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Project co-funded by the European Commission within the Seven Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the Consortium (including the Commission Services)	
CO	Confidential, only for members of the Consortium (including the Commission Services)	

Contribution to project objectives – with this deliverable, the project has contributed to the achievement of the following objectives (from Annex I / DOW, Section B1.1.):

N.º	**Objective**	**Yes**	**No**
1	Reduce uncertainties in our knowledge of the functioning of Tropical Atlantic (TA) climate, particularly climate-related ocean processes (including stratification) and dynamics, coupled ocean, atmosphere, and land interactions; and internal and externally forced climate variability.	X	
2	Better understand the impact of model systematic error and its reduction on seasonal-to-decadal climate predictions and on climate change projections.	X	
3	Improve the simulation and prediction TA climate on seasonal and longer time scales, and contribute to better quantification of climate change impacts in the region.		X
4	Improve understanding of the cumulative effects of the multiple stressors of climate variability, greenhouse-gas induced climate change (including warming and deoxygenation), and fisheries on marine ecosystems, functional diversity, and ecosystem services (e.g., fisheries) in the TA.		X
5	Assess the socio-economic vulnerabilities and evaluate the resilience of the welfare of West African fishing communities to climate-driven ecosystem shifts and global markets.		X

Author(s) of this deliverable: Belén Rodríguez de Fonseca, Noel Keenlyside, et al.

Deviation from planned efforts for this deliverable: None to our knowledge. [A necessary change to the experimental design in WP6 and WP7 has delayed the timely completion of the experiments pertaining to these WPs. To avoid delays in D8.2, it was decided to make use of alternate experiments, either already performed by team members or freely available from the Coupled Model Intercomparison Project phase 5 (CMIP5). However, this has not affected planned efforts per beneficiary and/or WP, nor use of resources, for this deliverable. See 2nd periodic core report for details.]

Report

Executive Summary:

This deliverable is part of the work planned for work package 8. Among the main objectives of WP8 is to clarify how the bias within the tropical Atlantic impacts on the representation of the mean state and variability outside of the tropical Atlantic (partners UCM, Spain; UiB, Norway; GEOMAR, Germany) and vice versa.

In particular, in the present deliverable, the impact of systematic error on the representation of the connection between tropical ocean basins (Rodriguez-Fonseca et al., 2009; Martín del Rey, 2012; Losada et al, 2012; Ding et al., 2012;) is investigated (UCM, UiB). The understanding of the factors modulating this connection in observations and Phase 5 of the Climate Modelling Intercomparison Project (CMIP5) control runs is analysed to pose different hypotheses that will be tested by partially coupled simulations. The deliverable tackles the Atlantic influence on the El Niño Southern Oscillation (ENSO) and the impact of bias. In a first step CMIP5 simulations are analysed for different samples with enhanced and reduced bias in the Atlantic, with the aim of looking for possible influences on remote regions. UiB and UCM have contributed to assess the impact of tropical Atlantic variability on Indo-Pacific variability using partially coupled experiments in which the tropical Atlantic SST is restored to observations during the historical period. We focus on assessing whether correcting biases in the Atlantic (variability and mean) improves the simulation of structure, skewness, and timing of ENSO variability and its teleconnections.

The main results of the deliverable put forward how multidecadal changes associated with Atlantic Meridional Overturning Circulation (AMOC) and coupled to multidecadal changes in the Intertropical Convergence Zone (ITCZ) location modulate this connection. In this way, during periods in which the ITCZ is located close to the equator (negative AMOC), the equatorial dynamics processes are enhanced. Thus, during these decades, the tropical basins coupled their variability and the Atlantic appears as a potential predictor of ENSO.

In relation to bias, it has been shown how models with warmer bias in the south Pacific and colder in the south Atlantic need to warm up the southern Atlantic in an negative AMOC configuration to reach the background state needed for the inter-basin teleconnections.

The shift of the ITCZ can also be reached by changing the shortwave radiation in the top of the atmosphere in the southern extratropics, in a way that models with a reduced bias in that region simulate the Atlantic-Pacific connection, compared to models with a warm bias in the southern extratropics that do not.

Finally, experiments without bias in the Atlantic indicate how southward displacement of rainfall in the Atlantic associated with the south Atlantic warming after the 70s, leads to an enhanced atmospheric response to Atlantic Niño events that enables them to influence ENSO variability in boreal summer leading to stronger ENSO events in boreal winter.

Part A: Analysis of existing CMIP5 simulations

A.1: Influence of bias in the representation of tropical modes

Authors: Irene Polo Sánchez, Belén Rodríguez-Fonseca, Elsa Mohino Harris and Teresa Losada Doval (scientific publication to be submitted)

Before tackling the influence of bias in the Atlantic-Pacific connection, the influence of bias in the representation of the main interannual modes of variability is analysed (Fig. A.1.1, from Polo et al., to be submitted) and, as described in D8.1[1], using 18 CMIP5 models in pre-industrial conditions, the main modes of interannual SST variability in the tropical Atlantic and Pacific basins are analysed. Regarding the Pacific, the warmer the tropical SST bias the better the mode is represented. This fact implies a reduction of the cold bias in the equatorial Pacific exhibited by most of the CMIP5 models, but an enhancement of the warm bias in the south Atlantic.

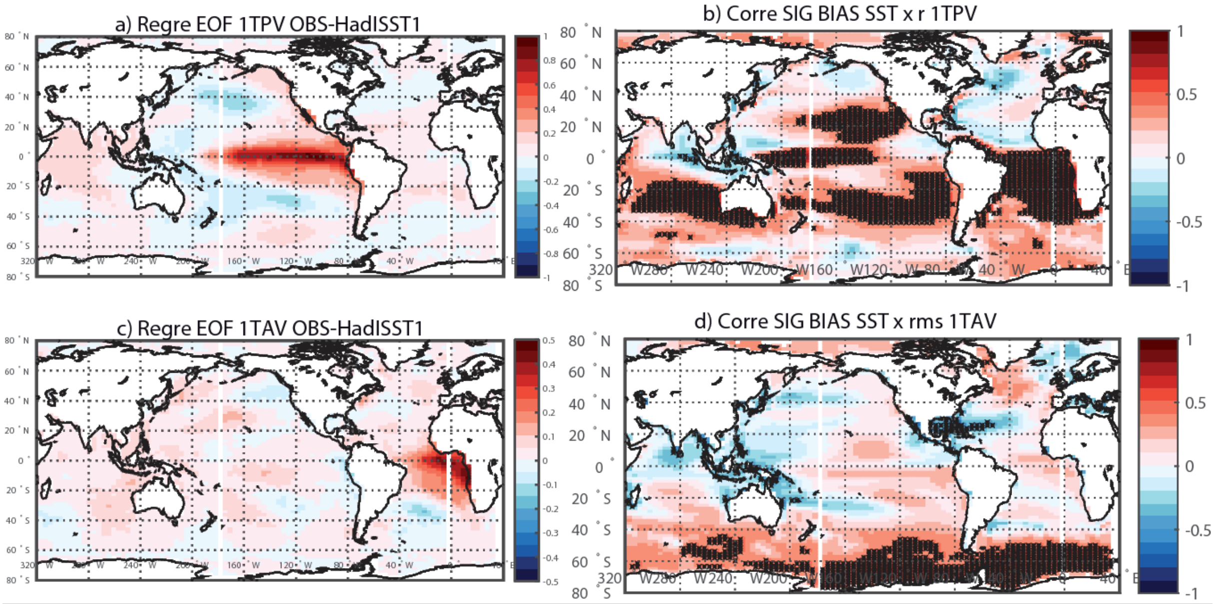

Figure A.1.1: a) Leading interannual mode of SST variability in the tropical Pacific based on observed SSTs (From HadSST data), plotted as a regression map; b) correlation map between model bias variability and the projection of the observed leading EOF onto each of the anomalous SSTs for each of the CMIP5 models using Pi-control simulations; c) and d) same as a) and b) but for the tropical Atlantic variability.

Regarding the Atlantic and for a correct representation of the tropical Atlantic main mode of interannual SST variability: the greater the warm bias (Fig. A.1.1.d) in the southern extratropical oceans, the greater the error (in terms of root mean squared error) in the representation of the pattern. This result indicates that experiments performed in Mechoso et al. (2016) where the Southern Ocean bias is reduced should show improvement in the representation of tropical Atlantic variability and the Atlantic-Pacific connection (see Part B). In that publication, an artificial reduction

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[1] D8.1 "Interdependence between biases in the Tropical Atlantic and in other regions"; public report available at www.preface-project.eu

of the shortwave incoming radiation over the Southern Ocean alleviates to some extent the systematic errors in the subtropics in the southern hemisphere.

In the section below (A.2), CMIP5 models are analysed (Rodriguez-Fonseca et al., 2016; to be submitted) in order to understand the factors modulating the Atlantic-Pacific connection. Also CMIP5 simulations are analysed with the aim of understanding the influence of mean model bias on the simulated modulation of the inter-basin teleconnection.

A.2: Mechanisms for the Atlantic-Pacific inter-basin connections; the influence of model bias

Authors: Belén Rodríguez-Fonseca, Irene Polo Sánchez, Elsa Mohino Harris, Teresa Losada Doval, Marta Martin-Rey and Noel Keenlyside (scientific publication to be submitted)

A.2. Abstract

Pacific El Niño is the leading mode of interannual variability of sea surface temperature and the principal predictor in current seasonal forecast systems. Recent studies have found, in observations, windows of predictability of ENSO from the tropical Atlantic. Thus, Atlantic Niño is able to influence in the atmospheric processes that trigger Pacific Niño by equatorial dynamics. These windows of opportunity occur at multidecadal timescales, with the Atlantic-Pacific connection enhanced from the 1970s and at the beginning of the 20th century, in phase with the evolution of the Atlantic Multidecadal variability. Nevertheless, no physical explanation has been found to explain the mechanisms behind this modulation. Here we analyse the connection in Pi-control simulations from CMIP5. CMIP5 models control runs exhibits a strong ENSO influence on the Atlantic and, only for some cases, the Atlantic is leading the Pacific. For those periods in which the model captures a connection as found observations after the 70's, the simulations exhibit an interhemispheric gradient of sea surface temperature, a weakening of the AMOC, an equatorward ITCZ shift over the Atlantic and Indian ocean, and a weakening of the Walker Circulation. The results of this study put forward the influence of model bias in the representation of the Atlantic-Pacific connection. Below is a brief summary of results for PREFACE deliverable D8.2 which are being prepared for a joint publication.

A.2. Introduction

Pacific El Niño is the principal predictor in current seasonal forecast systems. Predictability of ENSO from the Atlantic has been evidenced from the end of the 1970s, with a strong enhancement of ENSO predictability from the tropical Atlantic (Polo et al., 2008,2014; Rodríguez-Fonseca et al., 2009; Ding et al., 2012; Martín-Rey et al., 2012,2014,2015;2016; Mohino et al., 2011; Losada et al., 2010). Observations and coupled model sensitivity experiments have confirmed and described in detail the associated mechanisms in the way that an Atlantic Niño alters tropical convection and the Walker circulation producing anomalous subsidence over the central and western tropical Pacific. The associated surface winds in the western Equatorial Pacific, piles up the water, triggering oceanic kelvin waves that shallow the thermocline through the east, helping to develop a La Niña in the Pacific. The opposite takes place during an Atlantic La Niña event (Rodriguez-Fonseca et al (2009), Ding et al. (2011), Losada et al (2010, 2011), Martin-Rey et al (2012) and Polo et al (2015)). Interdecadal changes of the relationship have been reported, with the Atlantic-Pacific connection emerging during periods of negative AMO (Kucharski et al., 2016; Polo et al. 2015; Martin-Rey et al , 2014, 2015), and during weakening of the AMOC (Svendsen et al., 2013). In relation to this, the Atlantic Multidecadal Oscillation (AMO; Sutton et al., 2003; Knight et al., 2005) has been found to impact interannual variability of other basins (Dong et al., 2006, Kucharski et al., 2014; Kang et al. 2014) as well as to impact regional climate (Sutton et al., 2007), increasing the variability of the Pacific during the negative AMO phases. In the tropical regions, an enhancement of the convection over the western equatorial Atlantic (Martín-Rey et al. 2014) and an increase of ENSO variability (Dong et al. 2006) have been reported for negative AMO phases. Nevertheless, no physical mechanism has been proposed to explain why the Atlantic-Pacific Niños connection takes place during those decades.

