NH temperature). The method proposed does not have a clear motivation (hypothesis). Further, it remains unclear how the authors obtain different lengths of the periods. Also the reference period from 1250-1450 seems to be not well motivated (given the fact the eruption of 1258 is included where most of the models show a very strong response). I would suggest to use the entire period 850 -1850 as reference. The second criterion of the temperature gradient seems to be selected in particular to find ITCZ shifts, so there is a danger that the authors make circular analyses and statements.

Indeed the selection of the periods was based on a somewhat subjective ad-hoc procedure. However, we believe that such a selection is justified based on the rationale put forth by the latest IPCC report, which concluded, that the "**Medieval Climate Anomaly (950 to 1250) that were in some regions as warm as in the mid-20th century and in others as warm as in the late 20th century.** With *high confidence*, these regional warm periods were not as synchronous across regions as the warming since the mid-20th century". And "…but also internal variability, contributed substantially to the spatial pattern and timing of surface temperature changes between the Medieval Climate Anomaly and the Little Ice Age".

Given these conclusions our hypothesis is that the changes observed during those periods result from a combination of external forcings and internal variability. The forced component of the response could in theory be expected to coincide in all the simulations, but the internally generated variability, if simulated in the models, cannot be expected to occur at the same time. It is also worth pointing out that even in the PMIP3 setup for the Last Millennium simulations there are a number of options for the solar and volcanic forcing. Hence even the forced response is subject to uncertainties and differences depending on choice of forcing combinations. Therefore our criterion for selecting these periods was to "select within the period defined by the IPCC as the MCA and LIA the time in which the warming and cooling was strongest". This approach results in a "conditioned composite", ensuring that we extracted the largest possible signal in each of the simulations considered.

We have rerun all our calculations with the reference period as suggested: 1000-1850 AD, which is the largest common period of all simulations (see the Table for length of simulations for individual models).

With regards to the second criterion, we verified that both criteria, for example warmest years in the 950-1250 period, and the temperature gradient coincided. This guarantees that no circular arguments were made, as the reviewer correctly pointed out. We wish to point out that there was no need to change the LIA and MCA periods of the individual models.

III. Section 2.2 and 3.2: The Hadley circulation is not defined for sectors only as zonal mean. This is text book knowledge and I am amazed that the authors are not aware of this fact. The reason is simply that if one averages only over a section mass can be exchanged in longitudinal direction. So I strong recommend to read e.g. the book of Holton 'An Introduction to Dynamic Meteorology'. As the Hadley circulation is not defined for sectors the entire analysis and interpretation is useless.

We recalculated the global Hadley Cell (figure attached) and also calculated the local Hadley Cell by using the methodology described in Zhang and Wang (2013). In their paper, in order to evaluate the local Hadley Cell they separated the horizontal winds into their non-divergent and irrotational components and only used the irrotational part to evaluate the meridional flow. Both figures are qualitatively the same. But we now include the local Hadley Cell in the paper as well. Conclusions did not change.

IV. Definition of the ITCZ, page 5658: The authors use max. precipitation to define the ITCZ. This is problematic as authors have shown (Nicholson, S. E., Clim. Dynam. 32,1155-1171, 2009; Laederach, Tellus A, 65, 20413, 2013.). More importantly the authors extrapolate to a finer gird which makes no sense at all: (i) the model resolutions are coarse (maybe up to 1 degree) and there is no information gain when extrapolating gridded data to finer grids, (ii) precipitation can depend on very local structures also over the ocean (e.g. atmospheric waves) and may be affected by the numerics (e.g. Gibbs phenomenon). This can lead to problems when extrapolating the data.

For the definition of the ITCZ we used the precipitation centroid method, following Frierson and Hwang (2012), as well as Donohoe et al (2013). We are aware that each method of ITCZ has is own merits and problems. We thank the reviewer for the interesting papers on this regard. In order to minimize the problems over the continents, we explicitly only focused on the oceanic part. Also, given that we are interested only in the difference between the two periods, if there are any systematic errors, these will likely cancel out by looking at the difference.

V. Most of the results in section 3 and figure lack a significance test and it is not clear how the significance is performed. This is important as the changes are rather low, e.g. in Fig. 7, 6, 4, 2. I doubt that most of the changes shown are not significant and thus not relevant. This may also be related to the obscure definition of the periods.

The differences between LIA and MCA composites were tested using a bootstrap test (Efron, 1979). We performed 1000 iterations with the threshold for a statistical significance set to 5%, and used the bias-corrected and accelerated percentile method to estimate the confidence interval. Figures 2, 3a, 4, 5, 6 and 7 include this statistical significance test.

Specific comments

5651, title: The Authors use only PMIP3 simulations and not CMIP5, so please remove this from the title.

PMIP3 LM simulations are part of CMIP5, but we are also using the HadCM simulation, which does not belong to the PMIP3/CMIP5 model ensemble. Therefore we changed the title to: ….climate models.

5652, 2: 'South American Monsoon System (SAMS) variability in the Last Millennium'

Changed in text.

5652, 8: What is a small forcing? Do you mean external forcing?

Yes, we refer to small external forcing. Included in the text.

5652, 11: The sentence starting with 'However' is unclear.

We have changed the sentence and hope it is clearer now: "Therefore we used an ad-hoc definition of these two periods for each model simulation in order to maximize their differences. With this definition, several coherent large-scale atmospheric circulation anomalies were identified."

5652, 16: 'poleward shift of the South Atlantic Convergence Zone'

Changed "in" to "of".

5652, 13-19: This sentence is too long and unclear.

We have divided this statement into two separate sentences. We hope it is clearer now. It reads:"The models feature a stronger Monsoon during the LIA associated with: (i) an enhancement of the rising motion in the SAMS domain in austral summer, (ii) a stronger monsoon-related upper-troposphere anticyclone, (iii) activation of the South American dipole, which results to a certain extent in a poleward shift of the South Atlantic Convergence Zone and (iv) a weaker upper-level subtropical jet over South America. The diagnosed changes provide important insights into the mechanisms of these climate anomalies over South America during the past millennium."

5652, 25: The sentence starting with 'Because' is awkward.

We have changed the wording. "Because on precessional time scales summer insolation in both hemispheres is in anti-phase (for example, when Northern Hemisphere (NH) summer insolation is at its maximum, summertime insolation in the Southern Hemisphere (SH) is at its minimum), it weakens the monsoonal circulation and precipitation in one hemisphere while enhancing it in the other."

5653, 20: 'Vuille et al. (2012) reviewed'

Changed "reviews" to "reviewed"

5653, 25: I suggest to write meridional temperature gradient.

Suggestion implemented.

5654, 1: 'Pacific during the LIA'

Changed "through the" to "during the".

5654, 3: 'regional ITCZ favors'

Changed.

5654, 11: Better use 'Moreover, modelling studies support a southward (northward) shift'

Suggestion implemented.

5654, 21-25: This sentence remains unclear.

We have change the sentence to: "Furthermore, the modelling experiments discussed by Broccoli et al. (2006) and Lee et al. (2011) indicate that when cooler-than-normal temperatures are imposed in the North Atlantic domain, as occurred during the LIA, the Atlantic ITCZ shifts southward. In their experiments, this in turn is related to a strengthening of the northern Hadley cell in austral summer and a slight southward shift of its rising branch".

5654, 26: 'approaches suggest that the particular'

Changed.

