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Lead beneficiary for this deliverable: UCM

Due date of deliverable: 30.04.2017

Actual submission date:

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

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Deviation from planned efforts for this deliverable:

There were no significant deviations in the efforts from the original plan. The delay in the deliverable was due to the new timing on the milestone MS28 (“Seasonal to interannual TAV meeting”) that was held jointly with PREFACE's General Assembly 2016, as previously agreed upon among beneficiaries involved and with the Project Officer at the European Commission.

Executive Summary:

The main goal of the PREFACE project work package WP9 is to improve our understanding of tropical Atlantic variability and its impacts through the analysis of observational data and climate model simulations. The deliverable D9.1 contributes to the first specific objective of WP9: "*To analyze the origin, development and impacts of Atlantic interannual modes of variability, including the two-way Atlantic-Pacific relationship*", and to its related task 9.1: "*Understanding the representation of interannual Atlantic modes of variability*".

This deliverable is focused on the variability of the tropical Atlantic region from seasonal to interannual time scales. In these time scales, the main mode of variability in the Tropical Atlantic Ocean is the Atlantic El Niño (Zebiak et al. 1993). PREFACE (D9.1) has undertaken a number of works to better understand the mechanisms explaining such mode and its impacts.

Related to such impacts, an issue of special interest to PREFACE is the link between the variability in the equatorial Atlantic sea surface temperatures (SSTs) and those in the Pacific. In the framework of D9.1 this connection has been further studied, evaluating the modulation by the background state and its relevance in seasonal prediction for ENSO's predictability.

Recent works evidence the existence of regular oscillations in the equatorial Atlantic ocean related to equatorial deep jets (EDJs). In PREFACE (D9.1) we have improved our understanding of the driving mechanism and potential influence on ocean surface circulation of such EDJs.

PREFACE (D9.1) has also devoted efforts to better understand the seasonal to interannual variability of rainfall over the continental areas adjacent to the Atlantic. The structure of large-scale circulation over central Africa and rainfall variability over Southern Africa, Ethiopia, West Africa and Brazil have been further analysed and related to SST anomalies over different basins with a special focus on the Pacific El Niño and the stationarity of the links found.

In PREFACE (D9.1) we have improved our knowledge on intra-seasonal variability in the tropical Atlantic. The main mode of tropical variability at these time scales is the Madden Julian Oscillation (MJO, Madden and Julian 1994). We have investigated the processes leading to an improved simulation of it, evaluated its impact on West Africa and the possible changes the MJO could show in a warmer climate.

The deliverable has been structured into five sections that cover the main areas of interest presented above. Each section is introduced by a discussion in which PREFACE results are highlighted in the framework of previous works.

Contents

1. The Atlantic El Niño and its impacts

The Atlantic El Niño is the main mode of variability in the tropical Atlantic (TA) SSTs at interannual time scales (Zebiak et al. 1993). Its positive phase is related to an anomalous warming in the tropical eastern Atlantic peaking in boreal summer. Previous works suggest that dynamical processes are the dominant mechanism (Carton and Huang 1994; Carton et al. 1996). The prevailing theory on the Atlantic El Niño is based on the Bjerknes feedback (Chang et al. 2006; Keenlyside and Latif 2007; Jansen et al. 2009), by which a warm anomaly in the eastern equatorial Atlantic weakens the trade winds, which, in turn, reduce upwelling and deepen the thermocline in the east causing further warming (Bjerknes 1969). However, in the framework of PREFACE, Nnamchi et al. (2015), using atmosphere-ocean coupled experiments with multiple models, showed that thermodynamic feedbacks excited by stochastic atmospheric perturbations can generate Atlantic El Niño explaining nearly 70% of the observed interannual variability. To shed further light on this dynamic vs thermodynamic mechanism, Dippe et al. (2017, in preparation) decomposed the SST variance in the eastern equatorial Atlantic into dynamical and stochastic driven thermodynamic components both in observations and in model simulations. They show that in observations the contribution of the dynamic component is 4 to 7 times larger than the stochastic one in summer. However, when the analysis is applied to model simulations, the summer peak in the dynamical SST variance is suppressed. Such results suggest that though most of the summer SST variance in the eastern equatorial Atlantic is dynamically controlled, most current state-of-the-art atmosphere-ocean coupled models might not able to reproduce properly such mechanism.

The Atlantic El Niño is a time evolving pattern that starts at the Angola/Benguela region and propagates westward and equatorward, decaying in the western part of the basin (Polo et al. 2008). To better understand the particular processes that lead to such evolution, in the framework of PREFACE, Planton et al (2017, submitted) analysed an experiment performed with an ocean model forced by interannually varying atmospheric forcings. They show that the warm anomalies associated with the positive phase of the Atlantic El Niño in the center of the basin are produced by a downwelling Kelvin wave, which triggers stratification anomalies and mixed-layer depth anomalies. The dampening of the mode in July is associated with a cooling due to negative horizontal advection anomalies. Such results are largely consistent with the analysis performed by Polo et al. (2015a) also in the framework of PREFACE using observations. However, Polo et al. (2015a) show that the processes can be different in coupled models than in observations: reversed propagation of SST anomalies (from the western equator to the African coast in the model, conversely to observations). Such misrepresentation in models could be due to a poor reproduction of the mixed layer depth seasonality.

The connection between the Atlantic El Niño and the South Atlantic Ocean Dipole (SAOD) has also been analyzed. The results from Nnamchi et al. (2016) suggest that the former could be an intrinsic equatorial arm of the SAOD.

In the framework of PREFACE, the stability of the TA variability modes has been investigated. Martín-Rey et al. (2017, under review) have shown that the characteristics of the Atlantic El Niño change depending on the background state. Under a negative phase of the Atlantic Multidecadal Oscillation (AMO, Kerr et al. 2000), the evolution of the Atlantic El Niño is associated with a weakening of both Atlantic subtropical highs, there is a westward extension of the warm anomalies in the TA and it promotes a la Pacific La Niña the next winter. Conversely, under a positive phase of the AMO, the mode is related to an intensified Azores High, it shows a dipole-like configuration in the pattern with cold anomalies north of the equator and it is not followed by the development of a Pacific La Niña. Losada and Rodriguez-Fonseca (2016), using two atmospheric general circulation models, have shown that changes in the spatial structure of the Atlantic El Niño after the change of phase of the AMO in the 1970s lead to changes in its impact on the Pacific atmosphere in the next winter. They show that the atmospheric response to the Atlantic El Niño over the tropical Pacific are stronger after the 1970s, partly due to the westward extension of the warm anomalies in the equatorial Atlantic in this period. In turn, Mohino and Losada (2015) have shown that changes in the background state could greately alter the impacts of the Atlantic El Niño: in their idealized experiments with the SPEEDY atmospheric general circulation model, they find that even if the spatial pattern of the Atlantic El Niño does not change, its impact at the end of the 21st century will be different from the present ones not only in the tropical rainfall but also in extratropical surface temperature. A question still open is if the differences in the background state of the global SSTs could also play a role in the observed tropical response to the Atlantic El Niño before and after the 1970s, as suggested bymodelling results presented in D8.2.