CMIP5 models, and in particular pre-industrial control simulations, provide a climate laboratory to test the interdecadal variability of this connection. Nevertheless, these models struggle in reproducing the equatorial Atlantic mean and interannual variability (Breugem et al., 2006; Richter and Xie, 2008; Richter et al., 2012; see also supplementary material). Thus, the existence of strong warm bias in the development of the cold tongue in the tropics could influence the simulation of the Atlantic-Pacific connection (Sasaki et al., 2014; Richter et al., 2012). Although the interannual tropical Pacific variability (Fig. A.2.1) is relatively well reproduced in CMIP5 simulations, there has not been much improvement from CMIP3 ones (Guilyardi et al., 2006). Part of the bias in the tropical Atlantic in CMIP3 has been reduced in CMIP5 simulations (Richter et al., 2012), but there is still an important reduction of the tropical Atlantic variability, which contracts with the overestimation of observed ENSO variability in CMIP5 models. In the Atl4 region there is no seasonality in the variability in both models and observations, although the variability is also reduced in CMIP5.

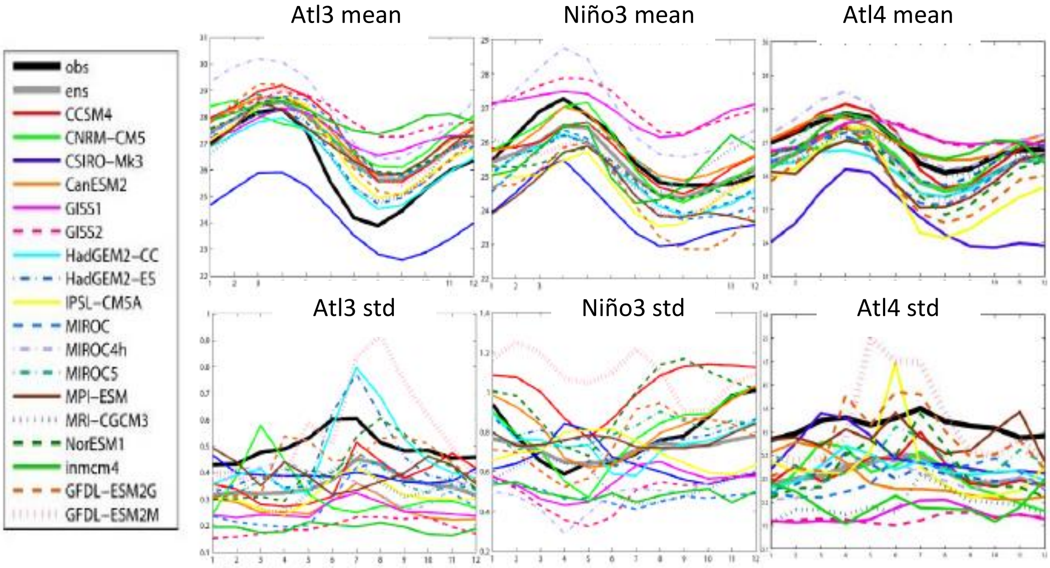


Figure A.2.1: Seasonal cycle of the Equatorial Indexes Atl3, Atl4 and Niño3 defined as the average of the SST averaged over the region [20W-00; 3S-3N], [40W-20W; 3S-3N] and [150W-90W; 5S-5N] respectively. a)-b) mean and standard deviation of the Atl3 index SST averaged over [20w-0; 3S-3N]; c)-d) Same as a)-b) but for Niño3 index SST averaged over [150W-90W; 5N-5S].

Recent studies have studied the inter-basin teleconnections in pre-industrial CMIP5 simulations. Results show how the timing of the Atlantic-Pacific connection depends on the strong warm SST biases in the Atlantic Benguela upwelling region and in the Pacific Ocean (Ott et al., 2015, Kucharski et al., 2014). An atmospheric bridge and the modification of the Walker circulation is proposed as the main process associated with the teleconnection (Ott et al., 2015, Kucharski et al., 2014), in agreement with Polo et al. (2014). Nevertheless, there is no mention of the interdecadal variability of this connection.

This study demonstrates for the first time the mechanism responsible for the establishment of the Atlantic-Pacific Niños connection at multidecadal time scales, using observations and long control coupled simulations from CMIP5 models.

A.2. Results

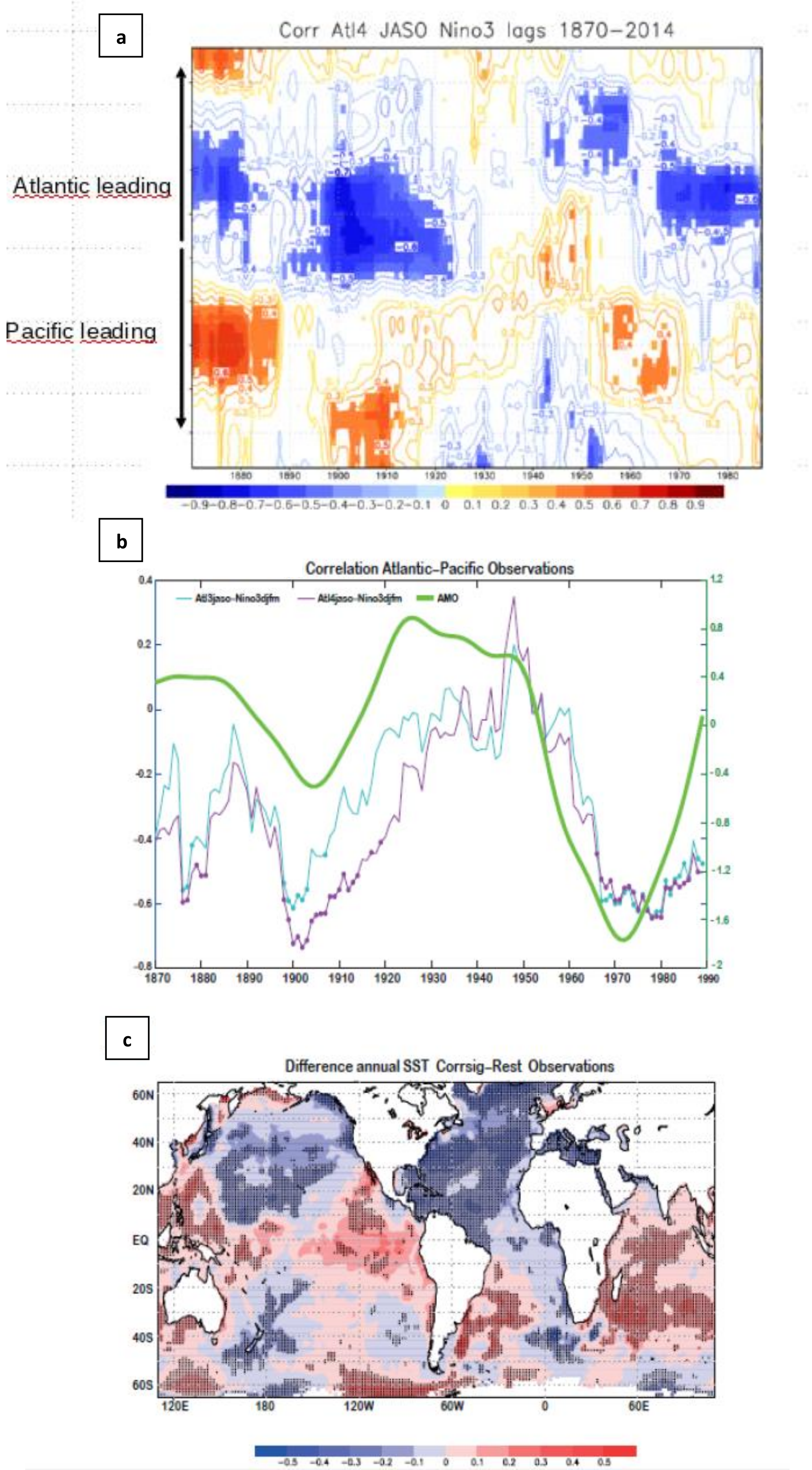
Observed modulation of the interannual inter-basin teleconnection

As has been shown in different studies from Polo et al. (2014) and Martin del Rey et al.(2014,2015), observations present periods of strong anti-correlation between the Atlantic and Pacific interannual SST variability for the beginning and end of the 20th century (Fig. A.2.2a,b). Also, they present periods with positive correlations between the Atlantic and Pacific interannual variability, although weaker and not significant. The correlation is stronger with the western Equatorial Atlantic (Atl4) than with the central-eastern equatorial region (Atl3).

In agreement with previous studies, the Atlantic-Pacific connection appears to evolve in phase with a global pattern which, in the Atlantic sector, resembles the Atlantic Multidecadal Oscillation (AMO, Fig. A.2.2b), with stronger connection during negative AMO phases. For those periods, together with the negative AMO-like SST pattern that emerges in the Atlantic Ocean, anomalies in the tropical Pacific and Indian Oceans, as well as in the extratropics are also present (Fig. A.2.2c). The spatial pattern remains that obtained by Kucharski et al. (2015), in which the authors examine the external impact of the AMO, showing how the AMO can impact on the Pacific mean state.

The global pattern in Figure A.2.2c is characterised by an interhemispheric gradient of sea surface temperature. The associated heating in the southern hemisphere could influence on the ITCZ location displacing it to the south. Thus, a possible mechanism to test in models is related to an interdecadal ITCZ shift and enhancement of equatorial dynamics processes. Wang et al (2014) have recently found how CMIP5 models with a warmer bias in the southern hemisphere simulate a weaker mean AMOC. Thus, according to the observational result in Figure A.2.2c and those from Svendsen et al. (2013), models with warmer bias in the southern oceans should favour a southward ITCZ and the enhancement of the inter-basin teleconnections. In the next section, CMIP5 models are analysed in order to test not only the mean conditions required for the Atlantic-Pacific connection but also the influence of bias in the interdecadal variability of this connection.

Caption for figure on next page: **Figure A.2.2**: **(a)** Adapted from Figure 1a in Rodríguez-Fonseca et al. 2009. 21 year lead-lag correlation, running one year from 1870–1890 to 1990–2010, between the observed boreal summer Atl4-index (JJAS) and observed Niño-3-index, for positive (from 0 to 24 months after summer) and negative (from 0 to 24 months before summer) lags. The contour interval is 0.1 and the zero line has been removed. Only those regions for which the correlation between the Niño3 and the Atl3 index is 95% statistically significant under a t-test for the effective degrees of freedom are shaded; **(b)** 21-years moving correlation between the anomalous SST in the equatorial Atlantic, Atl3 [20W-0, 3N-3S] (blue line) and Atl4 [40W-20W,3N-3S] (purple line) in summer (JASO) and in the Equatorial Pacific, Niño3 region [150W-90W,5N-5S], in the following winter (JFMA). The year in x-axis corresponds to the first year of the 21 yr-window. Significant correlations exceeding 95% confidence level according to a Monte Carlo test are shown in bold circles; **(c)** Difference between the global annual SST for the years with significant negative correlations between Atl4 in JASO and Niño3 in JFMA (purple dots in Fig.A2.2.b) and the years with no correlation. The dotted area shows the significant differences according to a t-test of equal means for 95-confidence level.


a
Corr Atl4 JASO Nino3 lags 1870–2014
Atlantic leading
Pacific leading
1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980
−0.9 −0.8 −0.7 −0.6 −0.5 −0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
b
Correlation Atlantic–Pacific Observations
Atl3jaso-Nino3djfm
Atl4jaso-Nino3djfm
AMO
0.4 0.2 0 -0.2 -0.4 -0.6 -0.8
1.2 0.8 0.4 0 -0.4 -0.8 -1.2 -1.6 -2
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
c
Difference annual SST Corrsig–Rest Observations
60N 40N 20N EQ 20S 40S 60S
120E 180 120W 60W 0 60E
−0.5 −0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 0.5

CMIP5 reliability of the interannual inter-basin teleconnection

The observed Atlantic-Pacific Niños lead-lag relation calculated in Figure A.2.2a, and centred in boreal summer months is well reproduced by all the 18 CMIP5 Pi-control simulations analysed (Fig. A2.3). Models present a strong inter-basin connection with positive correlation when El Niño is leading the Atlantic interannual equatorial variability and negative correlation when Atlantic leads the Pacific (Fig. A.2.3top). The inter-basin relation has a clear 3-4 years periodicity in both observations and model simulations (Fig. A.2.3top), suggesting an inter-basin oscillator that could be led by equatorial dynamics during some periods (Wang, 2006; Martín-Rey et al., 2014; Polo et al., 2015). For simulations the SST anomalies in the western equatorial Atlantic seem to be a much better indicator of the Atlantic-Pacific connection (Fig. A.2.3). Moreover, no consensus can be found when using the ATL3 index (Fig. A.S1), which could be explained because of the large SST bias present in the simulation of the equatorial Atlantic in CMIP5 models (Richter et al., 2012). Although CMIP5 models are able to reproduce the inter-basin connection, the seasonality does not agree with the observations and only a few windows presents significant anti-correlation in lag 0 (Fig. A.2.3bottom).