5655, 1-2: 'have been incorporated in the third phase'

Changed.

5655, 5: Please make a line break here.

Line break introduced.

5655, 7: 'insights in the response'

Changed

5655, 9-10: The sentence is unclear, what is meant by near-global temperature anomalies', what are the main features of South American climate and in which sense main, temporal, spatial???

We changed the sentence to: "We focus on the models' ability to simulate the variability observed in a few key aspects of the South American climate during two periods of near-global temperature anomalies. These aspects include precipitation, temperature and atmospheric circulation."

5655, 11: Please make a line break here.

Line break introduced.

5656, 4-5: 'past millennium are the MCA (950–1250CE) and LIA (1450–1850CE). This report also' reads better

Changed as suggested.

5656, 1. Paragraph: Just to let you know that there are new studies on the way or published assessing simulated and reconstructed temperatures: PAGES2K-PMIP3, Climate of the Past, 11, 1673-1699. Fernandez-Donado et al., Clim. Past, 9, 393-421. I think the authors should include this in the introduction, here and the conclusions as they are fundamental publications on how to compare models and reconstructions

Thanks for these references. We now discuss them in the text.

5656, 10-15: Why do the authors only use three reconstructions, this seems to be not justified given the fact that IPCC makes a much more comprehensive comparison. Another point is that this exercise is not new and the reason why the authors make the comparison for NH temperatures is also not justified.

We have updated the figure with the complete set of reconstructions used in the IPCC AR5.

5656, 17: 'mostly a result'

Changed.

5656, 27: Wrong unit, a temperature gradient has NOT the unit degree C.

Changed "gradients" to "differences".

5657, 6: Distribution of which variable?

The sentence now reads: "Figure 1b shows the Gaussian fit of the frequency distribution of NH temperatures of all the years defined as LIA years (red curve) and MCA years (blue curve) respectively."

5658, section 2: It remains unclear how the authors combined the model output to a common grid.

We have included the followng sentence: "All variables have been re-gridded using a simple linear interpolation to a common 2x2 degree grid"

5662-5663: This paragraph (in comparison to the first paragraph of the section 4) sounds like that PMIP3 simulations use different models than CMIP5. This is not the case. PMIP3 uses the CMIP5 models.

We have clarified which model simulations we are using.

5665, 1-2: There are no proxy archives, which directly record circulation. The archives are mostly either temperature or precipitation sensitive and then authors try to say something about circulations, which may lead to circular statements/interpretations.

We have clarified that the large-scale circulation is consistent in particular with expected changes in precipitation.

"Our results indicate that the CMIP5/PMIP3 models quite accurately reproduce changes in the large-scale circulation that in turn are consistent with proxy evidence of precipitation changes over the past millennium".

Figures:

Fig. 1 b: Which temperature is shown, NH annual mean temperature?

Yes, NH annual mean temperatures. This has been clarified in the caption.

Fig. 2: Color scale makes no sense as no regional structures are visible, also apply a significance test and increase the labels of the color bars

We have included the significance test and larger labels.

Fig. 3a: Orange lines are not visible.

We have eliminated the orange lines.

Fig. 4: Unit arrow is missing so changes in the wind are not assessable. Include significance test, preferable a non-parametric test.

Unit arrow is included. Significant changes are coloured in red.

Fig. 5: Makes no sense as the mass stream function is not defined over a sector.

We now show the regional Hadley Cell by using the irrotational part of the wind field.

Fig. 6: Unit arrow is missing. Include significance test, preferable a non-parametric test.

Unit arrow is included. Significant changes are coloured in red.

Fig. 7: Include significance test, preferable a non-parametric test.

Significance test is included.

References discussed in response to reviewer 1

Donohoe, A., Marshall, J., Ferreira, D., McGee, D., 2013. The relationship between ITCZ location and cross equatorial atmospheric heat transport; from the seasonal cycle to the last glacial maximum. J. Climate 26, 3597–3618.

Efron, B. (1979), Bootstrap Methods: Another Look at the Jackknife. *The Annals of Statistics*, 7(1), 1-26.

Frierson, D. M. W., and Y.-T. Hwang, 2012: Extratropical influence on ITCZ shifts in slab ocean simulations of global warming. J. Climate, 25, 720–733.

Zhang and Wang, 2013: Interannual Variability of the Atlantic Hadley Circulation in Boreal Summer and Its Impacts on Tropical Cyclone Activity. Journal of Climate, 26, pgs 8529-8544, DOI: 10.1175/JCLI-D-12-00802.1

Reviewer 2:

This study analyzes climate model simulations from the CMIP5/PIMP3 to investigate the variability of the South American Monsoon with emphasis on the Medieval Climate Anomaly (MCA) and Little Ice Age (LIA) periods.

The study is interesting and can be considered after major revisions.

The main comment I would like the authors to consider regards the identification of the MCA and LIA periods. The criterion used (described on page 5656) considers the temperature variability in each model separately, although all models were forced with similar forcings. However, the spread among the time periods for all models is very large (Table 1) sometimes differing by 150-200 years. The ensemble model mean and uncertainties need to be considered in the analysis.

Indeed the criteria for selecting the periods were not the same as used by the IPCC. Instead we defined the MCA and LIA, through a more subjective ad-hoc method, which results in a "conditioned composite" analysis.
The reason for this approach is twofold:
a) The IPCC concluded that the MCA in particular (but also LIA) are characterized by an important contribution from internal variability; hence we cannot expect that all models produce an MCA-like state at the exact same time.
b) The simulations we use have similar but not identical forcings. For example there are various options for solar and volcanic forcings used in the implementation of the various simulations (see Schmidt et al 2012).

Given these two reasons, we expect that much of the variability seen in these simulations occurs in response to internal variability. Hence in order to maximize the extraction of a signal we choose to select the warmest years in the 950-1250 period for the MCA, and the coldest time in the 1450-1850 period for the LIA.

We now include a measure of the significance of the differences by applying a bootstrap test in all Figures where appropriate.

Other comments:

Page 5657 Line 2: please replace "that" by than

Corrected.

Page 5658 line 6: please explain why the precipitation was interpolated to 1 degree

To identify the ITCZ we used the method defined by Frierson and Hwang (2012): Precipitation centroid. In their own words: "The precipitation is interpolated to a 0.18 grid over the tropics to allow the precipitation centroid to vary at increments smaller than the grid spacing".

Page 5659 line 29: do the proxy paleo records differentiate the transition seasons?

Unfortunately there is no adequate proxy network in place that would have the required resolution, or the sensitivity to transition season temperature or precipitation to capture such changes in the transition seasons.

Page 5662 lines 19-24: what could be the reasons for these differences? any speculations?

The main reason is likely because the other studies mentioned here all imposed a much stronger forcing over the North Atlantic domain. It may have been a bit misleading to compare the PMIP3/CMIP5 last millennium simulations (small forcing) with these other studies. We have clarified this in the revised manuscript.

<u>References discussed in response to reviewer 2</u>

Frierson, D. M. W., and Y.-T. Hwang, 2012: Extratropical influence on ITCZ shifts in slab ocean simulations of global warming. J. Climate, 25, 720–733.