1.1. Stochastic vs dynamic contributions to TA variability

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(Dieppe et al. 2017 in preparation)

The Atlantic Niño is the dominant mode of interannual SST variability in the eastern equatorial Atlantic (generally constrained by the Atl3 region, 3°S-3°N, 20°W-0°E). Via its close relationship with the ITCZ, it affects rainfall patterns across neighbouring countries. Current coupled global climate models (CGCMs), however, struggle to reproduce its variability. One reason for the poor model performance is that most state-of-the-art CGCMs suffer from an equatorial SST bias that inhibits summer cold tongue growth. Additionally, recent research raised doubts about the dynamical nature of the Atlantic Niño, arguing that stochastic atmospheric processes alone are sufficient to produce Niño-like variability.

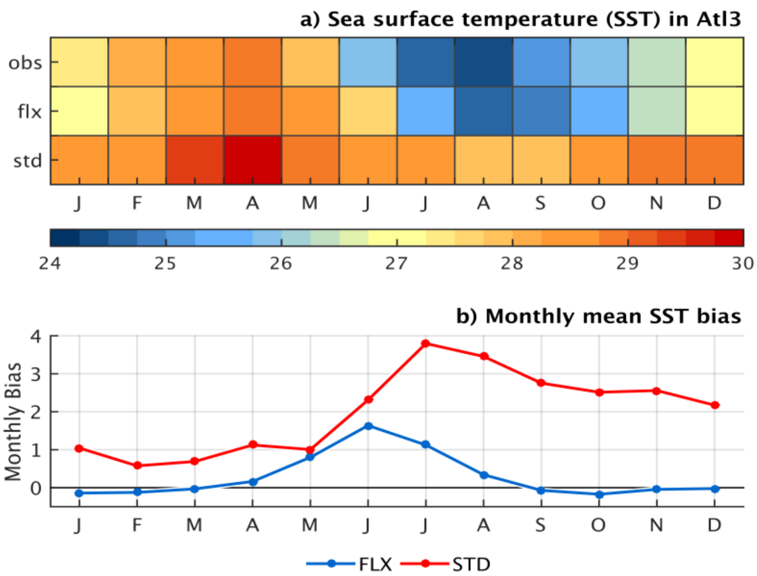

Figure 1: (a) Monthly mean SST in Atl3 for ERA-Interim, FLX, and STD in the upper, middle, and lower row, respectively. (b) Monthly mean bias for FLX (blue) and STD (red).

We use a low-resolution version of the CGCM Kiel Climate Model (KCM) and focus on two questions: (i) Do dynamical processes contribute to Atlantic Niño SST variability?, and (ii) Does the equatorial Atlantic warm bias affect the KCM's ability to produce realistic dynamical SST variability? We address question (i) by decomposing Atl3 SST variance into dynamical and stochastic driven thermodynamical components. We employ an approach that is based on empirical linear models of dynamical SST using two predictors, sea surface height (SSH) in Atl3 and zonal surface wind (u10) in the western equatorial Atlantic (WAtl, 3°S-3°N, 40°W-20°W). The choice of our predictors is inspired by the Bjerknes feedback, which is active in the equatorial Atlantic in boreal summer and helps to establish the seasonal cold tongue. For question (ii), we repeat our SST variance decomposition for two KCM experiments. One standard experiment (STD) produces the known warm SST bias in the equatorial Atlantic; the other experiment, FLX, corrects this bias via surface heat flux correction. Both experiments are run in partially coupled mode, a technique that has been developed to produce dynamically consistent equatorial initial conditions for hindcasting purposes. In the partially coupled KCM, the ocean and sea ice components of the model are forced with observed wind stress anomalies that have been added to the model wind stress climatology. In this way, both SST and the atmospheric wind field remain fully prognostic variables. Our analysis period is 1993-2012, the overlap between our validation datasets ERA-Interim (SST, u10) and AVISO (SSH) and our KCM experiments. The cold tongue behaviour and the monthly mean SST bias in the eastern equatorial Atlantic are illustrated in Figure 1.

Adressing question (i), we find that observed dynamical SST variance shows a pronounced seasonal cycle (black lines in the top left panel of Figure 2). It peaks during the active phase of the Atlantic Niño and is then roughly 4-7 times larger than stochastic SST variance (Figure 2, top right panel). This suggests that dynamical processes contribute strongly to the Atlantic Niño, implying a certain degree of predictability. For question (ii) we find that the SST bias in the KCM STD experiment (red line) suppresses the summer peak in dynamical SST variance. Bias reduction (FLX experiment, blue line), however, improves the representation of the seasonal cold tongue (Figure 1) and enhances dynamical SST variability (Figure 2) by supplying a background state that allows key feedbacks of the tropical ocean-atmosphere system to operate in the model (not shown here). Although the monthly mean SST bias in FLX is greatly reduced (Figure 1), dynamical SST variability is still not captured exceedingly well in the experiment. This suggests that our symptomatic bias reduction approach is not sufficient to correct a fundamentally biased system, reinforcing our findig of an Atlantic Niño variability that is dynamically linked to other components of the equatorial climate system.

Finally, again inspired by the Bjerknes feedback and the well-known lagged impact of spring WAtl u10 variability on summer Atl3 SST variability, we repeat our analysis including lagged SST-predictor relationships (middle and bottom rows of Figure 2). For each month and both predictors SSH and u10, we cross-correlate SST with the predictor for up to six months and identify the month in which the correlation coefficient between SST and the predictor is largest. When building our linear models of dynamical SST for that month, we replace the predictor time series with the time series of the month during which the relationship is strongest. For example, when May SST is strongest correlated to April u10, we replace May u10 by April u10 when building the linear model of dynamical SST. In the bottom row of Figure 2, we allow both positive and negative lags between SST and u10; in the middle row, we restrict the lagging to the more relevant cases when the predictors lead SST. Figure 2 shows that the -- admittedly small (not shown) -- lags in the tropical Atlantic hardly affect the distributions of our dynamical SST variances. We conclude that our results are robust.