In addition, model simulations tend to overestimate the Pacific leadership, showing higher number of windows with significant positive correlation in respect to negative one, contrary to observations (Fig. A.2.3bottom).

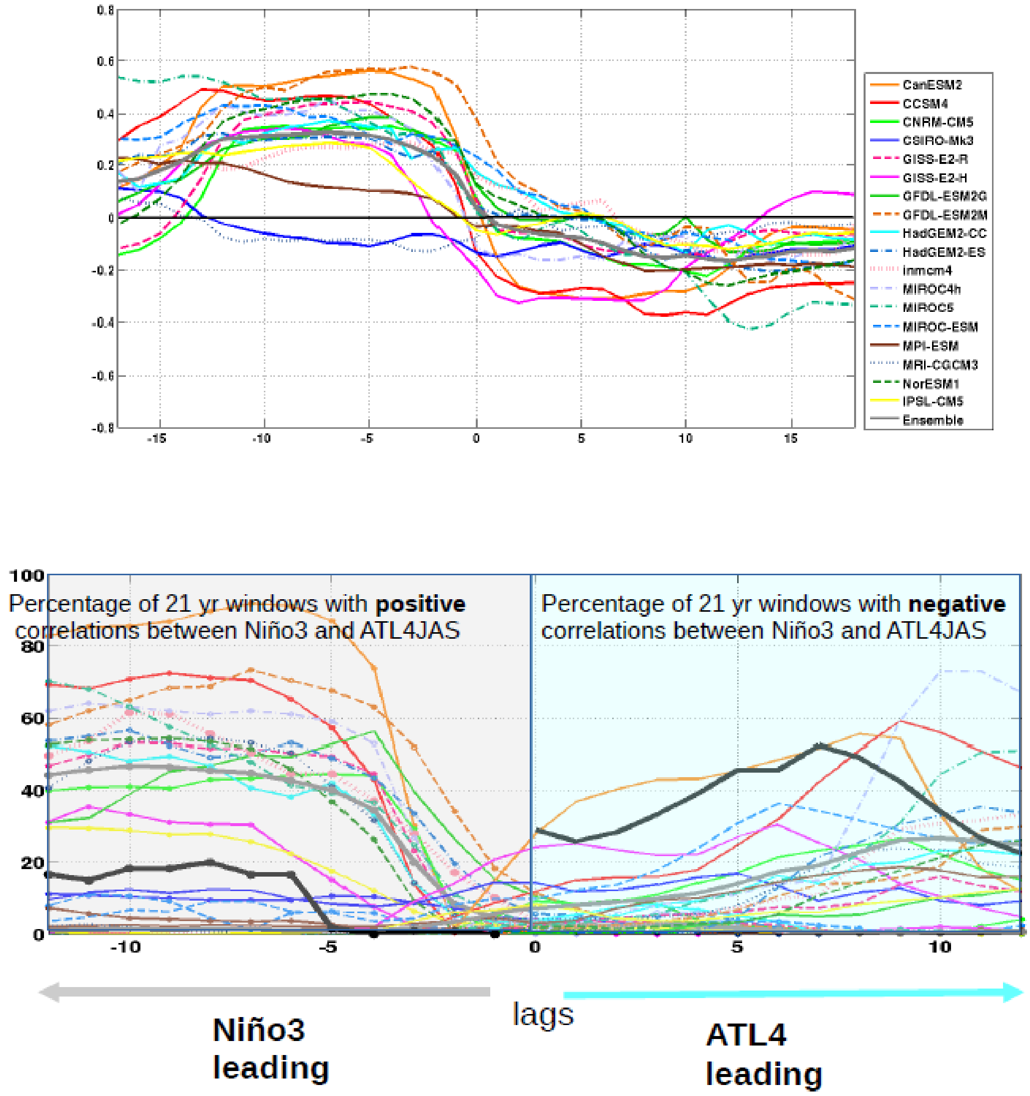


Figure A.2.3: Atlantic-Pacific connection in CMIP5 models. **Top:** Lead–Lag correlation between the Atl4 index in summer (July to October) and the anomalous SST in the Niño3 region during the previous (negative x-axis) and following (positive x-axis) 4-month seasons. **Bottom:** percentage of 21-year windows in which models simulate a Pacific Niño leading the Atlantic Niño (negative lags) and in which models presents an Atlantic-Niño leading the Pacific Niña (positive lags). Black curve represents observations and grey one represents the ensemble mean.

Although previous studies have suggested the AMO as the possible modulator of the non-stationary Atlantic-Pacific connection (Martín-Rey et al., 2014), models present a global SST and heat content structure that do not resemble the AMO pattern (Fig. A.2.4). On average, CMIP5 models present the Atlantic-Pacific connection during periods with warmer southern hemisphere, mainly over the extratropics and the Indian ocean. The warming in the extratropical southern hemisphere has been associated with a southward shift of the ITCZ (Mechoso et al., 2016). A significant equatorward shift of the rainfall belt appears significant over the Atlantic and Indian basins but no signal appears significant over the eastern and central tropical Pacific ITCZ, a feature that is also clear in the sea level pressure field.

During these decades with a favourable background state , the Atl4 projects, for most of the models, in summer in a pattern as that in Figure A.2.5 (top) and, in the next winter, in a pattern as that in Figure A.2.5 (bottom).

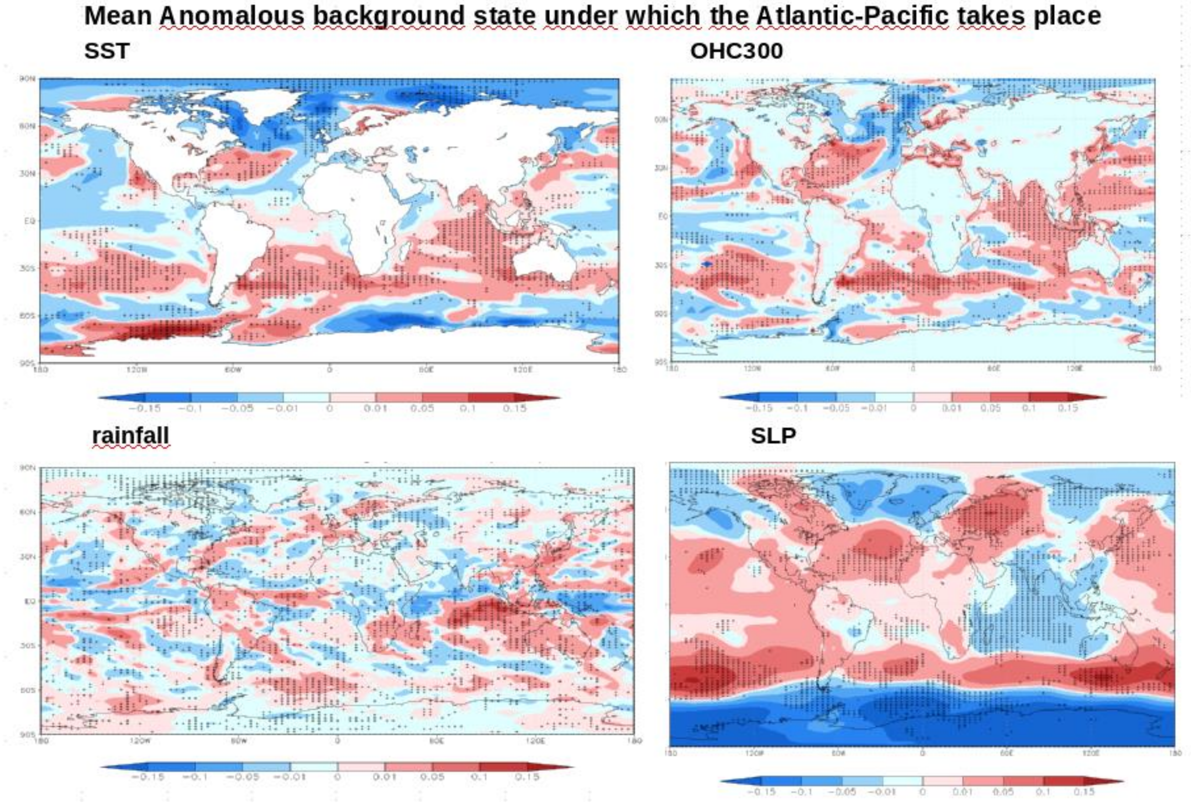


Figure A.2.4: Difference between the annual mean SST, ocean heat content (OHC300), rainfall and sea level pressure (SLP) averaged during the periods in which the Atlantic and Pacific Niños appear anticorrelated in both lag 0 (boreal summer) and lag 6 (next winter); and the annual mean of the same variables in the periods in which there is no relation. Shading indicates the ensemble of the 18 models and hashed areas indicate the regions in which at least in 12 of 18 models agree in sign.