Schmidt, G. A., Jungclaus, J. H., Ammann, C. M., Bard, E., Braconnot, P., Crowley, T. J., Delaygue, G., Joos, F., Krivova, N. A., Muscheler, R., Otto-Bliesner, B. L., Pongratz, J., Shindell, D. T., Solanki, S. K., Steinhilber, F., and Vieira, L. E. A.: Climate forcing reconstructions for use in PMIP simulations of the Last Millennium (v1.1), Geosci. Model Dev., 5, 185–191, doi:10.5194/gmd-5-185-2012, 2012.

The South American Monsoon Variability over the Last Millennium in climate models

M. Rojas, P. A. Arias, V. Flores-Aqueveque, A. Seth, and M. Vuille

Abstract

In this paper we assess South American Monsoon System (SAMS) variability in the Last Millennium as depicted by global coupled climate model simulations. High-resolution proxy records for the South American monsoon over this period show a coherent regional picture of a weak monsoon during the Medieval Climate Anomaly and a stronger monsoon during the Little Ice Age (LIA). Due to the small external forcing during the past 1000 years, model simulations do not show very strong temperature anomalies over these two specific periods, which in turn do not translate into clear precipitation anomalies, in contrast with the rainfall reconstructions in South America. Therefore we used an ad-hoc definition of these two periods for each model simulation in order to account for model-specific signals. Thereby, several coherent large-scale atmospheric circulation anomalies were identified. The models feature a stronger Monsoon during the LIA associated with: (i) an enhancement of the rising motion in the SAMS domain in austral summer, (ii) a stronger monsoon-related upper-tropospheric anticyclone, (iii) activation of the South American dipole, which results in a poleward shift of the South Atlantic Convergence Zone, and (iv) a weaker upper-level subtropical jet over South America. The diagnosed changes provide important insights into the mechanisms of these climate anomalies over South America during the past millennium.

Keywords

South American monsoon, Last Millennium, Little Ice Age, Medieval Climate Anomaly, CMIP5/PMIP3 simulations, precipitation reconstruction

1. Introduction

It is well established that monsoon systems respond to orbital forcing (Kutzbach and Liu, 1997; Kutzbach et al., 2007; Bosmans et al., 2012). At orbital timescales (especially related to the precessional cycle of approx. 19 and 21 kyrs), changes in the latitudinal insolation gradient, and hence temperatures, force the monsoon circulation globally (e.g., Bosmans et al., 2012). In the precession frequency band the summer insolation is in anti-phase between hemispheres (for example, when Northern Hemisphere (NH) summer insolation is at its maximum, summertime insolation in the Southern Hemisphere (SH) is at its minimum). This results in weakened monsoon circulation and precipitation in one hemisphere while in the other the monsoon is strengthened. The mechanism for the orbital-induced monsoon variability is therefore mainly related to meridional temperature gradients. Thus, it is not

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surprising that other phenomena that produce important changes in hemispheric temperature gradients are also responsible for monsoon variability. Examples of these are abrupt Dansgaard-Oeschger events during the last glacial (Kanner et al., 2012; Cheng et al., 2013) and Heinrich events, including the Heinrich 1 event, during the last deglaciation (ca. 17 ka BP) (e.g., Griffiths et al., 2013; Deplazes et al., 2014; Cruz et al., 2006; Strikis et al., 2015).

In recent years, similar variability has also been observed for shorter timescales, in particular between the two most prominent climate anomalies over the Last Millennium (LM), the Medieval Climate Anomaly (MCA, ca. 950-1250 CE) and the Little Ice Age (LIA, ca. 1450-1850 CE) (e.g., Masson-Delmotte et al., 2013a). Recent high-resolution records from the area of the South American Monsoon System (SAMS) domain have been used to reconstruct precipitation over this region. Records include speleothems (Novello et al., 2012, 2016; Kanner et al., 2013; Apaestegui et al., 2014), pollen (Ledru et al., 2013), lake sediments (Bird et al., 2011), as well as tree-ring reconstructions (Morales et al., 2012). Vuille et al. (2012) reviewed current available proxy records for the SAMS region. Most reconstructions show good correlations with NH temperature and Intertropical Convergence Zone (ITCZ) reconstructions. According to these paleoclimate studies, the LIA was characterized by a cool north equatorial Atlantic and a warm south equatorial Atlantic (Haug et al., 2001; Polissar et al., 2006) whereas an opposite pattern was present during the MCA. This meridional temperature gradient led to a southward (northward) migration of the Atlantic ITCZ during the LIA (MCA) (Haug et al., 2001). Indeed, SAMS reconstructions during the last millennium show a weaker monsoon during the MCA period and a relatively stronger monsoon during the LIA period (e.g. Bird et al., 2011; Vuille et al., 2012; Ledru et al., 2013; Apaestegui et al., 2014), indicating an anti-correlation with reconstructions of the Southeast Asian monsoon (Zhang et al., 2008; Shi et al., 2014; Polanski et al., 2014), as well as with the North African and North American monsoons (Asmerom et al., 2013), for those periods.

Moreover, modelling studies support a southward (northward) shift of the Atlantic ITCZ during LIA (MCA) derived from temperature and precipitation reconstructions. For instance, model simulations by Vellinga and Wu (2004) suggest that anomalous northward ocean heat transports during the MCA was linked to an enhanced cross-equatorial temperature gradient in the Atlantic and a northward movement of the ITCZ. Kageyama et al. (2013) analysed fresh water hosing simulations over the North Atlantic to force fluctuations in the strength of the Atlantic Meridional Overturning Circulation (AMOC). Their analyses suggest that the model response to an enhanced high latitude fresh water flux is characterized by a general cooling of the North Atlantic, a southward shift of the Atlantic ITCZ, and a weakening of the African and Indian monsoons. Furthermore, modelling experiments discussed by Broccoli et al. (2006) and Lee et al. (2011) indicate that cooler-than-normal temperatures imposed in the North Atlantic domain, as occurred

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during the LIA, shifts the Atlantic ITCZ southward. In their experiments, this shift is related to a strengthening of the northern Hadley cell in austral summer and a slight shift in its rising branch to the south. Thus, a number of paleoclimate reconstructions and modelling studies suggest that the particular temperature anomalies observed during the MCA and LIA periods, especially in the North Atlantic, were large enough to modify the location of the ITCZ over the tropical Atlantic, thereby affecting the strength of the summer SAMS throughout the past millennium (see also a review by Schneider et al., 2014).

Recent climate modelling experiments for the LM (850–1850 CE) have been incorporated in the third phase of the Paleoclimate Modelling Intercomparison Project (PMIP3). About a dozen models included in the Climate Model Intercomparison Project Phase Five (CMIP5) ran this experiment, which considers solar, volcanic, greenhouse gases, and land use scenarios during the LM (Schmidt et al., 2011, 2012).

In this paper, we explore if and how these coupled General Circulation Models (GCMs) simulations capture the variability of the SAMS associated with LIA and MCA temperature anomalies, as suggested by rainfall reconstructions and diverse modelling studies in the region. This evaluation provides further insights regarding the response of the current generation of GCMs to external forcing during the LM. We focus on the models' ability to simulate the variability of the main characteristics of the South American climate during two periods of near-global temperature anomalies. These characteristics are analysed by concentrating on three main features: precipitation, temperature, and atmospheric circulation.

This paper is organized as follows: section 2 presents a short description of the model simulations considered and the methodology used to identify the MCA and LIA periods; section 3 presents the main results from the climate simulations of the SAMS during both periods; and section 4 presents a discussion and the main conclusions from this study.