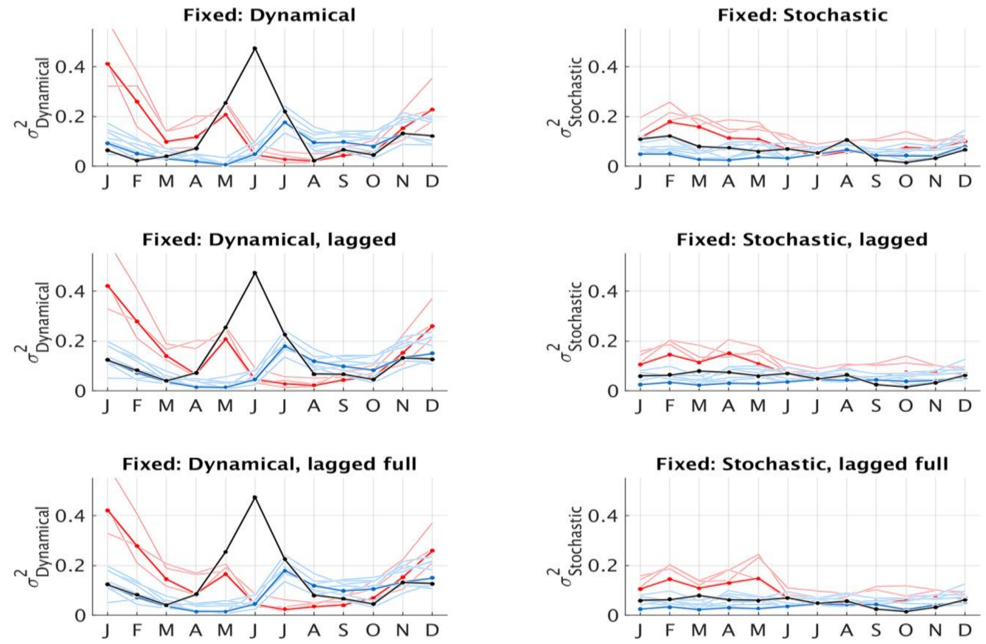

Figure 2: Atl3 SST variance decomposition based on SSH and u10 into (left) dynamical and (right) stochastic contributions for (upper) instantaneous, (middle) all lags, including positive lags, and (bottom) negative lags only. The line colours indicate (black) ERA-Interim/AVISO, (blue) FLX, and (red) STD. Thin lines in lighter colours indicate the SST variance decomposition for the individual ensemble members of the KCM experiment. Lagged SST variance decomposition for the individual ensemble members is based on a lag analysis for the individual ensemble members.

1.2. Main processes of the Atlantic cold tongue Interannual Variability

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Planton et al. (2017 submitted)

The interannual variability of the Atlantic cold tongue (ACT) is studied by means of a mixed-layer heat budget analysis. A method to classify extreme cold and warm ACT events is proposed and is applied to ten various analysis and reanalysis products. This classification allows five cold and five warm ACT events to be selected over the period 1982-2007. Cold (warm) ACT events are defined by the presence of negative (positive) SST anomalies in the center of the equatorial Atlantic in late boreal spring, preceded by negative (positive) zonal wind stress anomalies in the western equatorial Atlantic. An ocean general circulation model, able to reconstruct correctly the interannual variability of the ACT, is used to demonstrate that cold ACT events develop rapidly from May to June mainly due to intense cooling by vertical mixing and by horizontal advection. The simulated cooling in the center of the basin is the result of the combined effects of non-local and local processes. The non-local process is an upwelling associated with an eastward-propagating Kelvin wave. It shallows the mixed-layer and preconditionates the upper-layers to be cooled by an intense heat loss at the base of the mixed-layer, amplified by a stronger local injection of energy from the atmosphere. The early cooling by vertical mixing in March is also shown to be a good predictor of the June cooling.

In July, horizontal advection starts to abnormally warm the mixed-layer and damps SST anomalies. The advection anomalies, which result of changes in the horizontal temperature gradient, are associated in some cases with the propagation of Rossby waves along the equator. During warm ACT events, processes are reversed, generating positive SST anomalies: a downwelling Kelvin wave triggers stratification anomalies and mixed-layer depth anomalies, amplified by a weaker injection of energy from the atmosphere in May-June. In July, warm ACT events are abnormally cooled due to negative horizontal advection anomalies resulting from similar processes as during cold ACT events. This additional cooling process extends the period of cooling of the ACT, reducing SST anomalies.

1.3. Growth and decay of the equatorial Atlantic SST mode by means of closed heat budget in a coupled general circulation model

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(Polo et al. 2015a)

Tropical Atlantic variability is strongly biased in coupled General Circulation Models (GCM). Most of the models present a mean SST bias pattern that resembles the leading mode of interannual SST variability. Thus, understanding the causes of the main mode of variability of the system is crucial. A GCM control simulation with the IPSL-CM4 model as part of the CMIP3 experiment has been analyzed. Mixed layer heat budget decomposition has revealed the processes involved in the origin and development of the leading interannual variability mode which is defined over the Equatorial Atlantic (hereafter EA mode). In comparison with the observations, it is found a reversal in the anomalous SST evolution of the EA mode: from west equator to southeast in the simulation (Figure 3), while in the observations is the opposite. Nevertheless, despite the biases over the eastern equator and the African coast in boreal summer, the seasonality of the interannual variability is well-reproduced in the model. The triggering of the EA mode is found to be related to vertical entrainment at the equator as well as to upwelling along South African coast. The damping is related to the air-sea heat fluxes and oceanic horizontal terms. As in the observation, this EA mode exerts an impact on the West African and Brazilian rainfall variability. Therefore, the correct simulation of EA amplitude and time evolution is the key for a correct rainfall prediction over tropical Atlantic. In addition to that, identification of processes which are responsible for the tropical Atlantic biases in GCMs is an important element in order to improve the current global prediction systems

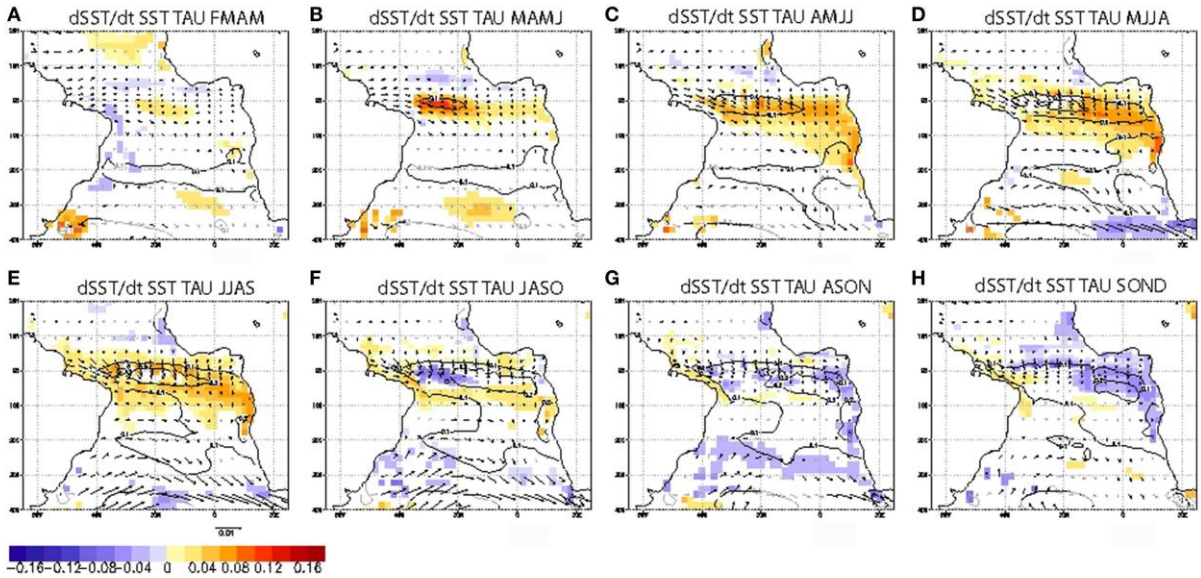

Figure 3: Evolution of the EA mode. Regression map of SST anomalies (contours in C), dSST/dt (shaded in C/month) and wind stress (vectors in N/m^2) from FMAM (A) to SOND (H) 4-months seasons onto time-series of the EA mode. Only significant areas have been plotted from a t-test at 90% confidence level.