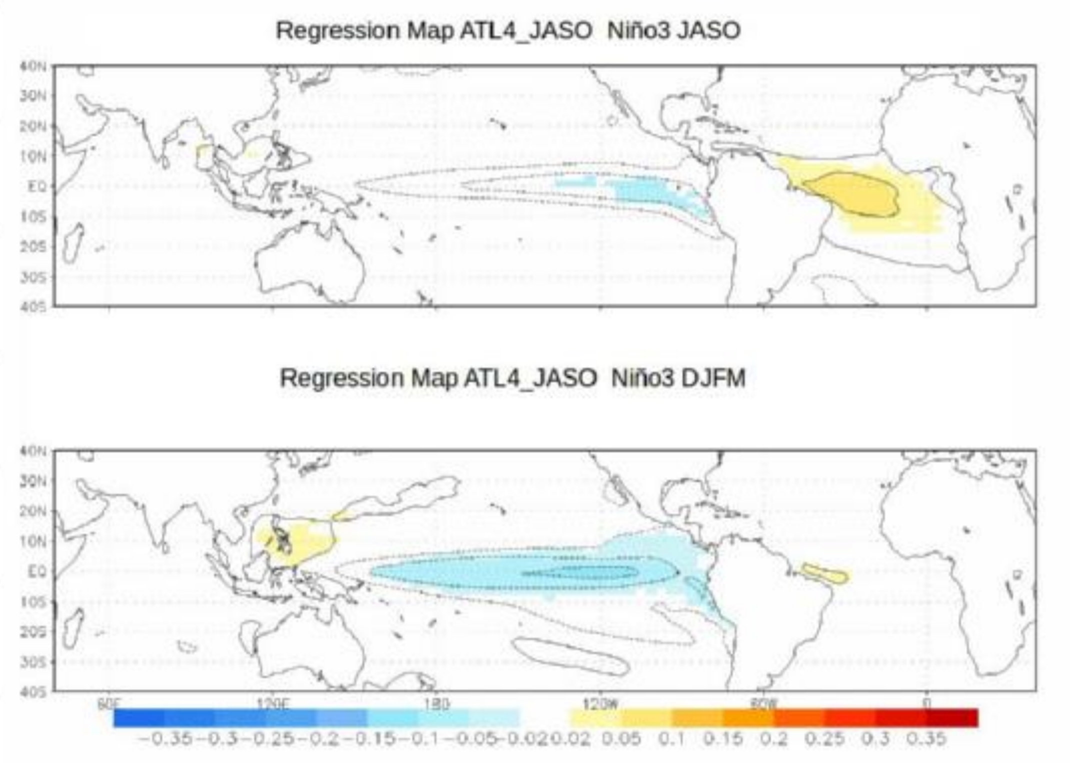


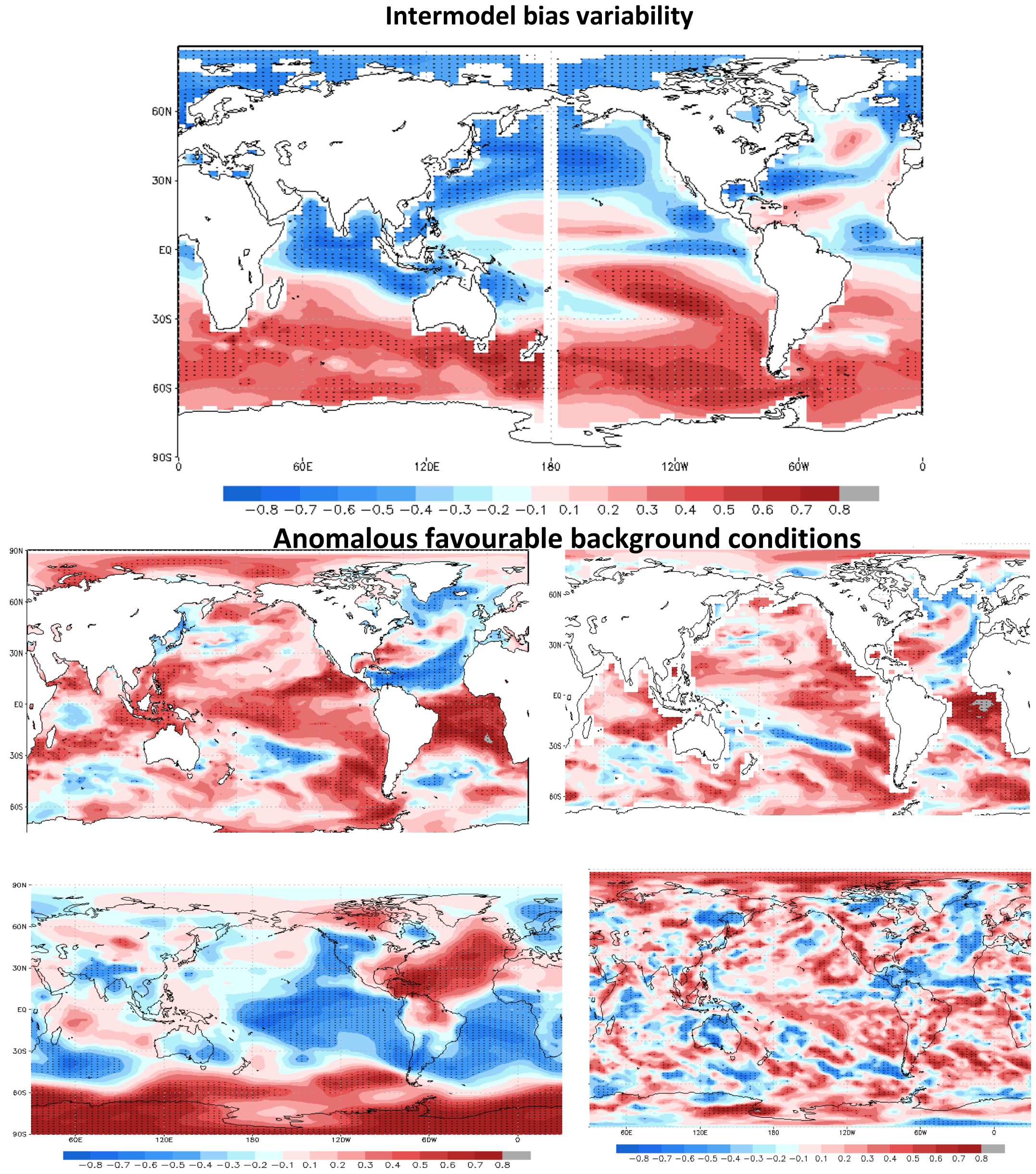
Figure A2.5: Atl4 in JASO regressed on the tropical anomalous SSTs in JASO (top) and in the next DJFM (bottom) during the decades in which there is an Atlantic-Pacific connection. The 18 regression maps for each of the CMIP5 models have been averages, shading only the regions in which at least 12 of the 18 models coincide in sign.

Comparing the result obtained from CMIP5 with observations, an agreement is found with a pioneer study that analysed the multidecadal evolution of the Atlantic ITCZ (Chiang et al., 2000). In that publication, an apparent nonstationarity of the Atlantic ITCZ was attributed to nonlinear relationship between SST and convection in the eastern equatorial Pacific and its consequent effect on the Walker circulation and the Atlantic ITCZ. Nevertheless, the present results put forward an active role of the Atlantic on the Pacific. Recent studies present an SST trend of warming the south and cooling the north in relation to a southward displacement of the tropical rainfall belt (Bronniman et al., 2015).

What is known about negative AMO phases is the presence of strong convection over the western tropical Atlantic (Martin-Rey et al., 2014, Alexander et al., 2014). Negative AMO has been linked to a slowdown of the AMOC (Zhang and Wang, 2013), which impacts result in a southward shift of the intertropical convergence zone over the Atlantic and Pacific, an El Niño–like pattern, and a weakened Walker circulation (Zhang et al., 2005). In relation to observations, a multidecadal variability of the Walker Circulation has been found (L'Heureux et al. , 2013) together with a weakening of the trend of the Walker Circulation over the last century, being the latter controversial over the Indo-Pacific region (Clement et al., 2015; Tokinaga et al., 2012), and a strengthening in the last three decades (*i.e.*, from 1980 to 2012, Ma and Zhou, 2016) The present study indicates how the Atlantic-Pacific connection takes place during equatorward shift of the ITCZ over the Atlantic and Indian ocean, and a weakening of the Walker Cell induced by an interhemispheric gradient of SSTs and ocean heat content which could enhance the equatorial dynamics associated with the connection.

In terms of energetics, the interhemispheric gradient of SST that takes place during these decades produces a southward shift of the ITCZ towards the equator, enhancing equatorial dynamics. In this way, the energy released associated with convection during an Atlantic Niño event is tied to the equatorial band, altering the Walker circulation and producing changes in the surface winds in the western Pacific. Thus, the equatorial location of the ITCZ acts as a switch for the inter-basin connection.

Despite the aforementioned common tendency for models to show the connection when the southern hemisphere is warmer than the northern one, there is a spread among the SST patterns (Fig. A.S2). This is likely related to the large biases in coupled models that are seen in the representation of the mean ITCZ and SST (Fig. A.S1). The intermodel differences in biases is reflected in different configurations of the ITCZ. This fact produces that the interhemispheric gradient, required for having an equatorial ITCZ, is reached in models in decades with different background conditions depending on the model bias. Here we consider as favourable background that defined, for each model, as the mean for the periods in which there is relation compared to the periods in which there is no relation. The relation of the favourable background with the model bias is assessed using MCA .Thus, models with a too warm bias in the southern hemisphere (Fig. A.2.6) except in the south Atlantic, reach the equatorial ITCZ configuration under a background state associated with a southward Atlantic ITCZ configuration and a weaker Atlantic and eastern Pacific Walker circulation. This behaviour is different to that reached by models with a colder bias in the southern hemisphere and warmer in the Atlantic. For some models the connection takes place almost during the whole integration, which means that the warm bias of the models favours the mechanism under which the connection takes place.


Intermodel bias variability

Anomalous favourable background conditions

Figure A.2.6: Top: Leading MCA mode performed between the anomalous intermodel bias. **Bottom:** the deviation from model favourable mean state of Figure A.2.4 of SST (top left), Ocean heat content (top right), sea level pressure (bottom left) and rainfall (bottom right) that is needed for the Atlantic-Pacific connection. Correlation maps are plotted.

A.2. Conclusions

The Atlantic and Pacific inter-basin connection takes place in CMIP5 models in a two way direction by which the Pacific and the Atlantic are connected in a 4 year cycle.

As it happens in the observations, the relation is not present during the whole integration and multidecadal modulations are observed. In this way during some decades the basins are connected and during others, the basins work independently.

CMIP5 models reproduce the Atlantic-Pacific connection at multidecadal time scales. The Atl4 region is key for the simulation of the inter-basin connection in observations and models. CMIP5 simulations reveal that for the establishment of the Atlantic-Pacific connection, an interhemispheric SST and heat content gradient, an equatorward shift of the Atlantic and Indian ITCZ and a weakening of the Walker circulation take place.

This study provides a mechanism that explains the role of ocean multidecadal variability in the connection between the Atlantic and Pacific SST interannual modes. Thus, during the decades in which the southern hemisphere is warmer than the northern hemisphere, the Atlantic equatorial mode impacts the Pacific, triggering the ocean processes involved in the development of an ENSO event.

In terms of energetics, the interhemispheric gradient of SST that takes place during these decades produces a southward shift of the ITCZ towards the equator, enhancing equatorial dynamics. In this way, the energy released associated with convection during an Atlantic Niño event is tied to the equatorial band, altering the Walker circulation and producing changes in the surface winds in the western Pacific. Thus, the equatorial location of the ITCZ acts as a switch for the inter-basin connection.

There is a linear dependence between bias and variability so the energy required for having an equatorial ITZC is reached by models depending on the bias.

Multidecadal ITCZ shifts have been related to AMOC but also, recent studies have related the intermodel bias variability with the representation of the AMOC. Thus, models with a weak AMOC tend to develop a warm bias in the southern ocean. On the contrary, stronger AMOC tend to develop colder bias in the southern ocean (Wang et al., 2014).

Multidecadal variability of tropical teleconnections have been reported also, for instance, in the relationship between the interannual tropical variability and the West African Monsoon (Chiang et al., 2000; Mohino et al., 2011; Losada et al., 2012 Rodriguez-Fonseca et al., 2016, 2015, 2011) and in the response to ENSO on the European precipitation (Lopez-Parages and Rodriguez-Fonseca, 2012), pointing out how the interannual variability can be strongly modulated by low-frequency patterns as well as global warming (Trenberth et al., 2011). Thus, this study fills important caveats on the mechanisms through which tropical teleconnections are not stationary in time and provides compelling evidence for the influence of multidecadal ocean driven ITCZ changes in controlling this non-stationarity.