2. Methodology and Model Simulations

We use nine available coupled GCMs, eight of which correspond to CMIP5/PMIP3 LM simulations and one that does not follow the exact PMIP3 experimental setup. The model simulations are listed in Table 1. These simulations cover the period 850-1850 CE, although some of them continued up to the present. But since not all modeling groups have continuous runs to the present (including the period 1850-2000) available, the analysis in this paper covers only the period until 1850 CE. The LM simulations were forced with orbital variations (mainly shifts in the perihelion date), common solar irradiance, two different volcanic eruption reconstructions, land-use change, and greenhouse gas (GHG) concentrations. A full description of the exact forcings used in these LM simulations is

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given by Schmidt et al. (2011, 2012). Furthermore, a detailed list of individual forcings applied in each simulation is given in Annex 2 of Masson-Delmotte et al. (2013a).

2.1 Definition of periods

The fifth Intergovernmental Panel on Climate Change (IPCC) assessment report (AR5) (IPCC, 2013), defined the two periods of most prominent climate anomalies over the past millennium as the MCA (950–1250 CE) and the LIA (1450–1850 CE). This report also concluded that the MCA was a period of relative global warmth, although in general less homogenous than the current warmth, whereas the LIA was a much more globally uniform cold period (Masson-Delmotte et al., 2013a). A recent analysis of the consistency of the CMIP5/PMIP3 LM temperature simulations indicates that these simulations often differ from available temperature reconstructions in their long-term multi-centennial trends, which is related to the transition from the MCA to the LIA period (Bothe et al., 2013; Fernández-Donado et al., 2013). Figure 1a shows the NH temperature anomaly time series for each of the nine models considered, as well as its ensemble mean. For comparison, reconstructions used in Fig 5.7 of the fifth IPCC report are shown (Masson-Delmotte et al, 2013a,b). From Figure 1a it is clear that the temperature anomalies over the last millennium are small, and that there is not a clearly common identifiable MCA and LIA periods are not easily identifiable across models. This is consistent with the notion that at least the MCA is partially a result of internal climate variability.

The hypothesis that guides the methodology used to asses the SAMS variability in models, is that both periods resulted substantially from internal (non-forced) variability. In addition, given that not all GCM simulations used the exact same forcing, we cannot expect the models to exactly reproduce the temporal variability as indicated by the reconstructions. Therefore, we identify these two periods individually in each model, using two criteria. First, for each model, the warmest period during 950-1250 CE (MCA) and coldest period during 1450-1950 CE (LIA) are defined by calculating the annual temperature anomaly over the NH (north of 30ºN) with respect to the 1000-1850 mean (the longest common period in the simulations) and lying above and below the mean for the MCA and LIA respectively. Second, given the evidence for Atlantic southward/northward shifts of the ITCZ related to altered meridional sea surface temperature gradients between the tropical north and south Atlantic, we also verify that the periods identified with the first criterion correspond to periods when the surface temperature difference between the boxes (5º-20ºN) and (20º-5º S) in the Atlantic were negative (positive) for LIA (MCA). We then verify that both criteria coincide. For example, for the LIA, the period with cold NH temperature anomalies coincide with temperature anomalies in the North Atlantic box colder than that its South Atlantic box counterpart (negative gradient, not shown). This ad-hoc definition of periods can be considered as a "conditional composite" analysis. The MCA and LIA

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periods identified in each model are shown in Table 1. Note that in general the periods are on the order of 80-110 years long; shorter than the more general MCA and LIA definition. Figure 1b shows the Gaussian fit of the frequency distribution of NH temperatures of all the years defined as LIA years (red curve) and MCA years (blue curve) respectively. The difference between the two periods is statistically significant (bootstrap test, 5% significance level). Even though the anomalies are rather weak during both periods, a comparison with the values from their respective control simulation (piControl) shows that both periods are also significantly different, at the 5% significance level from the long-term mean. In addition, Figure 2 shows the maps of the annual mean temperature anomalies during LIA and MCA, as well as their difference, for the ensemble mean. Temperature anomalies in the models are largest over the NH and in particular over the North Atlantic domain. Importantly, however, the LIA and MCA periods identified in the models are not synchronous, as shown in Table 1.

2.2 Variables used

To identify the main differences in LM simulations of the SAMS, particularly during the LIA and MCA periods, we analyse monthly CMIP5/PMIP3 output for rain rate, and 850 hPa and 200 hPa horizontal winds. All variables have been re-gridded using a simple linear interpolation to a common 2x2 degree grid. In addition, the local Hadley Cell is evaluated using the meridional mass streamfunction (Ψ) calculated from the irrotational component of the meridional flow, as proposed by Zhang and Wang (2013). The computation involves the irrotational components of the zonal mean meridional wind [v_{IR}] over the American sector (80ºW-30ºW, 35ºS-15ºN). Here, Ψ is defined as the vertically integrated northward mass flux at latitude φ from pressure level p to the top of the atmosphere. Thus,

$$\Psi(\phi,p) = \frac{2\pi cos\phi}{g}\int_0^p [v_{IR}(\phi,p)]dp \qquad (1)$$

where g denotes the acceleration due to gravity. All the calculations were carried out from monthly mean values, from which climatological means were calculated, and seasonal and annual means evaluated.

The oceanic Inter-tropical Convergence Zone (ITCZ) is identified following the method proposed by Frierson and Hwang (2012). They define the ITCZ location by the precipitation centroid, as the tropical latitude with the maximum precipitation, at all longitudes over the ocean. Following their method, the precipitation was first interpolated onto a grid of 0.1 degrees to allow the precipitation centroid to vary. We explicitly do not consider the precipitation maxima over continents due to known problems in the correct definition of the ITCZ (e.g. see Laderrach and Raible (2013); Nicholson, 2009).

The next section examines the performance of the models and whether they simulate a

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stronger SAMS during the LIA, in comparison to the MCA, as suggested by precipitation proxies and previous modelling experiments. In addition, since the SAMS is a dominant feature of the South American climate during austral summer (e.g., Vera et al., 2006), we focused on its mature phase, the December-January-February (DJF) season.

3. Simulated SAMS circulation

3.1 Precipitation

Figure 3a shows the annual mean precipitation difference between the LIA and MCA periods. Blue and red curves correspond to the annual mean position of the oceanic ITCZ during LIA and MCA periods, respectively. The ensemble mean shows that the precipitation differences are small and statistically significant only in some regions (bootstrap test, $p<0.05$). There is more precipitation during the LIA compared with the MCA in Northeastern Brazil and across the tropical Atlantic, which are regions directly affected by the ITCZ position in the current climate. The mean position of the ITCZ between the two periods does not show any significant shifts (see Figure 3b), but a small southward shift in the Atlantic during the LIA is found, in accordance with the precipitation signal. Individually, models do show that during the LIA the ITCZ was shifted further southward at some longitudes (Pacific and Atlantic Oceans) when compared with the MCA (not shown).

Figure 4a shows climatological precipitation and 850 hPa atmospheric circulation over the SAMS region during austral summer. In general, models are able to reproduce the main summer circulation and precipitation characteristics over South America observed in present-day climate. A narrow oceanic ITCZ, a broad area of maxima rainfall over the continent (SAMS), and a southeast-northwest oriented South Atlantic Convergence Zone (SACZ) are observed in LM simulations, consistent with present-day observations (e.g., Garreaud et al., 2009). However, some models exhibit a double ITCZ over the eastern Pacific. This bias has been previously identified in CMIP3 and CMIP5 simulations, especially during austral summer and fall seasons (Hirota and Takayabu, 2013; Sierra et al., 2015). Despite the limitations of model resolution, austral summer lower tropospheric circulation simulated by the ensemble mean reproduces a cyclonic circulation over southeastern Bolivia (a.k.a. "Chaco low") as seen in observations and its associated northerly low-level jet, which is channelled by the Andes topography, transporting moisture to southern South America (Marengo et al., 2004).