1.4 On the South Atlantic Dipole and the role of South Atlantic Anti-cyclone

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(Nnamchi et al. 2016)

Equatorial Atlantic variability is dominated by the Atlantic Niño peaking during the boreal summer. Here, we have studied based on observations and regional coupled model simulations the role of the South Atlantic Anti-cyclone in driving equatorial Atlantic variability.

Studies have shown robust links of the Atlantic Niño to fluctuations of the St. Helena subtropical anticyclone and Benguela Niño events. Furthermore, the occurrence of opposite SST anomalies in the eastern equatorial and southwestern extratropical South Atlantic Ocean (SAO), also peaking in boreal summer, has recently been identified and termed the SAO dipole (SAOD). However, the extent to which and how the Atlantic Niño and SAOD are related remain unclear. Here, an analysis of historical observations reveals the Atlantic Niño as a possible intrinsic equatorial arm of the SAOD. Specifically, the observed sporadic equatorial warming characteristic of the Atlantic Niño (~0.4 K) is consistently linked to south-western cooling (~ -0.4 K) of the Atlantic Ocean during the boreal summer. Heat budget calculations show that the SAOD is largely driven by the surface net heat flux anomalies while ocean dynamics may be of secondary importance. Perturbations of the St. Helena anticyclone appear to be the dominant mechanism triggering the surface heat flux anomalies. A weakening of the anticyclone will tend to weaken the prevailing northeasterlies and enhance evaporative cooling over the southwestern Atlantic Ocean. In the equatorial region, the southeast trade winds weaken, thereby suppressing evaporation and leading to net surface warming. Thus, it is hypothesized that the wind–evaporation–SST feedback may be responsible for the growth of the SAOD events linking southern extratropics and equatorial Atlantic variability via surface net heat flux anomalies.

To assess how much the observed equatorial Atlantic climate variability can be explained by variations in the subtropical South Atlantic we use an ensemble of coupled ocean-atmosphere simulations for the observed and regionally coupled over the equatorial Atlantic. The influence of observed subtropical south Atlantic variability within the domain can be determined by changing the position of the southern boundary of regional atmospheric model. Two types of domains are used one with a boundary around 17°S and another with a domain around 40°S. For both we utilise eight different ensemble members. Experiments are either forced with either ERA40 or ERAI, and thus covering different periods, and also differ in resolution and some parameter values. These experiments were used to investigate the source of biases in the tropical Atlantic (Cabos et al., 2016). Correlation of the ensemble mean SST with observations shows that up to 50% of the equatorial Atlantic SST variance can be explained when the South Atlantic Anti-cyclone variability is prescribed at the south boundary from observations (Figure 4). This is the result of a seasonal coupling with the south (not shown). The dynamical and thermodynamical mechanisms for the link are being further investigated.

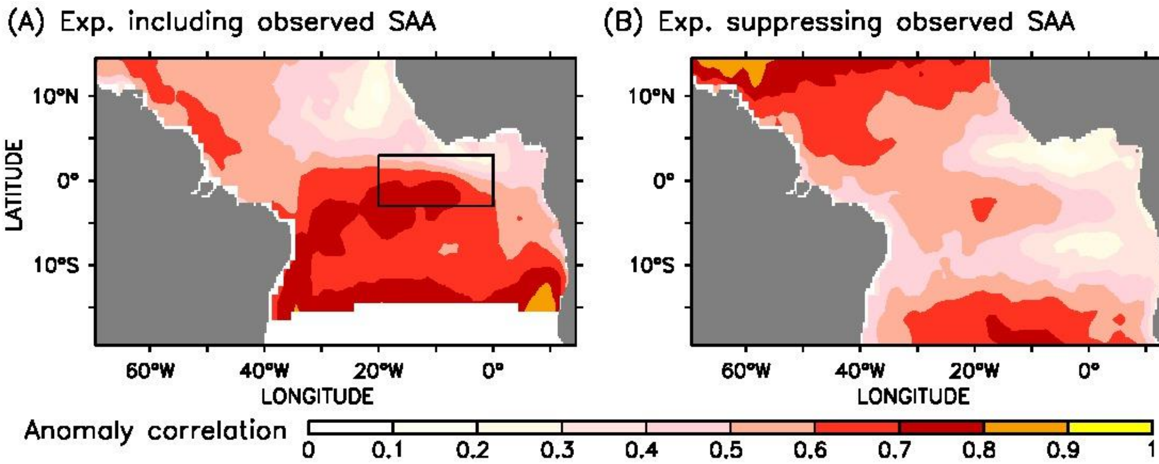

Figure 4: Impact of South Atlantic atmospheric variability on equatorial Atlantic SST. Correlation with observed SST for two the ensemble mean of two regional model experiments with an atmospheric boundary at (A) 17°S and (B) 40°S. The period considered is 1980-2001, and the ensemble sizes are eight.

1.5. On the tropical Atlantic interannual variability modes under different AMO phases

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(Martín-Rey et al. 2017, in revision)