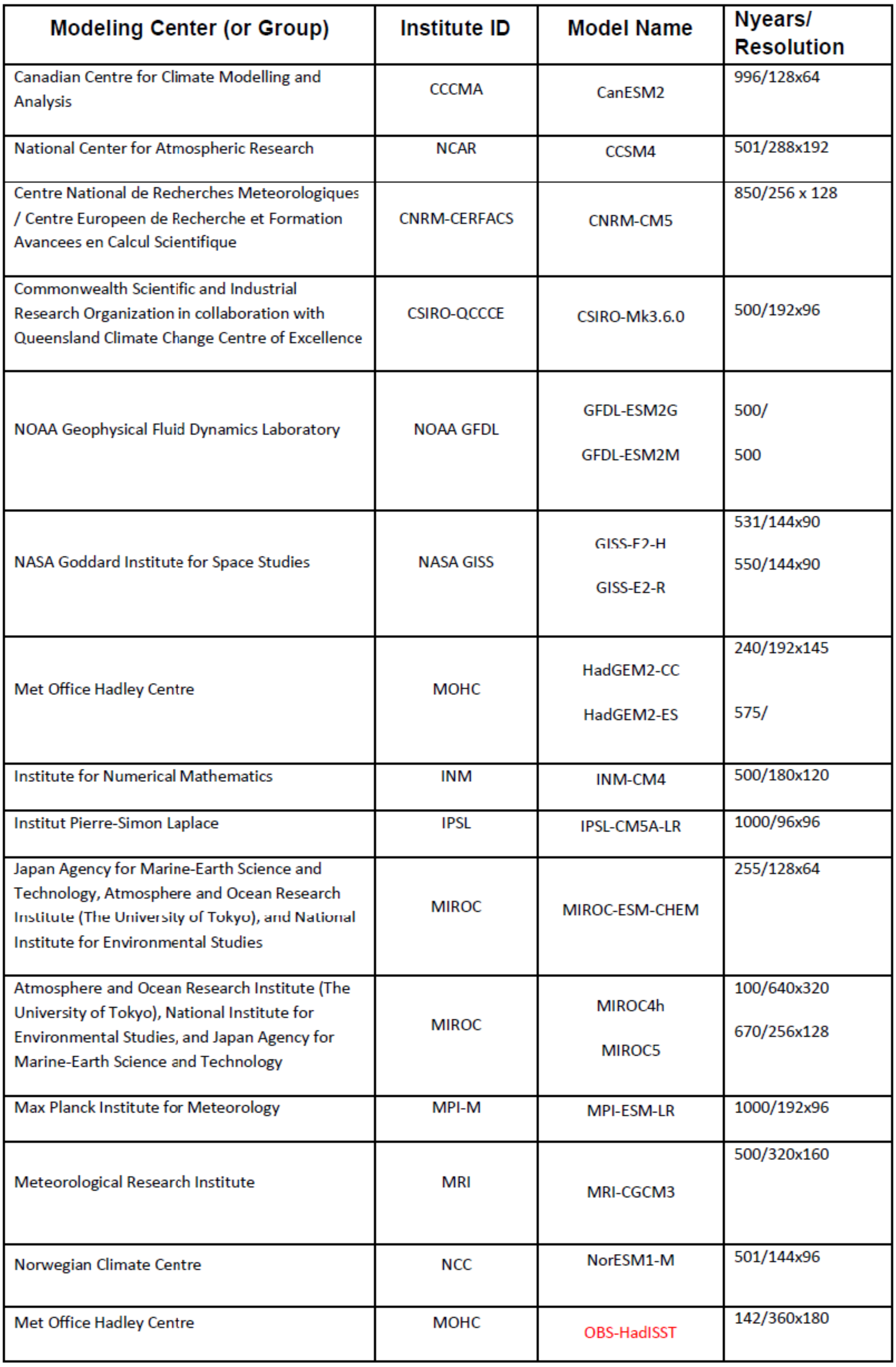
The results presented here have an important consequence for ENSO predictability. A good representation of the AMOC is crucial for assessing multidecadal variability of the ITCZ and thus, for the determination of decades in which the inter-basin teleconnection could help to enhance ENSO predictability.

A.2. Methods

All the study has been done applying correlation analysis. Pearson correlation coefficient is computed and the significance of the correlation is obtained applying a Monte Carlo (MC) technique. This consists in permuting the time series randomly, re-calculating the correlation score. 100 permutations are done and correlations lower, in absolute value, than the non-permuted correlation are counted. Only those scores for the associated counted MC scores sum up more than 95% are considered significant. 21-yr moving correlation is applied, moving one year the window. Then, the years within the significant windows are compiled without repetition and the mean SST is calculated. Here we consider as anomalous background that defined, for each model, as the difference between the mean for the periods in which there is relation and the mean in the periods in which there is no relation.}

A.2. Supplementary material

Table A.2.S1: Models used in this study by participating institutions.



Modeling Center (or Group)	Institute ID	Model Name	Nyears/ Resolution
Canadian Centre for Climate Modelling and Analysis	CCCMA	CanESM2	996/128x64
National Center for Atmospheric Research	NCAR	CCSM4	501/288x192
Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	CNRM-CERFACS	CNRM-CM5	850/256 x 128
Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	CSIRO-Mk3.6.0	500/192x96
NOAA Geophysical Fluid Dynamics Laboratory	NOAA GFDL	GFDL-ESM2G GFDL-ESM2M	500/ 500
NASA Goddard Institute for Space Studies	NASA GISS	GISS-E2-H GISS-E2-R	531/144x90 550/144x90
Met Office Hadley Centre	MOHC	HadGEM2-CC HadGEM2-ES	240/192x145 575/
Institute for Numerical Mathematics	INM	INM-CM4	500/180x120
Institut Pierre-Simon Laplace	IPSL	IPSL-CM5A-LR	1000/96x96
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	MIROC	MIROC-ESM-CHEM	255/128x64
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	MIROC4h MIROC5	100/640x320 670/256x128
Max Planck Institute for Meteorology	MPI-M	MPI-ESM-LR	1000/192x96
Meteorological Research Institute	MRI	MRI-CGCM3	500/320x160
Norwegian Climate Centre	NCC	NorESM1-M	501/144x96
Met Office Hadley Centre	MOHC	OBS-HadISST	142/360x180

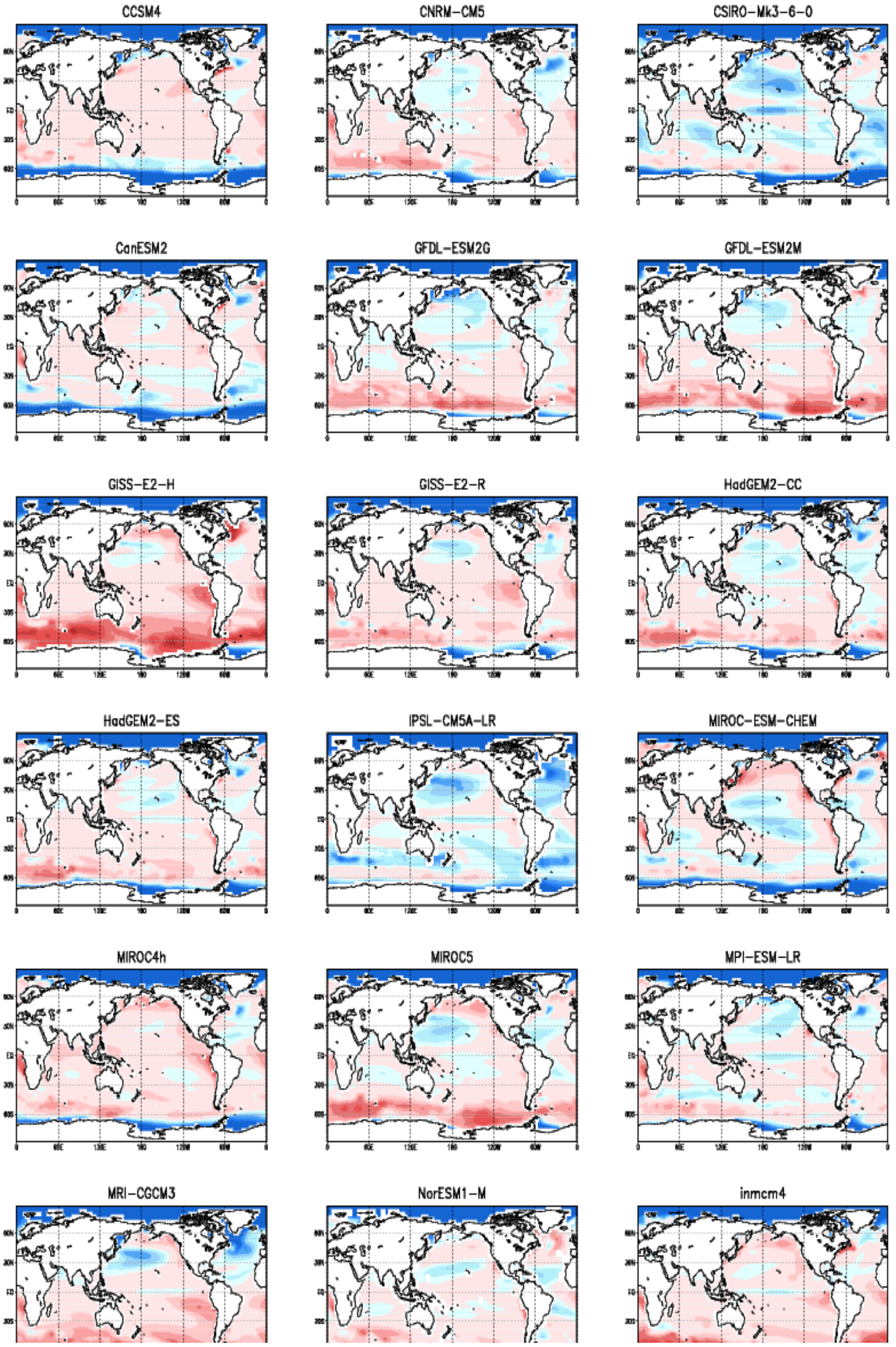


Figure A.2.S1: SST bias in the 18 CMIP5 models analysed

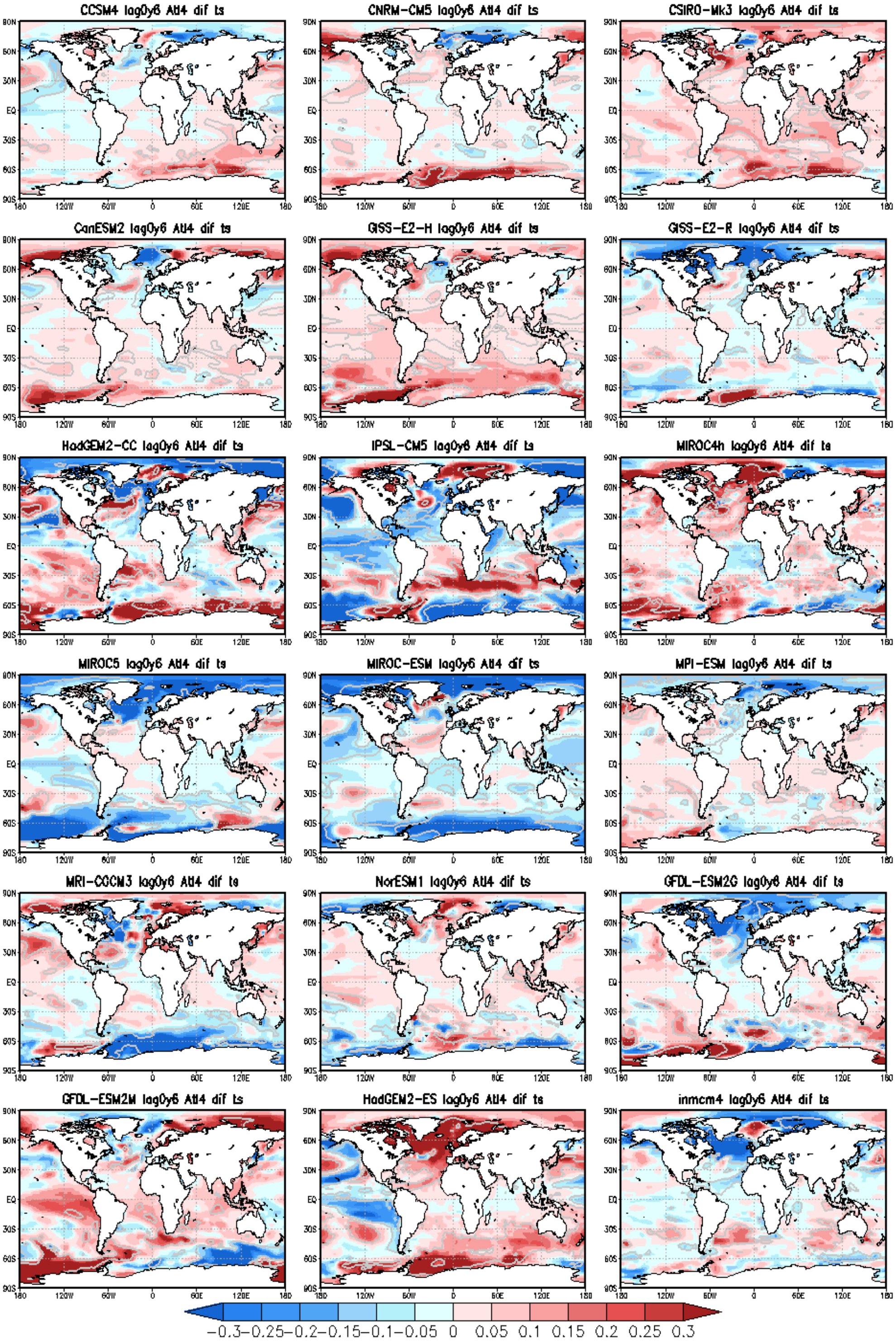


Figure A.2.S2: Difference between the annual mean SST, averaged during the periods in which the Atlantic and Pacific Niños appear anticorrelated at both, lag 0 (boreal summer) and lag 6 (next winter); and the annual mean of the same variables in the periods in which there is no relation. Grey bold contours mark the significant regions. Each figure corresponds to one of the CMIP5 models analysed.