When comparing LIA and MCA composites for DJF (Figure 4b), the models exhibit an increased easterly flow at approximately 5°S over the Atlantic and a weaker northerly low-level jet north of the Chaco low region, consistent with less precipitation over the SACZ during the LIA. Models also simulate less summer SAMS precipitation during LIA over the

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Amazon and the SACZ, but more in the Nordeste. This pattern is in opposition to rainfall reconstructions over the western Amazon, the SACZ, as well as Nordeste (e.g., Vuille et al., 2012; Novello et al, 2012; Apaestegui et al., 2014; Novello et al., 2016). By contrast, when considering annual mean simulations (Figure 3), most models show a southward migration of the Atlantic ITCZ (not very visible in the ensemble mean) and enhanced precipitation over the SAMS domain during the LIA, particularly over the eastern and southern Amazon, in agreement with paleo-climatological records for this period. This indicates that the LM simulations are not able to reproduce the expected changes of the austral summer Atlantic ITCZ location and SAMS rainfall during LIA and MCA periods. The positive changes in the annual mean seen in Figure 3 are due to the spring and autumn transition seasons.

3.2 Local Hadley cell

Several studies indicate that the strong seasonality of the SAMS is partially induced by the meridional migration of the local Hadley Cell (e.g., Trenberth et al., 2000; Dima and Wallace, 2003). Modelling results from Lee et al. (2011) suggest that the southward shift of the Atlantic ITCZ during a colder NH event strengthens the northern Hadley cell in austral summer, shifting its rising branch slightly southward into South America. Thus, to identify if the LM simulations exhibit coherent anomalies in the local Hadley Cell over the American sector (80ºW-30ºW, 35ºS-15ºN) during LIA and MCA periods, we analyse the climatological DJF meridional mass streamfunction estimated from the irrotational component of the winds for both periods (Figure 5). In general, models reproduce the main local austral summer Hadley Cell characteristics: a stronger branch located over the winter hemisphere (NH) with enhanced rising motion over the SH, mainly between 10ºS and the equator, and a weaker branch over the summer hemisphere (SH). The local Hadley Cell during the LIA is somewhat more intense compared with the MCA, especially over the descending part in the NH, and to a smaller extent in the ascending part over the SH, but there is no significant latitudinal shift of the cell (see Fig. 5b). This is only partially in agreement with the modelling experiment by Lee et al. (2011).
The intensification of the Hadley cell upward branch over South America, shown by most models during the LIA, is consistent with the enhanced precipitation as suggested by rainfall reconstructions in the region for this period (e.g., Vuille et al., 2012), although this pattern is not borne out in the corresponding rainfall simulated by these models.

3.3 Bolivian high and subtropical jet

The well-documented southward migration of the Hadley Cell and its rising centre from 10ºN in JJA to 10ºS in DJF is only a part of the monsoon rainfall seasonal migration over the Americas, which reaches a more southward location in austral summer (Dima and Wallace, 2003). Furthermore, this wide area of continental convection, although related to local convergence zones, is not only a result of the shift of the ITCZ into subtropical latitudes. The establishment of the Bolivian high, the characteristic monsoon upper-level anticyclone located over the central Andes during austral summer, and the position and

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strength of the SH subtropical jet (SHSJ) in South America are also related to this monsoonal convective activity (Lenters and Cook, 1997; Garreaud et al., 2003; Yin et al., 2014).

To identify changes in the Bolivian high during the LM, we analyse the austral summer upper-troposphere circulation during the LIA and MCA (Figure 6). Results indicate a stronger and more southeastward location of the SAMS anticyclone during the LIA. This strengthening of the Bolivian high is consistent with a stronger SAMS circulation. The southward shift of this upper-level anticyclone is related to an enhanced summer easterly flow over the central Andes, as suggested by previous studies (Lenters and Cook, 1999), and in turn would favour moisture transport and rainfall over the region (Garreaud et al., 2003). Moreover, the upper tropospheric wind anomalies strikingly resemble the South American dipole (e.g. Robertson and Mechoso, 2000), a primary mode of variability over this region. An anticyclonic anomaly is associated with a diffuse SACZ, enhancing moisture convergence and precipitation on its southwestern flank (i.e. leading to a poleward shift in the location of the SACZ). Again, model simulations do not show this enhanced austral summer rainfall in the Amazon and central Andes during the LIA, and feature only marginally more precipitation to the southwest (Figure 3).

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On the other hand, recent studies have identified that the strength and location of the SHSJ, which corresponds to the southward extent of the Hadley Cell, is a key factor for triggering convection during the dry-to-wet season transition in the Amazon (Yin et al., 2014). Particularly, when the SHSJ is weaker and/or reaches a more equatorward location, it promotes the incursion of synoptic disturbances to subtropical South America (e.g., Garreaud, 2000), enhancing lower-troposphere convergence and triggering the wet season onset over the region (e.g., Li and Fu, 2006). To identify simulated changes of the SHSJ during the LIA and the MCA, Figure 7 shows the 30m/s isotach of the climatological September-November 200 hPa zonal wind as well as the difference between LIA and MCA periods. In general, the ensemble mean does not exhibit significant changes in the SHSJ location over South America during either period, as also indicated by Figure 6b; however, the models simulate a weaker SHSJ during the LIA, not only in austral spring, but also for the annual mean and summer seasons (not shown). This weaker SHSJ, particularly during austral spring (i.e., the transition season from dry to wet conditions in the SAMS), would allow a stronger influence of cold air incursions to trigger SAMS convection and probably maintain a stronger monsoon during the LIA.

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4. Discussion and conclusions

According to our analysis, LM simulations are able to identify circulation features coherent with a stronger SAMS during the LIA: (i) an enhancement of the rising motion in the

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SAMS domain in austral summer, (ii) a stronger monsoon-related upper-troposphere anticyclone, (iii) activation of the South American dipole, which results to a certain extent in a poleward shift in the SACZ and (iv) a weaker spring SHSJ over South America. However, austral summer simulations do not exhibit the expected increase in precipitation in this region during this cold period, as suggested by proxy evidence, except over the Nordeste, where it is not expected based on proxy data (Novello et al., 2012). Furthermore, LM simulations only reproduce a slight, but insignificant, southward (northward) shift of the austral summer Atlantic ITCZ during the LIA (MCA), unlike results found in other modelling studies (Vellinga and Wu, 2004; Lee et al., 2011; Kageyama et al., 2013). This disagreement might be partially related to the fact that the above-mentioned modelling studies impose much stronger external forcing than the forcing used in the LM simulations. This meridional shift of the Atlantic ITCZ is commonly considered a key aspect to explain the changes in SAMS rainfall observed during these periods (e.g., Vuille et al., 2012).