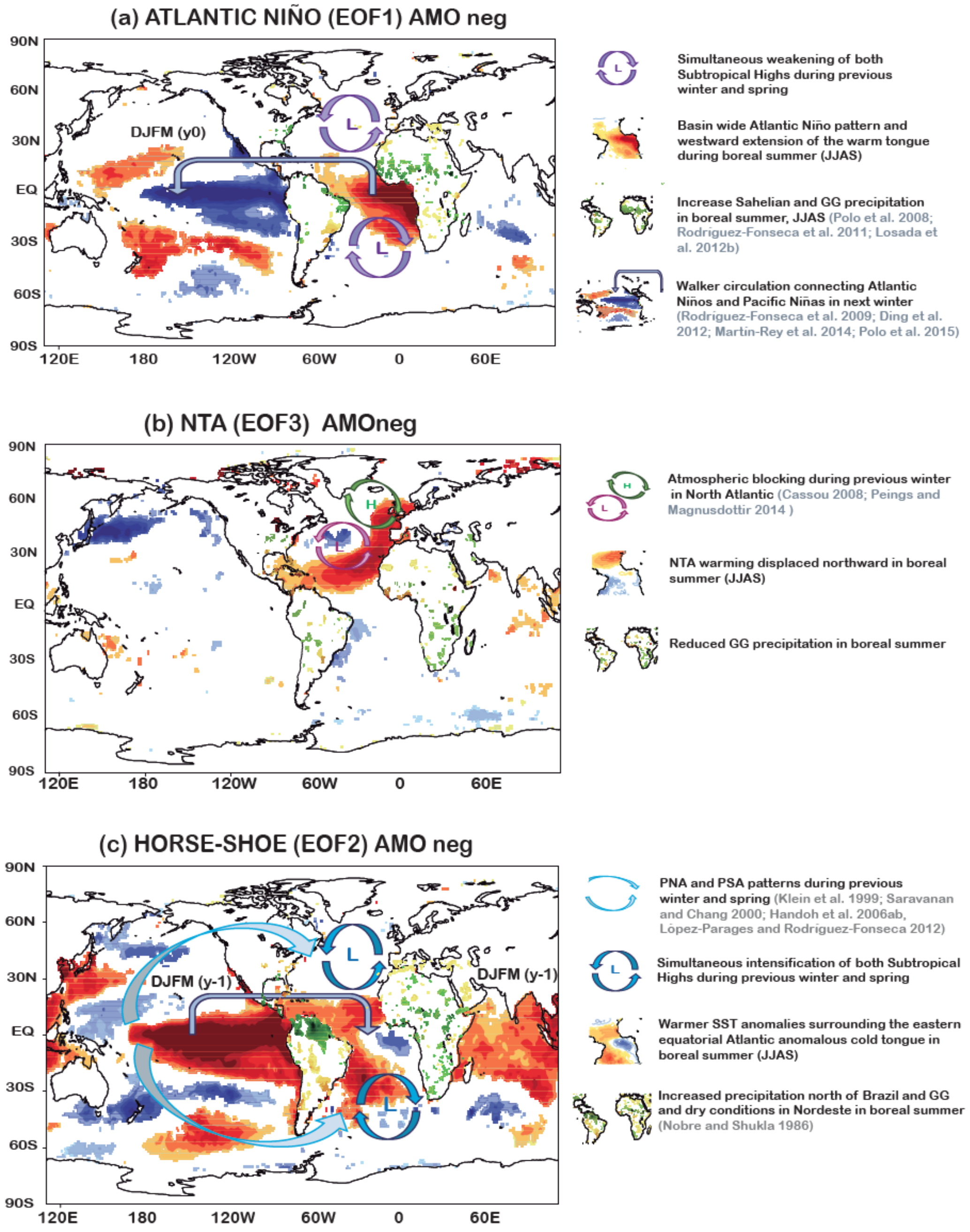

Figure 5: Scheme of the characteristics of TAV modes in different AMO phases with their forcings and impacts.

Previous studies have put forward that the Atlantic Multidecadal Oscillation (AMO) is related to the precipitation regime of adjacent and remote areas (Knight et al. 2006, Sutton and Hodson 2003; Sutton and Dong 2012) and could even modulate the tropical Pacific mean state, increasing ENSO variance (Dong et al. 2006; Dong and Sutton 2007; Wang et al. 2009). Nevertheless, the influence of the AMO on the Tropical Atlantic Variability (TAV) remains unclear (Haarsma et al. 2008; Tokinaga and Xie 2011; Polo et al. 2013; Svendsen et al. 2014).

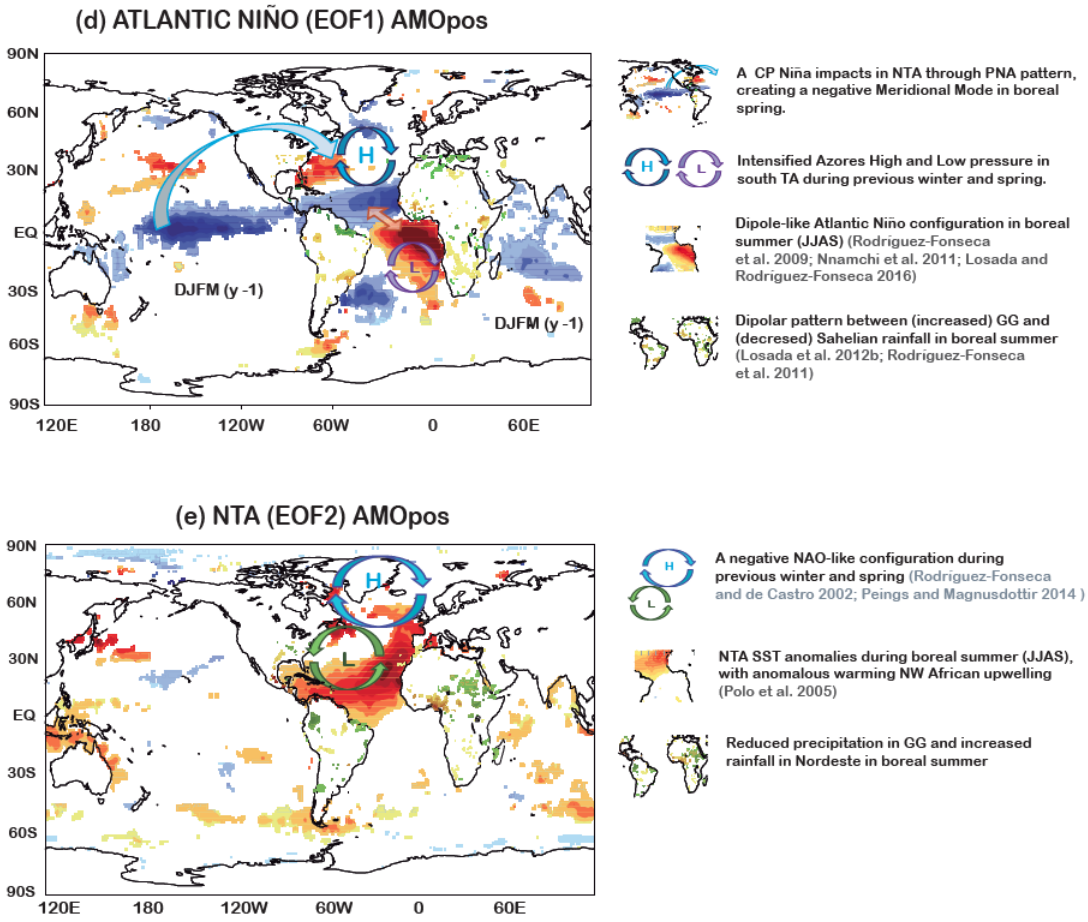

Figure 5 (continuation): Scheme of the characteristics of TAV modes in different AMO phases with their forcings and impacts.

The present study has explored the changes suffered by the boreal summer interannual Tropical Atlantic Variability (TAV) under different AMO phases in the observational record. It has been demonstrated that during negative AMO periods, the eastern equatorial Atlantic SST variability is enhanced, associated with a shallower mean thermocline. Consequently, the boreal summer interannual TAV modes are modified (Figure 5). The Atlantic Niño presents larger amplitude and a westward extension during negative AMO phases. It is preceded by the simultaneous weakening of both Subtropical Highs during previous winter-spring, contrasting to the seesaw SLP pattern observed during positive AMO. The North Tropical Atlantic (NTA) mode is related to a Scandinavian blocking pattern during winter-spring in negative AMO phases, while the NTA is part of the SST-tripole associated with the North Atlantic Oscillation (NAO) under positive AMO periods. A striking result is the existence of an overlooked variability mode, denoted as Horse-Shoe (HS) pattern, during negative AMO phases. This anomalous warm HS, surrounding an eastern equatorial cooling, could be remotely forced by an ENSO phenomenon. Under negative AMO, the tropical-extratropical teleconnections are enhanced and the Walker circulation is altered. This, together with the increased equatorial SST variability, could favor the remote impacts of TAV. This multi-decadal modulation of interannual modes gives a step forward in the better understanding of the TAV along the observational record, which is important to improve its modelling, impact and predictability.