Part B: Reducing shortwave (SW) income in the Atlantic sector of the Southern Ocean; impact on variability

Authors: Teresa Losada, Belen Rodriguez-Fonseca, Elsa Mohino, Antonio Castaño, Carlos Roberto Mechoso (scientific publication in preparation)

B Abstract

CGCMs show important biases in different regions and variables. One of the most outstanding of them is the warming of the SST over the subtropical Eastern oceans in the southern hemisphere, as well as an unrealistic warming of the Southern Ocean. A recent publication showed that artificially reducing the shortwave incoming radiation over the Southern Ocean can alleviate to some extent the systematic errors in the subtropics in the southern hemisphere. The sensitivity of the model to the SST-Stratocumulus feedback is key in the tropical response of the model. In the present work we study if the better representation of the mean SST in the Atlantic has an impact in the representation of the interannual variability of the tropics, focusing in the Atlantic-Pacific connection. To this aim we perform an experiment in which we reduce the incoming solar radiation only in the Atlantic sector of the Southern Ocean with the UCLA-CGCM. Our results show that reducing the SST bias in the tropical Atlantic has an impact in the Atlantic-Pacific connection in the model, which is better represented in the experiment than in a control simulation.

B Experiment definition: The incoming SW radiation is reduced following Mechoso et al. (2016), but only in the Atlantic sector. The reduction factor is depicted in Figure B.1.

The UCLA-CGCM is run for 60 years, and the results of the experiment (EXPT simulation) are compared with a control simulation (CTL of 56 yrs).

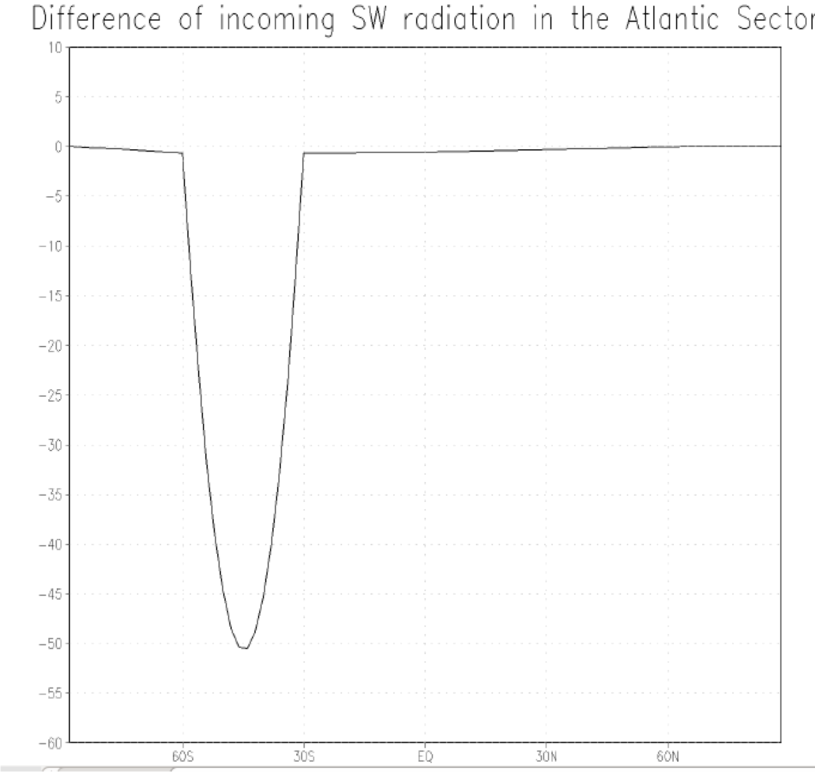


Figure B.1: EXPT-CTL incoming SW radiation between 70W-30E.

B Impact on mean SST

The reduction of the incoming SW radiation in the Atlantic leads to a decrease of the SST in the whole Southern Ocean as well as in the tropical south Atlantic and Indian Oceans, together with an increase in the Northern Hemisphere and the ENSO region (Fig. B.2). This SST response produces a South-North gradient of temperature that would impact the position of the ITCZ (not shown).

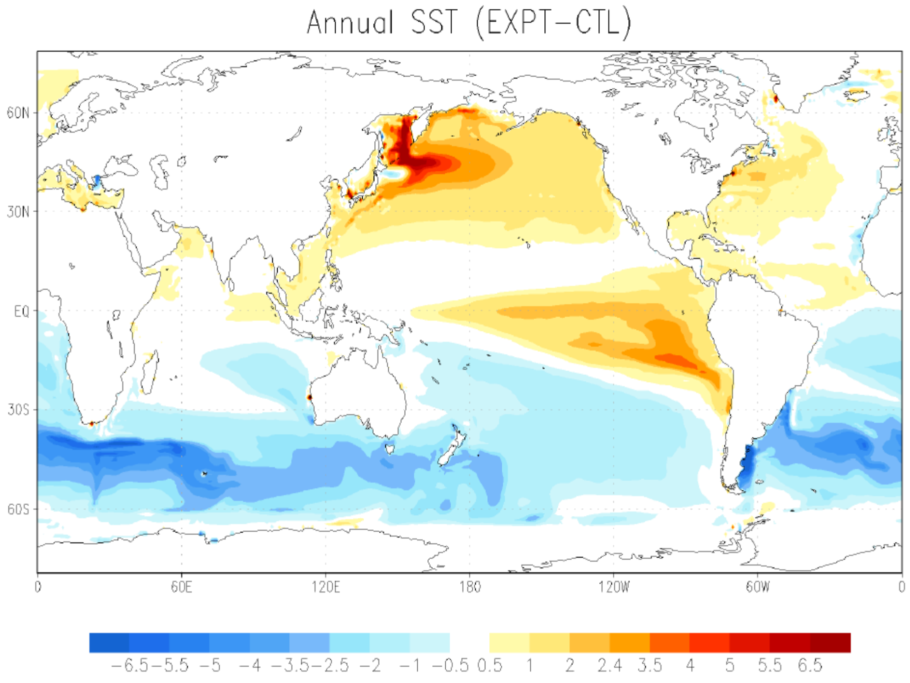


Figure B.2: Difference in annual SST between EXPT and CTL.

B Impact on interannual variability:

EXPT shows a much better representation of the Atlantic-Pacific connection, including the multidecadal variability of it (Fig. B.3). The EXPT is able to capture the Atlantic-Pacific connection (Fig. B.4), even though the amplitude of anomalies related to the Atl3 index is smaller than for CTL (Fig. B.5).

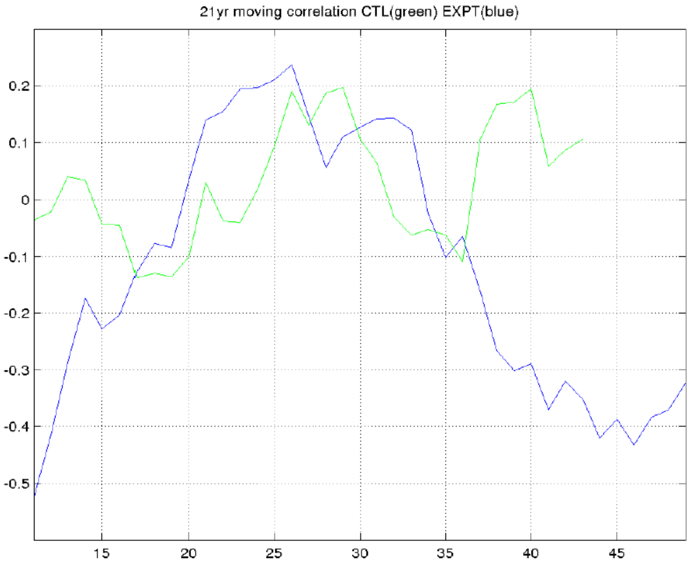


Figure B.3: 21yr-moving correlations between Atl3 in JJAS and Niño3 in NDJF for CTL (green) and EXPT (blue).

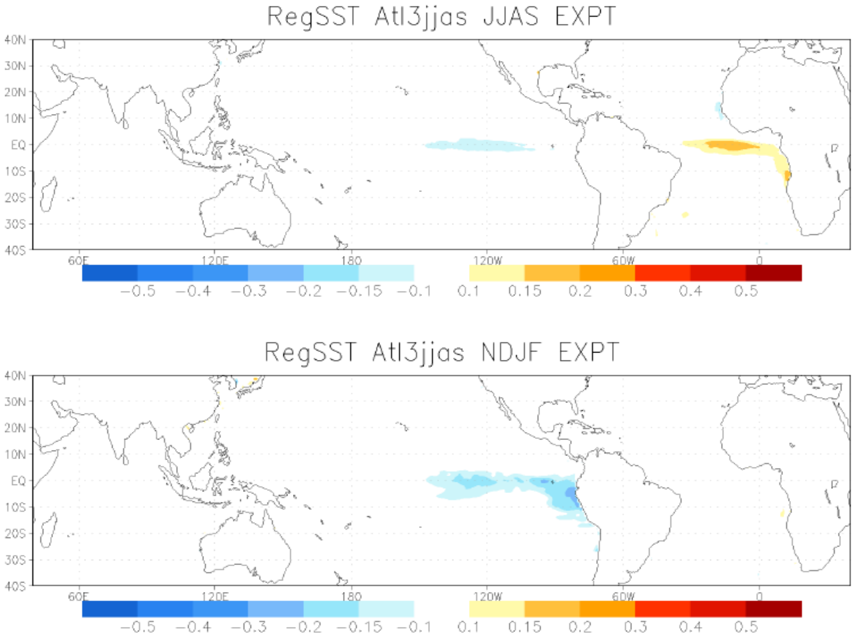


Figure B.4: Regression of SST anomalies onto the Atl3 index in summer (top) and the next winter (bottom) for EXPT.