Recent studies indicate that the new generation of models included in the CMIP5 still tend to perform poorly in simulating precipitation in South America, especially over the Amazon basin, and the Atlantic ITCZ (Yin et al., 2013; Siongco et al., 2014; Sierra et al., 2015). However, CMIP5 models have shown further improvement in simulating precipitation over the region, in comparison to the CMIP3 generation (Jones and Carvalho, 2013; Yin et al., 2013; Hirota and Takayabu, 2013).

What could bias the simulated austral summer SAMS rainfall response of the CMIP5 models during the past millennium? Recent studies indicate that CMIP5 simulations tend to overestimate rainfall over the Atlantic ITCZ (Yin et al., 2013) and exhibit either an East or West Atlantic bias, in association with overestimated rainfall along the African (Gulf of Guinea) or South American (Brazil) coasts, respectively (Siongco et al., 2014). Such a misinterpretation of the local ITCZ has been shown to bias rainfall simulations in the core of the SAMS (Bombardi and Carvalho, 2011). A stronger Atlantic ITCZ, for example, may contribute to enhanced surface divergence over tropical South America, inducing drier conditions in the region (e.g., Li et al., 2006), as observed in CMIP5 historical simulations (Yin et al., 2013; Sierra et al., 2015). However, a stronger local ITCZ does not necessarily translate into reduced SAMS rainfall since moisture convergence in this region is mainly influenced by the SACZ (Vera et al., 2009). Thus, the weaker SACZ during the LIA simulated by these models (Figure 3) could reduce moisture convergence and rainfall over the SAMS. Furthermore, positive feedbacks between land surface latent heat flux, rainfall, surface net radiation, and large-scale circulation are also found to contribute to the dry biases over the Amazon and SAMS in most of the CMIP5 historical simulations (Yin et al., 2013).

Another circulation feature related to SAMS rainfall is the intensity and location of the South Atlantic subtropical high. The eastward displacement of this anticyclone and its interaction with the SACZ provide favourable conditions for monsoon precipitation (Raia

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and Cavalcanti, 2008). Recent analysis of CMIP5 projections under different scenarios suggests that this surface anticyclone is likely to strengthen in association with globally warmer conditions (Li et al., 2013). Thus, a detailed examination of the response of this subtropical high to LM forcing is necessary in order to provide further explanations for the inadequate CMIP5/PMIP3 simulations of the SAMS rainfall variability throughout the past millennium.

The previous generation of LM model simulations reproduced warmer temperatures during the MCA when compared with the LIA, but generally underestimated the regional changes detected from available reconstructions or failed to simulate a synchronous response in accordance with these reconstructions (e.g., Gonzalez-Rouco et al., 2011). The latter has been mainly related to uncertainties in the forcing estimates, as well as reduced sensitivity to external perturbations, underestimated internal variability, or incorrect representation of important feedbacks in GCMs (e.g. Goosse et al. 2005; Braconnot et al., 2012). Some of these problems still persist in the PMIP3 LM simulations (PAGES 2k–PMIP3 group, 2015). Furthermore, a recent model simulation of the global monsoon during the LM, performed in a non PMIP3-experiment, indicates that the NH summer monsoon responds more sensitively to GHG forcing than the SH monsoon rainfall, which appears to be more strongly influenced by solar and volcanic forcing (Liu et al., 2012; Colose et al., 2016; Novello et al., 2016). Hence, a stronger sensitivity of SAMS rainfall to LM forcing estimations and the inadequate response of current GCMs to such forcings may also bias the CMIP5/PMIP3 simulations of the summer SAMS rainfall during the past millennium. Hence the weak temperature response seen in these models during the MCA (Figures 1 and 2) could contribute to the inadequate changes of austral summer rainfall in South America between LIA and MCA (Figures 3 and 4).

This evaluation of the SAMS throughout the past 1000 years in the latest generation of LM simulations confirms previous findings regarding the ability of the current generation of GCMs to reproduce large-scale circulation features in South America and their lack of an adequate representation of precipitation over the region. The availability of precipitation reconstructions from South America has been useful to provide new insights into the GCMs response to past forcings. However, the weak or absent temperature and precipitation response to the imposed forcing in climate models provides a formidable challenge for proxy-model comparisons. To better compare and eventually reconcile model reconstructions with proxy evidence will require a more detailed analysis of precipitation-generating mechanisms in climate models. Our results indicate that the CMIP5/PMIP3 models quite accurately reproduce changes in the large-scale circulation that in turn are consistent with proxy evidence of precipitation changes over the past millennium. These changes, however, do not translate into corresponding precipitation changes. This implies that the models may lack relevant feedbacks or that precipitation in the models may be too dependent on the microphysics and convective parameterization schemes, but not

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sufficiently sensitive to large-scale circulation mechanisms. On the proxy side, a stronger effort to not only reconstruct surface climate at individual locations, but also focus on reconstructions of modes of variability or entire climate components such as the SAMS, which implicitly include circulation changes, are needed. Proxies such as pollen or stable hydrogen and oxygen isotopes from lakes, speleothems and ice cores have shown potential to record larger-scale climate signals and changes in the tropical hydrological cycle over South America (Vuille and Werner, 2005; Vimeux et al., 2009; Bird et al., 2011; Vuille et al., 2012, Ledru et al., 2013; Flantua et al., 2016; Hurley et al., 2015). Multi-proxy reconstructions from such networks, which implicitly incorporate remote and large-scale circulation aspects, may therefore provide a better tool to assess the performance of climate models than reconstructions that are based solely on local precipitation estimates.

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Figure Legends

Figure 1. (a) Northern Hemisphere (north of 30°N) temperature anomaly evolution. Grey shading: 15 reconstructions used in Fig. 5.7 of Masson-Delmotte et al (2013a,b), colour lines: nine LM simulations considered in this study. (b) Distribution of Northern Hemisphere temperature anomalies during the Medieval Climate Anomaly (MCA, red curve) and Little Ice Age (LIA, blue curves), all with respect to the reference period 1500-1850 CE, corresponding to the longest common period in the reconstructions.

Figure 2. Multi-model average annual mean temperatures. (a) Difference between MCA and reference period 1000-1850 CE, (b) difference between LIA and reference period, (c) LIA - MCA. Stippling indicates regions where differences are significant at $p<0.05$.

Figure 3. (a) Multi-model average annual mean LIA - MCA precipitation difference (colours) and position of the oceanic Intertropical Convergence Zone (ITCZ) during the MCA (red line) and LIA (blue line). Stippling indicates regions where precipitation differences are significant at $p<0.05$. (b) Distribution of the zonal mean position [degrees] of the oceanic ITCZ during the MCA (red curve) and LIA (blue curve).

Figure 4. (a) Model mean Dec-Jan-Feb (DJF) 850hPa winds (vectors) and precipitation (colours) for the reference period (1000-1850 CE). (b) DJF mean LIA - MCA winds (vectors) and precipitation difference (colours). Red vectors indicate significant differences.

Figure 5. Multi-model mean DJF meridional mass stream function calculated from the irrotational wind over the region 80-30°W, depicting the regional Hadley Cell. (a) Climatology for reference period (1000-1850 CE), Red (blue) colours indicate clockwise (counterclockwise) circulation, (b) LIA - MCA. Only significant changes ($p<0.05$) are shown.

Figure 6. Multi-model mean DJF wind field at 200 hPa. (a) Climatology for reference period (1000-1850 CE). (b): LIA - MCA differences. Red box represents the South American Monsoon System (SAMS) domain. Red vectors indicate significant differences ($p<0.05$).