1.6. Tropical atmospheric response to decadal changes in the Atlantic Equatorial Mode

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(Losada and Rodríguez-Fonseca, 2016)

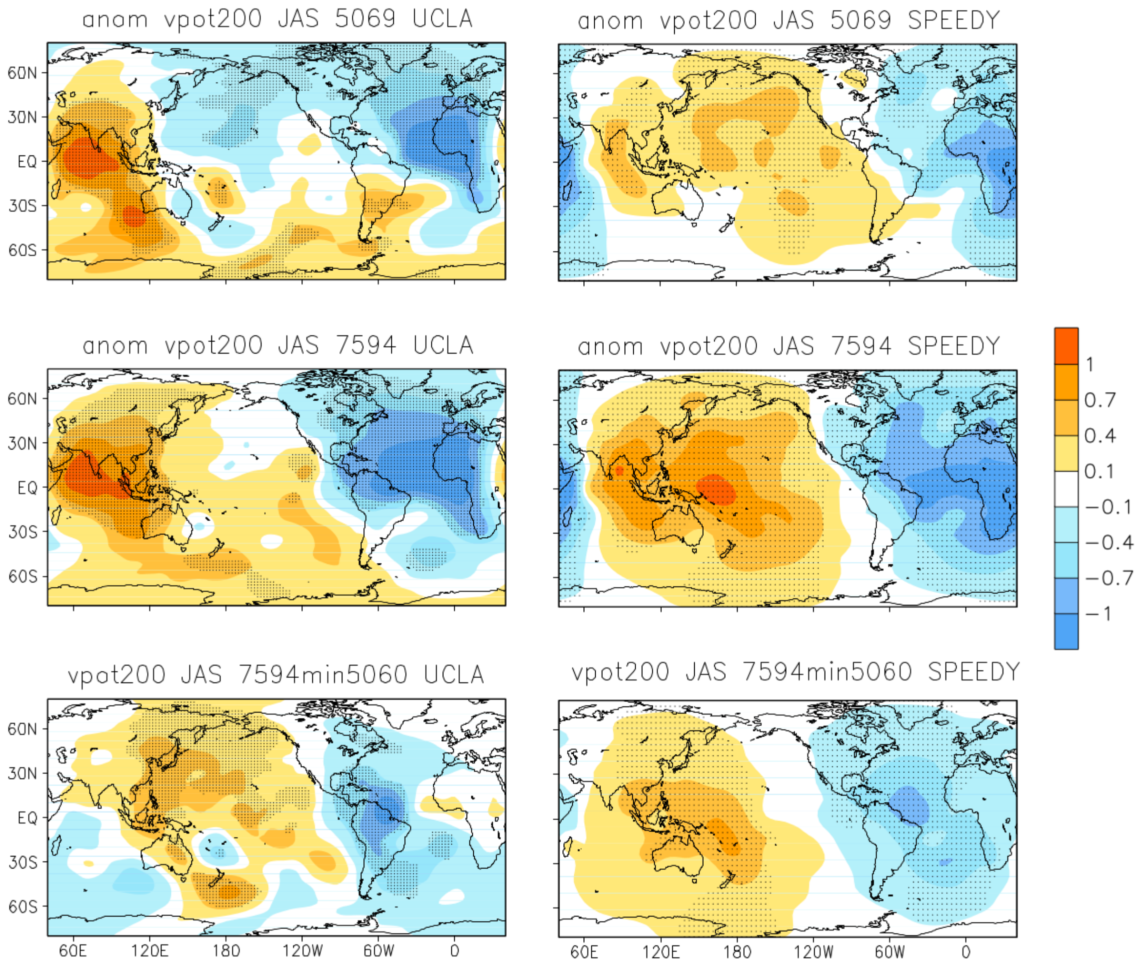

Figure 6: JAS anomalous velocity potential (10^6 m^2 s^{-2}) at 200 hPa for ATL_pre70 (first row), ATL_post70 (second row) simulations and the difference between them (third row) for UCLA (left) and ICTP (right) models. Dots denote those regions where the anomalies are significant at a 95 % confidence level

It has been shown that the atmospheric response to the Atlantic Equatorial Mode is non-stationary. After the 1970s, SST anomalies in the tropical Atlantic are able to alter the atmosphere in the tropical Pacific via modifications of the Walker circulation. Such changes could be related to the differences in the background state of the global SSTs before and after the 1970s, but also to changes in the interannual Equatorial Mode itself. In this work we first describe the differences in the interannual Equatorial Mode before and after the 1970s. Then we use two AGCMs (the UCLA and the SPEEDY models) to perform different sensitivity experiments changing the spatial structure of the Equatorial Mode, and we explore the differences in the atmospheric response over the tropical Pacific region to each of the SST patterns considered. The control simulation uses as boundary conditions the climatological monthly means of SST averaged over the period 1950-94. Two further experiments are performed, in which two different configurations of the Atlantic Equatorial Mode are added to the 1950-94 monthly mean. In the first one, denoted ATL_pre70, we add monthly anomalies consistent with the Equatorial mode observed before the 1970s; while in the second experiment (ATL_post70) the SST monthly anomalies added in the tropical Atlantic have the structure of the mode after the 1970s. The results show that the changes in the Walker Atlantic–Pacific cell produced by the EM are stronger after the 1970s (Figure 6), and are reinforced by the change in the impact of the EM over the Indian Ocean and the Maritime Continent. It is also shown that, although the Atlantic–Pacific connection is established by the aforementioned changes in the Walker circulation between the two basins, the modulation of the Indian sector is crucial for a realistic simulation of such connection by climate models.

1.7. Impacts of the Equatorial Mode in a warmer climate

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(Mohino and Losada, 2015)

The main source of SST variability in the Tropical Atlantic at interannual time scales is the Equatorial Mode or Atlantic El Niño. It has been shown to affect the adjacent continents and also remote regions, leading to a weakened Indian Monsoon and promoting La Niña-type anomalies over the Pacific. However, its effects in a warmer climate are unknown. This work analyses the impact of the Equatorial Mode at the end of the twenty first century by means of sensitivity experiments with an atmosphere general circulation model. The prescribed boundary conditions for the future climate are based on the outputs from models participating in the coupled model intercomparison project—phase V. Our results suggest that even if the characteristics of the Equatorial Mode at the end of the twenty first century remained equal to those of the twentieth century, there will be an eastward shift of the main rainfall positive anomalies in the Tropical Atlantic and a weakening of the negative rainfall anomalies over the Asian monsoon due to the change in climatological SSTs (Figure 7). We also show that extratropical surface temperature anomalies over land related to the mode will change in regions like Southwestern Europe, East Australia, Asia or North America due to the eastward shift of the sea level pressure systems and related surface winds.