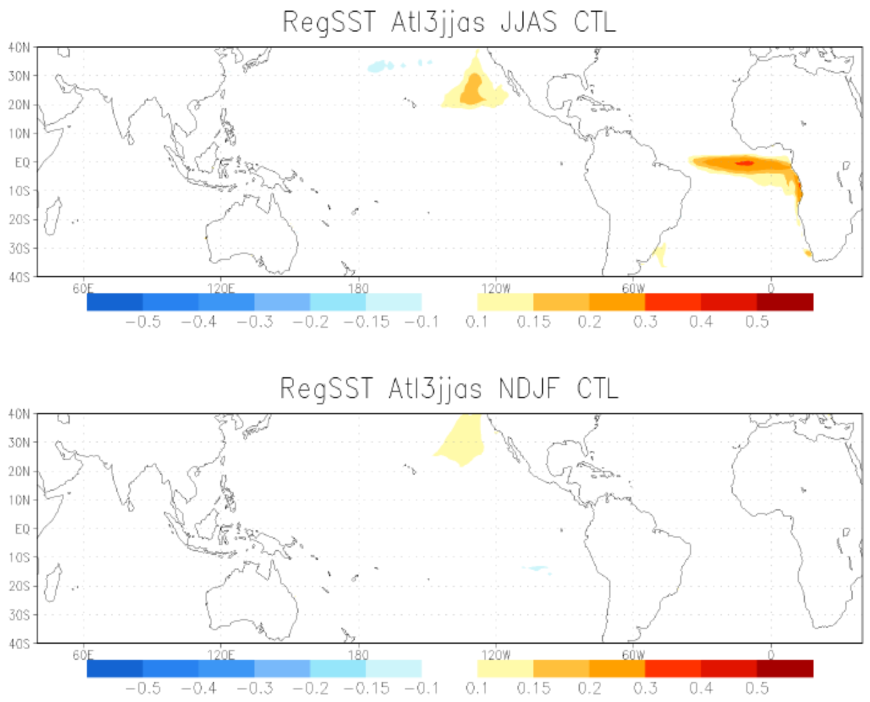


Figure B.5: Regression of SST anomalies onto the Atl3 index in summer (top) and the next winter (bottom) for CTL

Part C: The contribution of tropical Atlantic variability to enhance ENSO intensity since the 1970s

Authors: Hui Ding, Marta Martín-Rey, Noel Keenlyside, Mojib Latif, Belén Rodríguez-Fonseca, Irene Polo, and Fred Kucharski

C Abstract

Pacific El Niño variability underwent a substantial strengthening around the 1970's, with major implications for global climate. Current theories attribute the strengthening to background state changes in the equatorial Pacific, of either local origin or remotely driven. Here we show for the first time that the strengthening influence of the equatorial Atlantic Nino on the Pacific could explain 50% of the observed increase. The robustness of the results is confirmed in experiments with two climate models with Atlantic sea surface temperatures (SST) constrained to observations. A stronger south Atlantic warming drove a local southward displacement of the Inter-tropical Convergence Zone that strengthened the impacts of the Atlantic Niño on the atmosphere empowering it to influence El Niño development in boreal spring and summer. Atlantic induced changes in the background state in the Pacific appear to be of secondary importance. These results have major implications for our understanding of El Niño and how future global warming of the tropical Atlantic may influence it. The below is a brief summary of our results for PREFACE deliverable D8.2; these are being prepared for a joint publication.

C Introduction

During the 20th century, El Niño Southern Oscillation (ENSO) has undergone multi-decadal changes in structure, magnitude, and frequency. Most previous studies have explained changes in ENSO properties by changes in the mean state (Dong et al., 2006; Federov and Philander, 2001). However, attribution of changes can be complicated by the inherent nonlinearity and non-stationarity of ENSO (Wittenberg, 2009). ENSO properties also may be induced by changes in the excitation mechanisms (Philip and van Oldenborgh, 2009). He we aim to investigate the potential impacts of tropical Atlantic variability (TAV) on ENSO variability.

One of the most significant changes in ENSO properties is the increased ENSO intensity after the 1970s (An and Wang, 2000); Fig. C.1), with impacts on ENSO predictability and teleconnections. Using both observations and model experiments, Dong et al. (2006) suggest that the cold phase of the Atlantic Multidecadal Oscillation (AMO) from 1965 to 1995 lead to a change in the tropical Pacific mean state and amplified ENSO variability. This mechanism explains about 40% of the increase in amplitude [Dong et al., 2006]. They also note that ENSO did not show a weakening thereafter even though the AMO switched to its positive phase after the mid-1990s. Thus, other factors also must have contributed to the stronger ENSO after the 1970s.

Although ENSO has clear impact on the north Tropical Atlantic, its influence on the equatorial Atlantic is less robust, even after the 70's (Chang et al., 2006a). Alternatively, many studies have shown that equatorial Atlantic SST variability, which is dominated by the Atlantic Niño (Chang et al., 2006b), can impact tropical Pacific interannual variability (Ding et al., 2012; Keenlyside and Latif, 2007; Martín-Rey et al., 2014; Rodriguez-Fonseca et al., 2009; Wang, 2006). The Atlantic Niño SST variations tend to precede anomalies of opposite sign in the eastern equatorial Pacific by about six months (Keenlyside and Latif, 2007; Rodriguez-Fonseca et al., 2009). Observational and modelling studies indicate that the warm (cold) phase of the Atlantic Niño strengthens (weakens) the Walker

Circulation over the Pacific in boreal summer, which, amplified by the Bjerknes feedback, lead to significant cold (warm) SST anomalies in the eastern equatorial Pacific in the following winter (Ding et al., 2012; Rodriguez-Fonseca et al., 2009). In addition, warm (cold) SST anomalies over the northern tropical Atlantic (NTA) in spring may trigger the development of La Niña (El Niño) like SST anomalies in the following months (Ham et al., 2013) and also impacts SST over the northwestern tropical Pacific.

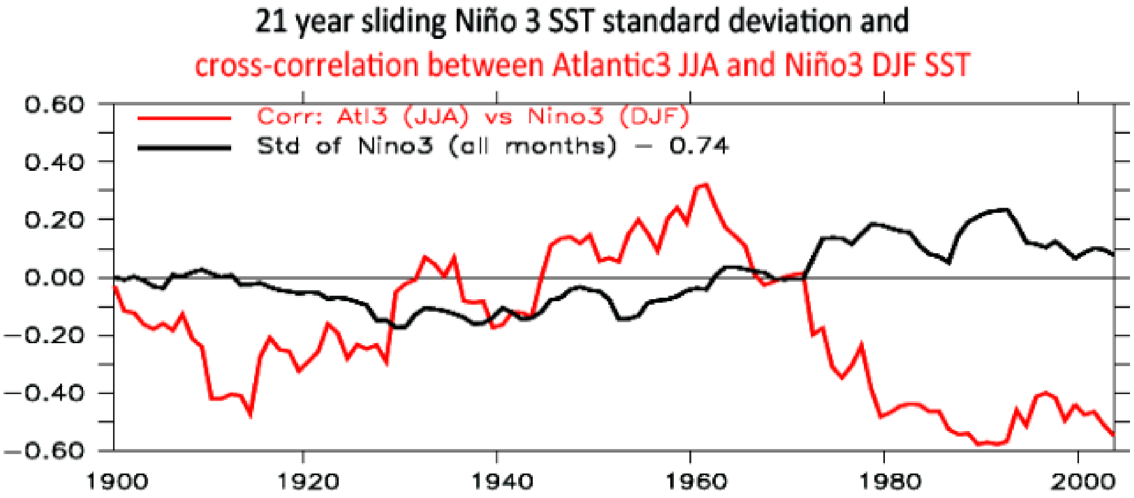


Figure C.1: Red line shows the correlation between boreal summer (June/July/August) seasonal mean Atl3 SST anomalies and seasonal mean Nino3 SST anomalies in the following boreal winter (Dec/Jan/Feb) in a running time period of 21 years. Dark line shows the standard deviation of Nino3 SST anomalies in the same time period, but all months are used.

Observations show that the Atlantic Niño and ENSO became closely related after 1970 (Fig. X.1) (Keenlyside and Latif, 2007; Rodriguez-Fonseca et al., 2009). While Rodriguez-Fonseca (2009) were the first to provide modelling evidence for a strengthened link, they did not identify the cause of the strengthening nor its impact on ENSO intensity. Model studies suggest the AMO was root cause of these changes (Martín-Rey et al., 2014), through changes in the Atlantic climatology (Martín-Rey et al., 2014) and Atlantic Niño variability (Losada and Rodríguez-Fonseca, 2016). However, the recent AMO changes have not lead to a weakening of the link as hypothesised by these studies (Polo et al., 2015). Nevertheless, prediction experiments show that equatorial Atlantic SST variability has the potential to enhance the amplitude of the two strongest El Niño events during the instrumental record, 1982/83 and 1997/98 (Keenlyside et al., 2013). In fact a recent modelling study supports that internannual variability in the tropical Atlantic can enhance ENSO variability (Sasaki et al., 2014). Here we examine the potential impact of SST variability in the tropical Atlantic on ENSO amplitude since the 1970s by conducting dedicated experiments with two climate models.

C Experiments

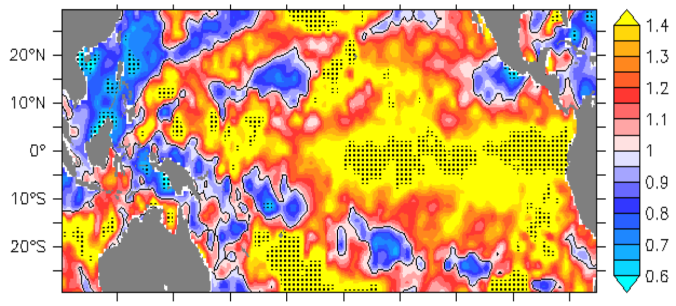
We use both the Max-Planck-Institute (MPI) (Jungclaus et al., 2006) and SPEEDY-RGO coupled models. The atmosphere component (ECHAM5) of the MPI model is run at T63 spectral resolution (1.875°x1.875°) with 31 vertical levels, while the ocean component (MPI-OM) has 1.5° average horizontal grid spacing with 40 vertical levels. SPEEDY-RGO consists of the SPEEDY atmospheric model (with T30 horizontal resolution and 8 vertical levels) coupled to an extended 1.5-layer reduced-gravity model (with a 2x1° horizontal resolution). SPEEDY-RGO employs a climatological surface heat-flux and wind stress flux-correction. MPI employs no form of flux correction.

Partial coupled model experiments are performed with both models in which observed, interannually varying SST, is strongly nudged into the model in the tropical Atlantic and less strongly in the extratropical Atlantic, while the model is fully coupled elsewhere. The MPI model experiments cover the period 1950-2005 and consist of five ensemble members; they were used by Ding et al. (2012). The SPEEDY-RGO model experiments cover the period 1871 to 2002 and consist of nine ensemble members; they were previously used by Martin-Rey et al. (2015).

C Observed and simulated changes before and after the 70's

SST anomalies averaged over the Atl3 (20°W-0°W, 3°S-3°N) and Niño3 (150°W-90°W, 5°S-5°N) regions are commonly used as indices for the Atlantic Niño and ENSO, respectively. The correlation between boreal summer (JJA) seasonal mean Atl3 SST anomalies and seasonal mean Nino3 SST anomalies during the following boreal winter in running periods of 21 years is shown in Fig. C.1 (red line). The mechanism for this link was summarised above. Both models are able to reproduce the changes in cross-correlation around the 1970's, although they tend to underestimate the changes (not shown).

We now turn to the decadal-scale change in the magnitude of SST variability in the tropical Pacific and examine the possible contribution from the tropical Atlantic. Figure C.2 shows the ratio in local SST standard deviation between 1971-2005 and 1952-1970 calculated from observations and the MPI model experiments. Only DJF is considered, but similar results are obtained for all months. The major feature of the ratio pattern is that the level of SST variability has increased over almost the entire equatorial Pacific. In observations the maximum increase of about 20-40% is seen to the east of 160°E, which is consistent with previous findings on enhanced ENSO amplitude. In the northwestern tropical Pacific, the pattern is more complicated, and both an increase and decrease of the variability is seen. The MPI model simulates a similar pattern of increase in the eastern equatorial Pacific, but the increase is around 50% weaker than observed. Although for a slightly different period (because of the differing experiment periods), the SPEEDY-RGO model is found to also reproduce the observed changes (Fig. C.3). In this case the pattern is broader than observed but the amplitude matches observations.