Figure 7. Multi-model mean LIA -MCA 200 hPa zonal wind for Sep-Oct-Nov (SON).

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Eliminado: (a) Northern hemisphere (north of 30°N) temperature anomaly evolution. Black line: mean on three reconstructions, grey envelope: maximum and minimum values of three reconstructions, colour lines: nine CMIP5/PMIP3 models considered in this study. (b) Distribution of temperatures during the Medieval Climate Anomaly (MCA, red curve) and Little Ice Age (LIA, blue curves), all with respect to the reference period 1250-1450 CE

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Black contour corresponds to the 30m/s isotach of reference period zonal wind (1000-1850 CE). Only significant differences ($p<0.05$) are shown.

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Table 1. LM model simulations used, including key reference and definition of LIA and MCA periods in each model.

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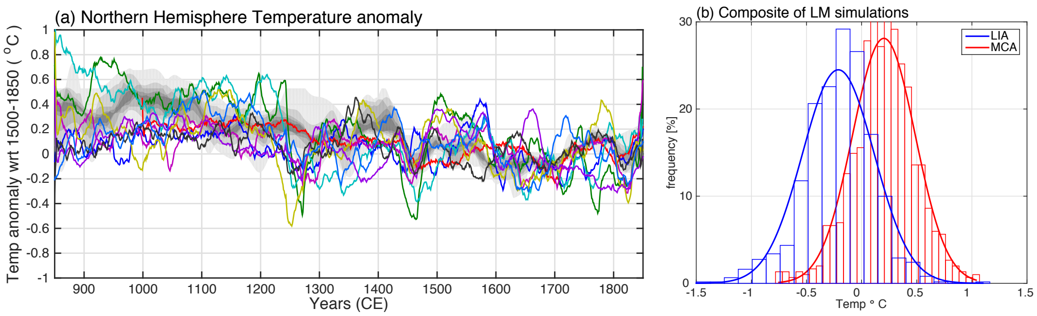
Model	MCA	LIA	Period (CE)	Reference
bcc-csm-1	1040-1130	1590-1790	851-2000	-
CCSM4	1110-1200	1710-1810	850-1850	Gent et al. (2001)
CSIRO-Mk3L-1-2	950-1050	1760-1850	851-2000	Phipps et al. (2011)
FGOALS-gl	1210-1270	1690-1820	1000-2000	Zhou et al. (2008)
FGOALS-s2	915-990	1710-1790	850-1850	Zhou et al. (2008)
HadCM3	1160-1250	1600-1700	801-2000	Schurer et al. (2013)
IPSL-CM5A-LR	910-950	1630-1710	850-1850	Dufresne et al. (2013)
MPI-ESM-P	1120-1220	1600-1680	850-1850	Raddatz et al. (2007)
MRI-CGCM3	1130-1230	1510-1620	850-1849	Yukimoto et al. (2011)

The South American Monsoon Variability over the Last Millennium in coupled climate simulations



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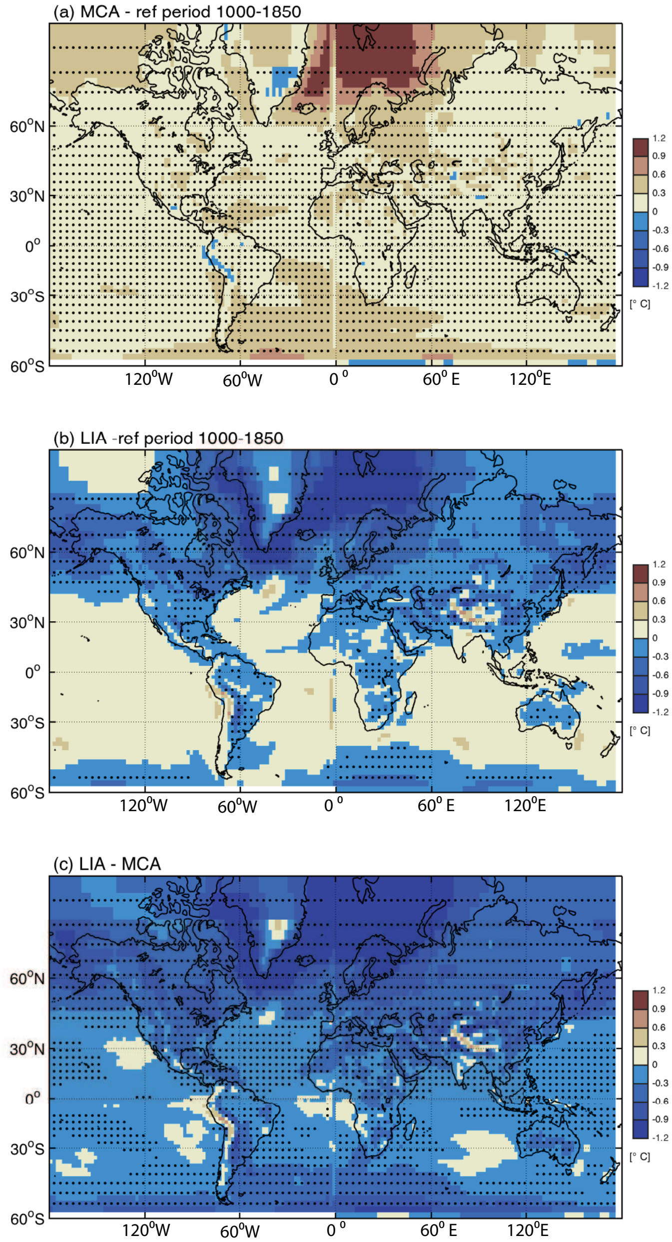

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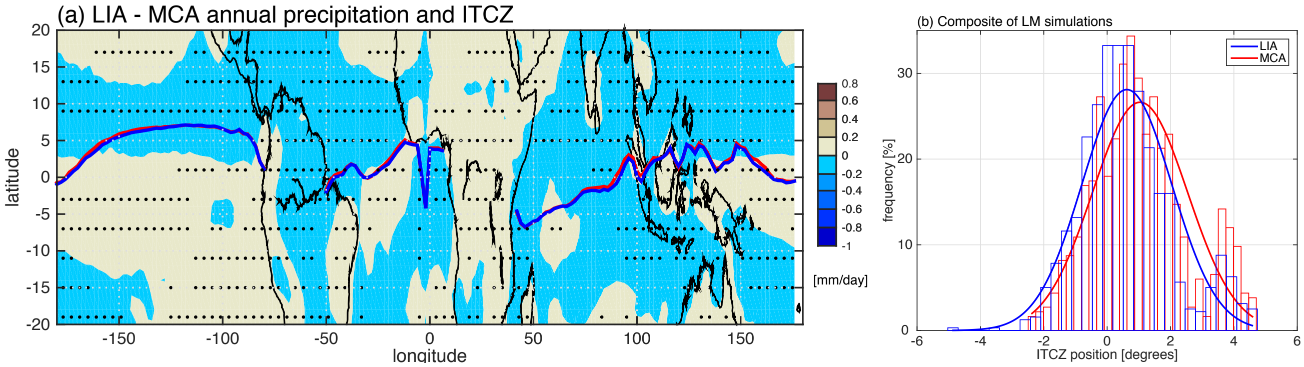
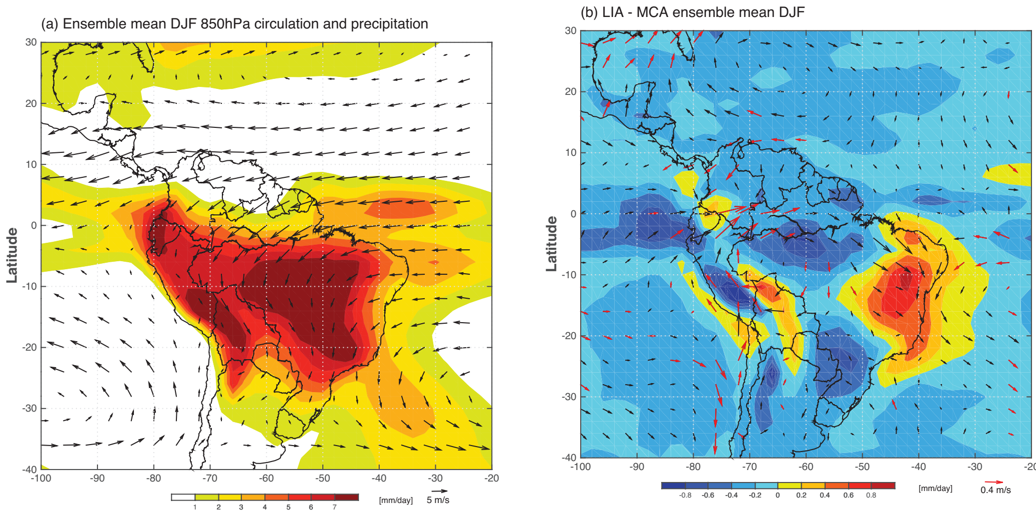