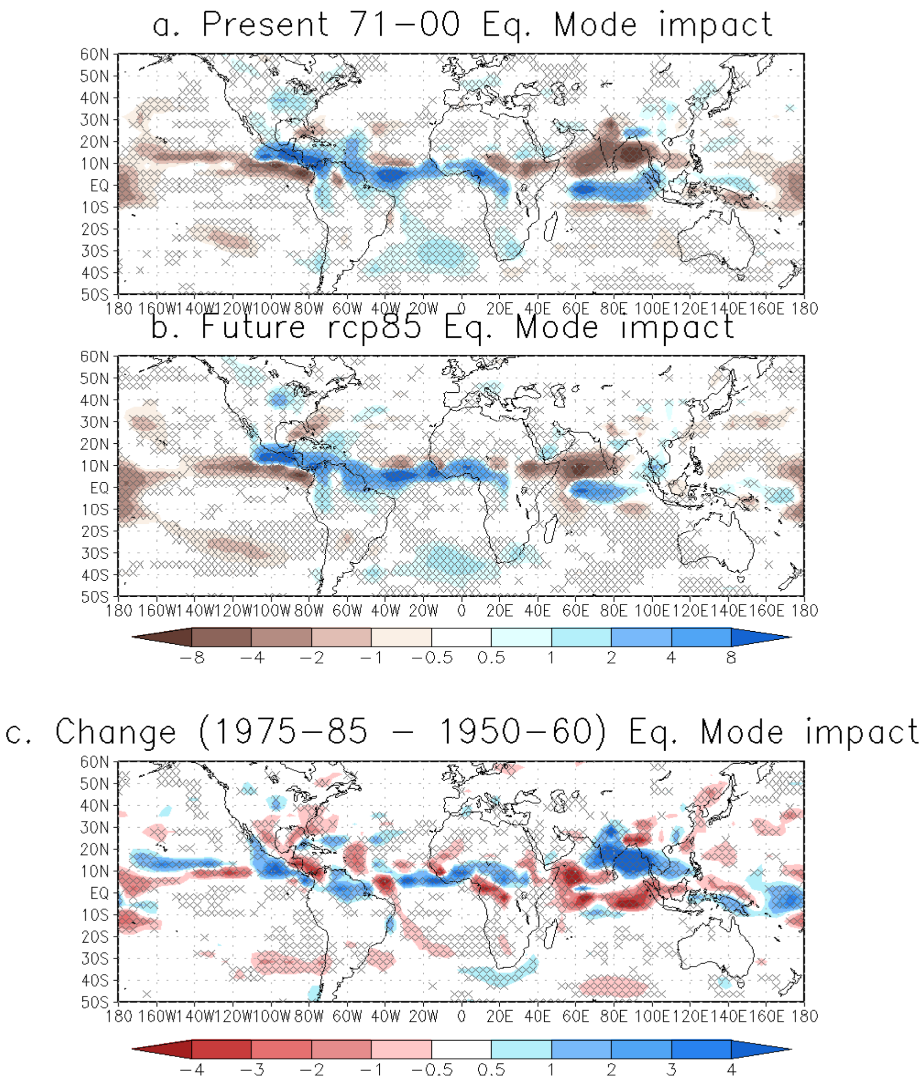

Figure 7: Impact of the Equatorial Mode on summer (July to September) rainfall (mm/day) in: a present; b future climate. c Difference between the impact for the future and the present simulations. Regions where differences are statistically significant (alpha = 0.05) are marked with crosses

2. The Altantic-Pacific connection

Previous works have shown a connection between the variability in the Atlantic and Pacific basins at interannual timescales. Some studies point to a leading role for the Pacific ocean (Saravanana and Chang 2000; Sutton et al. 2000; Huang et al. 2002, among others), while others suggest the Atlantic could influence the tropical Pacific (Rodríguez-Fonseca et al. 2009; Ding et al. 2012; among others). In the framework of PREFACE this Atlantic-Pacific connection has been further investigated using observations, partially coupled simulations and seasonal forecasts. On the one hand, Martín-Rey et al. (2014) have evaluated whether the Atlantic-Pacific connection is a mode of variability and if it is modulated at decadal timescales. They have demonstrated that, indeed, the Atlantic-Pacific Niños connection is a leading mode of interbasin covariability during certain decades. The positive phase of the mode can be described as warm anomalies over the equatorial Atlantic in summer related to ascending motions locally and descending ones over the Pacific. There, they generate an upwelling Kelvin wave that propagates eastward and favours the development of a Pacific La Niña in winter. The decades in which the mode appears coincide with negative phases of the AMO. Such results could be highly relevant for seasonal-to-decadal prediction systems. For this reason, in PREFACE the NMME2 seasonal prediction system has been analysed to evaluate if it is capable of reproducing the observed Atlantic-Pacific relationship.

2.1. On the Atlantic-Pacific connection: a multi-decadal modulated mode

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(Martín-Rey et al. 2014)

Atlantic and Pacific El Niño are the leading tropical oceanic variability phenomena at interannual timescales. Recent studies have demonstrated how the Atlantic Niño is able to influence the dynamical processes triggering the development of the Pacific La Niña and vice versa. However, the stationarity of this interbasin connection is still controversial. Here we show for the first time that the Atlantic–Pacific Niños connection takes place at particular decades, coinciding with negative phases of the Atlantic Multidecadal Oscillation (AMO). During these decades, the Atlantic–Pacific connection appears as the leading coupled covariability mode between Tropical Atlantic and Pacific interannual variability.

The mode is defined by a predictor field, the summer Atlantic SST, and a set of predictand fields which represent a chain of atmospheric and oceanic mechanisms to generate the Pacific El Niño phenomenon: alteration of the Walker circulation, surface winds in western Pacific, oceanic Kelvin wave propagating eastward and impacting on the eastern thermocline and changes in the Pacific SST by internal Bjerknes feedback (Figure 8). We suggest that the multidecadal component of the Atlantic acts as a switch for El Niño prediction during certain decades, putting forward the AMO as the modulator, acting through changes in the equatorial Atlantic convection and the equatorial Pacific SST variability. These results could have a major relevance for the decadal prediction systems.