(b) Ratio in SST std in Exp Full SST: (1971–2005)/(1952–1970)

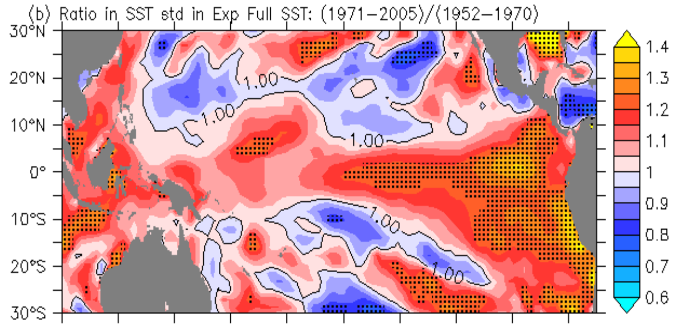


Figure C.2: The ratio of standard deviation of SST anomalies in DJF in the period 1971-2005 compared to 1952-2005 from (upper) observations and (lower) the MPI coupled model experiments.

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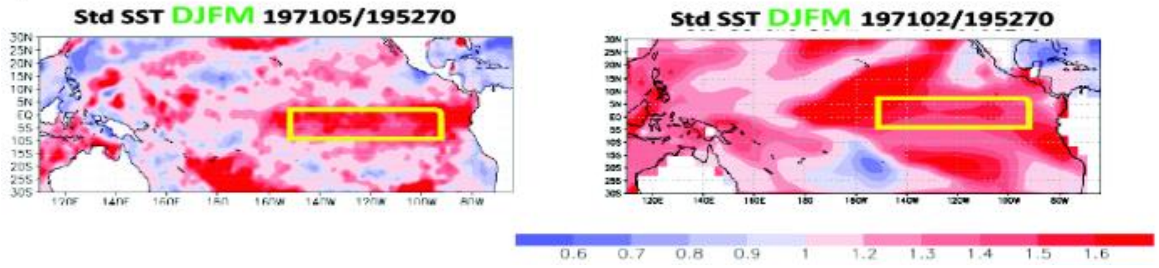

Figure C.3: As in Figure C.2, but for SPEEDY-RGO and for slightly different period.

C Background state changes

What is the mechanism for the TAV to induce stronger ENSO amplitude? Previous studies have suggested that the AMO induces background state changes in the Pacific that enhance ENSO variability (Dong et al., 2006). Observations indicate that compared to the period before the 70s, the period after is primarily associated with a much stronger warming of the South Atlantic and a positive phase of the Pacific Decadal Oscillation (Fig. C.4top). The two models simulate quite different and almost SST responses in the Pacific that are much weaker than observed. It thus seems unlikely that background state changes in the Pacific are the root cause of the simulated strengthening of Pacific variability in the two models.

The simulated precipitation changes associated with the warming of the South Atlantic there is a southward displacement of the ITCZ in the Atlantic (Fig C.5). The models differ somewhat in the magnitude and position of the changes, as expected from their differing simulation of tropical precipitation patterns (not shown). Again the results over the Pacific differ. Comparison to observations is not possible over the ocean as data are not available prior to 1979.

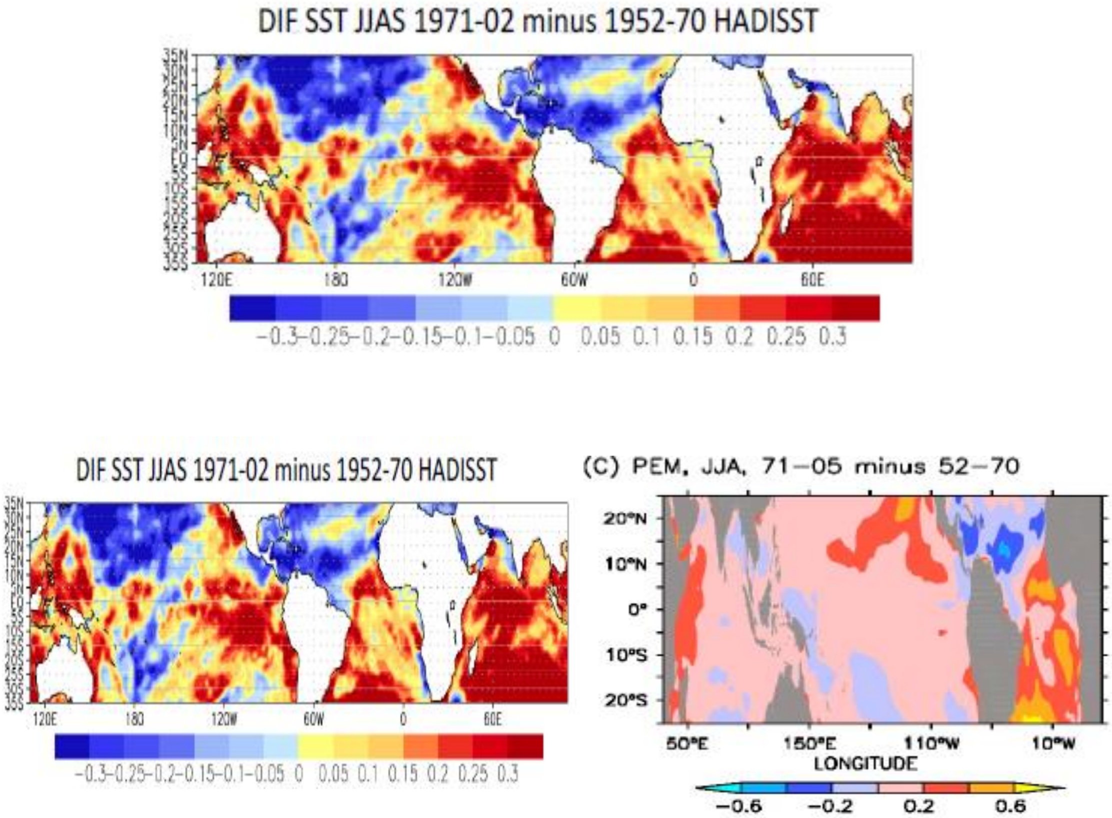

Figure C.4: Top: Observed changes in SST for the period 1971-2002 compared to 1952-1970. **Bottom left:** Simulated changes for the same period in the SPEEDY-RGO experiment with Atlantic SST prescribed from observations. **Bottom right:** Simulated changes in the MPI experiment for the period 1971-2005 compared to 1952-1970.

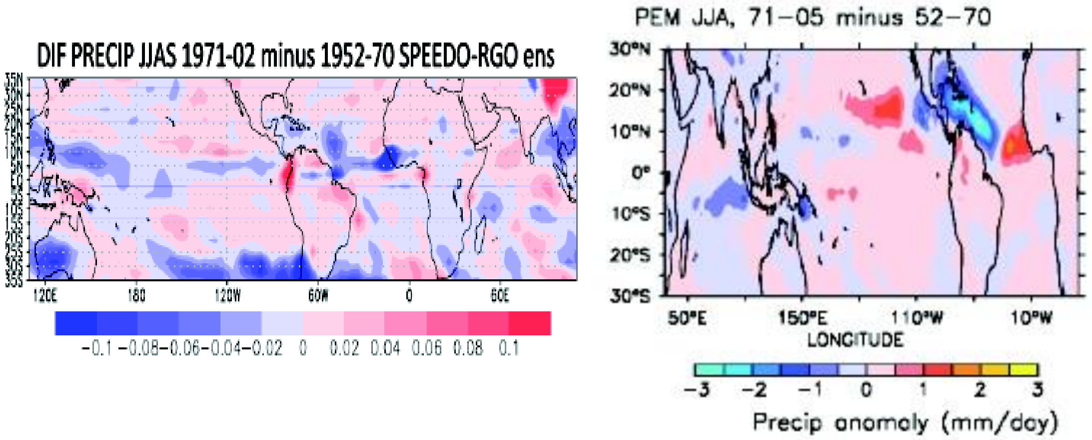

Figure C.5: Left: Changes in precipitation in the SPEEDY-RGO experiments for the period 1971-2002 compared to 1952-1970. **Right:** Simulated changes in precipitation in the MPI experiment for the period 1971-2005 compared to 1952-1970.

C Mechanism for an enhanced Atlantic Niño - Pacific impact after the 70's

Equatorial Atlantic SST variability during boreal summer is, at least partly, independent of the ENSO cycle (Chang et al., 2006a) and thus could provide an extra driver of the ENSO cycle by impacting its amplitude after the 70's. Here we present results from the MPI model that provide a hypothesis for these changes; similar analysis will be performed on the SPEEDY-RGO model. Analysis of observations is limited by observational data coverage.

Composite analysis for JJA Atl3 SST anomalies in the MPI experiment (Fig. C.6) indicates that before the 70's Atlantic Niño events are associated with dipolar rainfall and upper level velocity potential anomalies over the north tropical Atlantic. After the 70's the rainfall anomalies strengthen over the equatorial and south Atlantic, while they become almost absent over the Caribbean region. There is corresponding strengthening of the equatorial upper level velocity potential changes. These changes appear consistent with the climatological shift in rainfall patterns (Fig. C.5).

There is a completely different response over the Indo-Pacific region before and after 70's to JJA Atlantic Niño SST anomalies. After the 70's Atlantic Niño events lead to subsidence over the Pacific and suppressed rainfall. These lead to La Niña conditions later in the year. Before the 70's the response in the Pacific is rather weak, and there is little impact on Pacific SST variability. Thus it appears that the southward displacement of rainfall in the Atlantic associated with the south Atlantic warming after the 70s, leads to an enhanced atmospheric response to Atlantic Niño events that enables them to influence ENSO variability in boreal summer. Further analysis of the underlying mechanisms is underway in preparation for submission of this work for publication.

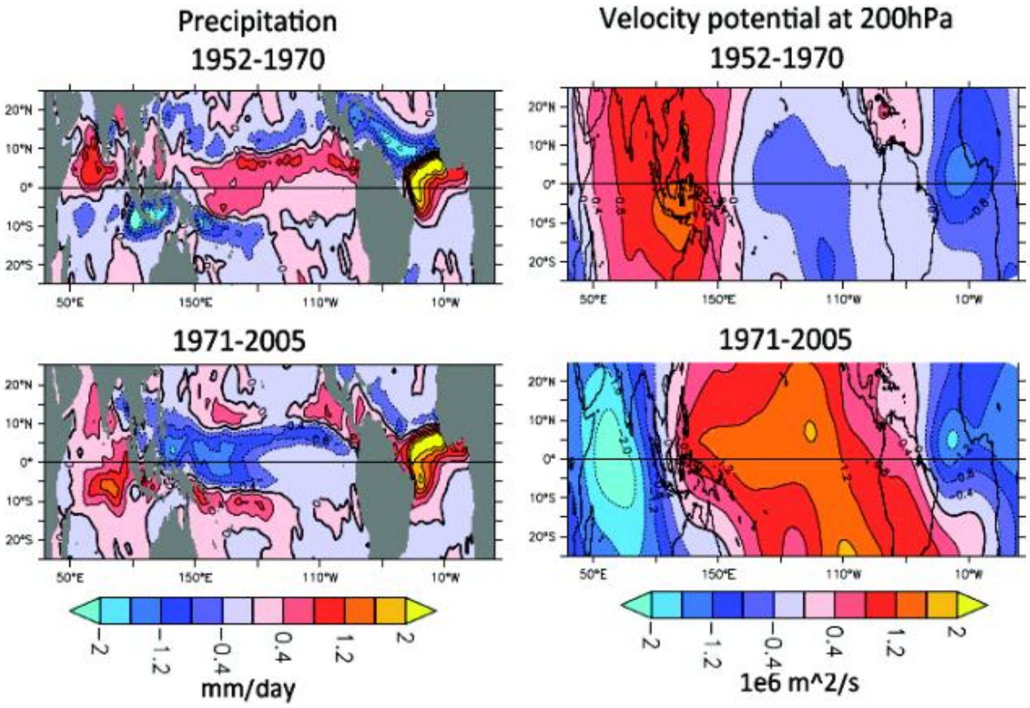

Figure C.6: Composite analysis for JJA Atl3 SST anomalies for the MPI experiments for (left) precipitation and (right) upper level velocity potential for the period (upper) 1952-1970 and (lower) 1971-2005.

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