Figure 3. (a) Multi-model average annual mean LIA - MCA precipitation difference (colours) and position of the oceanic Intertropical Convergence Zone (ITCZ) during the MCA (red line) and LIA (blue line). Stippling indicates regions where precipitation differences are significant at p¡0.05. (b) Distribution of the zonal mean position [degrees] of the oceanic ITCZ during the MCA (red curve) and LIA (blue curve).



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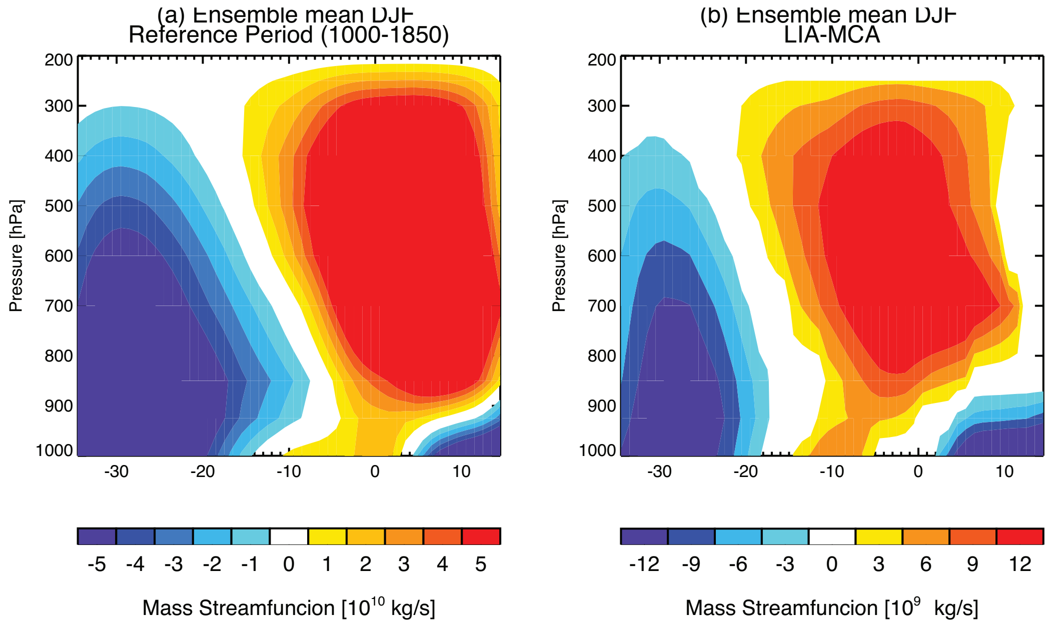

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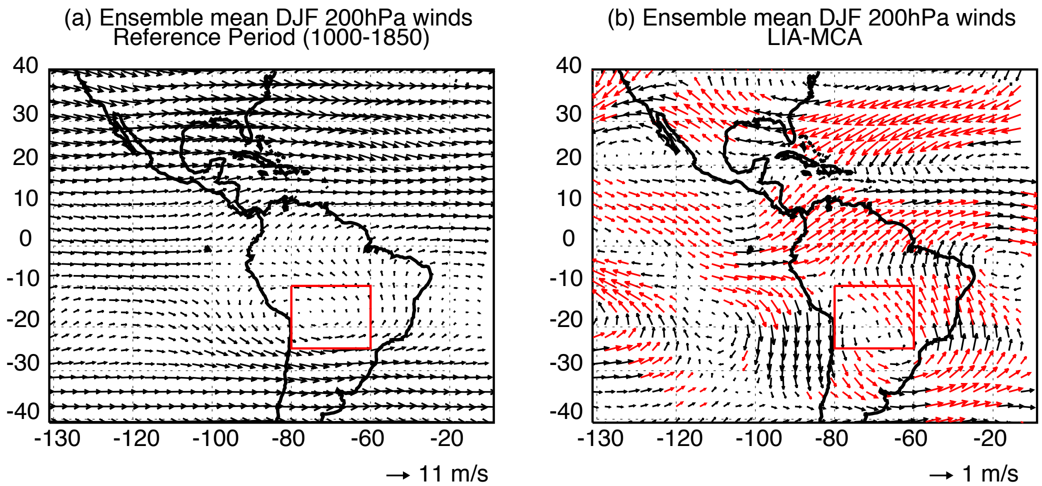

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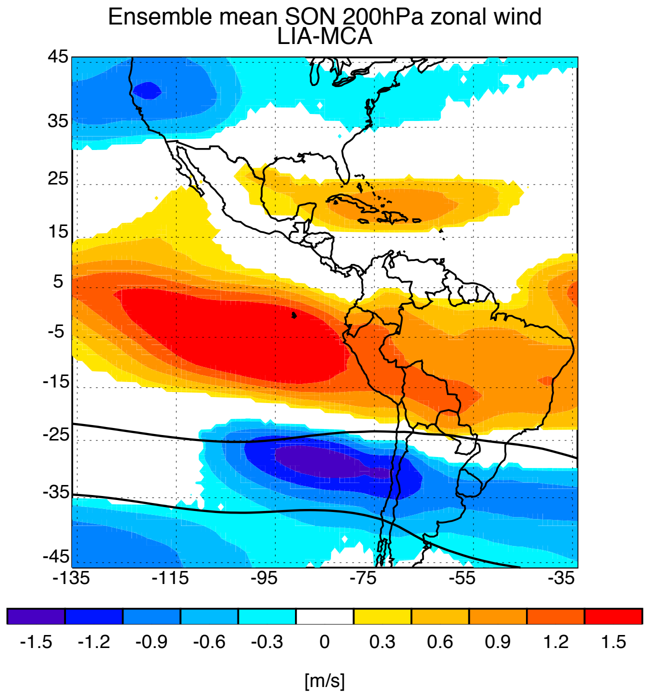

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