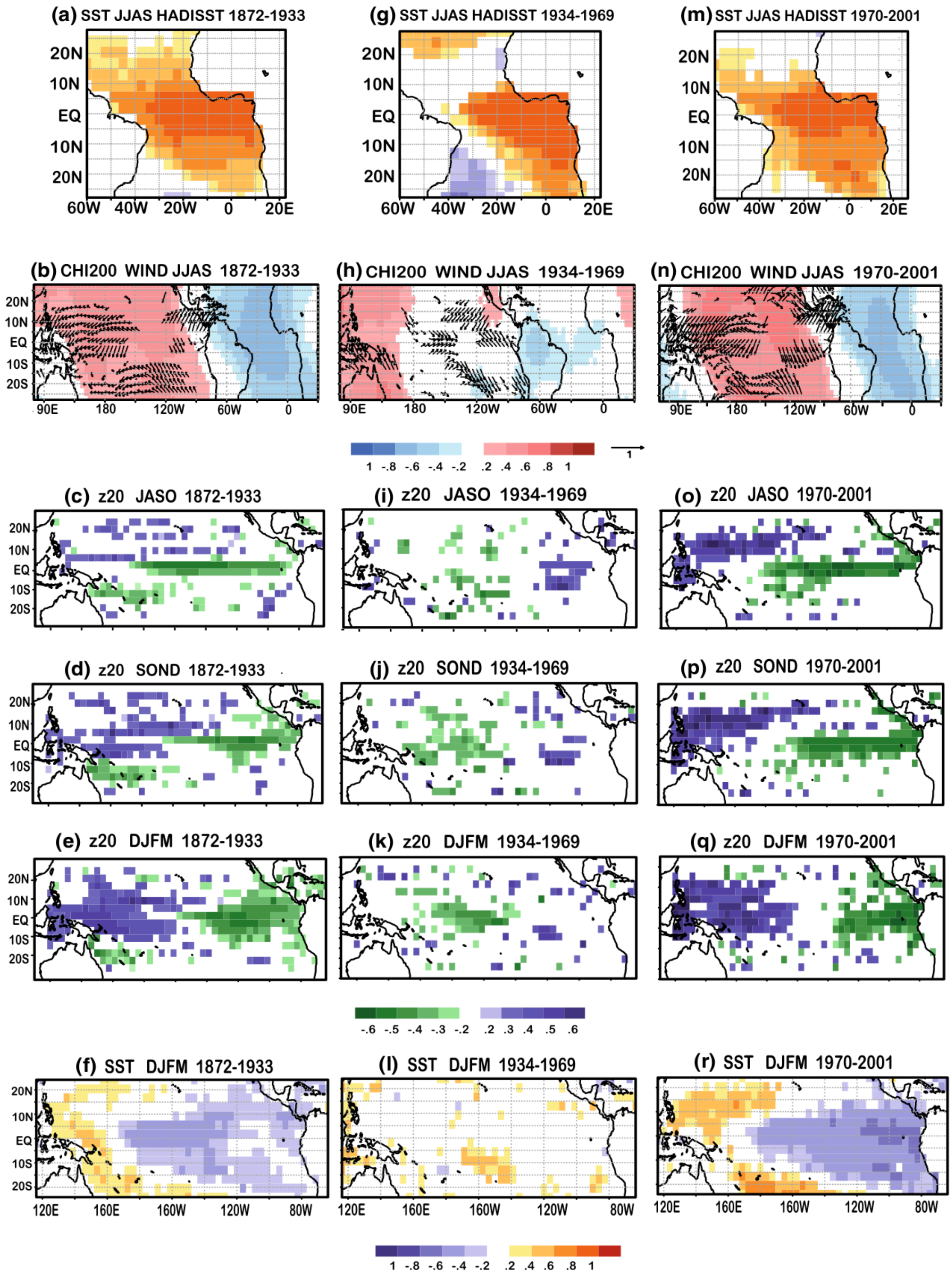

Figure 8: Leading Mode of the EMMCA for observations. a–r Homogeneous and Heterogeneous correlation maps for summer (JJAS) Tropical Atlantic SST and the expansion coefficients of the Tropical Atlantic SST in JJAS (in °C, shaded), tropical velocity potential at 200 hPa in JJAS (in m^2/s, shaded) and Tropical Pacific wind stress in JASO (in m/s, vectors), summer to winter (JJAS–SOND–DJFM) thermocline depth and Tropical Pacific SST in winter months, DJFM (in °C) for the periods 1872–1933 (a–f), 1934–1969 (g–l) and 1970– 2001 (m–r). Only significant values at 90 % confidence level according to a Monte Carlo test are presented

2.2. Skill assessment for ENSO and TAV

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Recent studies using observations and coupled models have clearly shown that the equatorial Atlantic SST impacts ENSO variability and predictability (Rodriguez-Fonseca et al., 2009; Ding et al. 2012, Polo et al., 2015b; Keenlyside et al. 2013). More specifically, observations indicate that equatorial eastern Atlantic SST variations (ATL3: 0E-20E, 3S-3N) lead those in the eastern Pacific (Nino3.4: 170W-120W, 5S-5N) by few months, with the relationship peaking at 5 months lag with ATL3 leading. This relation implies that Atlantic Niños (Niñas) that develop in late spring/early summer lead Pacific Niñas (Niños) developing in the following winter (Figure 9).

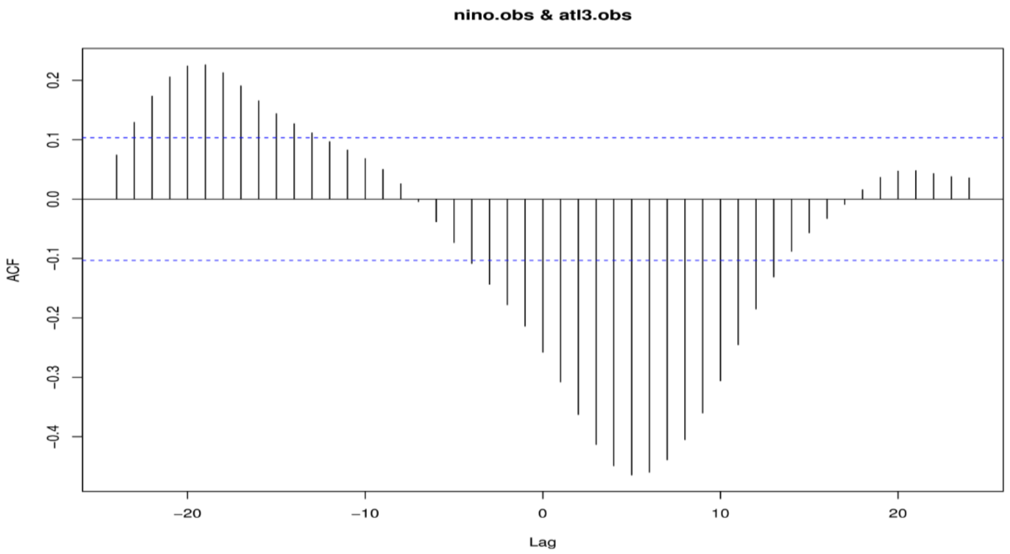

Figure 9: Lead-lag correlations (in months) between the observed monthly mean Nino3.4 index and the observed monthly mean ATL3 index (the regions of the indexes are defined in the text) for HadISST data between 1981-2010. Positive lags indicate ATL3 leading.

Even though it has been established that this relationship between equatorial Atlantic and equatorial Pacific is present in the observations (particularly after the 1970s), it remains unclear whether seasonal forecasts reproduce this relationship, and how it impacts ENSO predictability. Here, we assess this relationship in the NMME2 multi model seasonal prediction forecast system (Table 1). We use 10-months forecasts initialized in 1st of May every year between 1981-2010. We hereafter use the multi-model mean, averaged over all models and all ensembles available (Table 1).

Models	NCEP-CFSv2	CMC2-CanCM4	CMC1-CanCM3	GFDL-CM2p5-FLOR-A06	GFDL-CM2p5-FLOR-B01	COLA-RSMAS-CCSM4
Number of ensembles	24	10	10	12	12	10

Table 1: Seasonal forecasts used in this study.

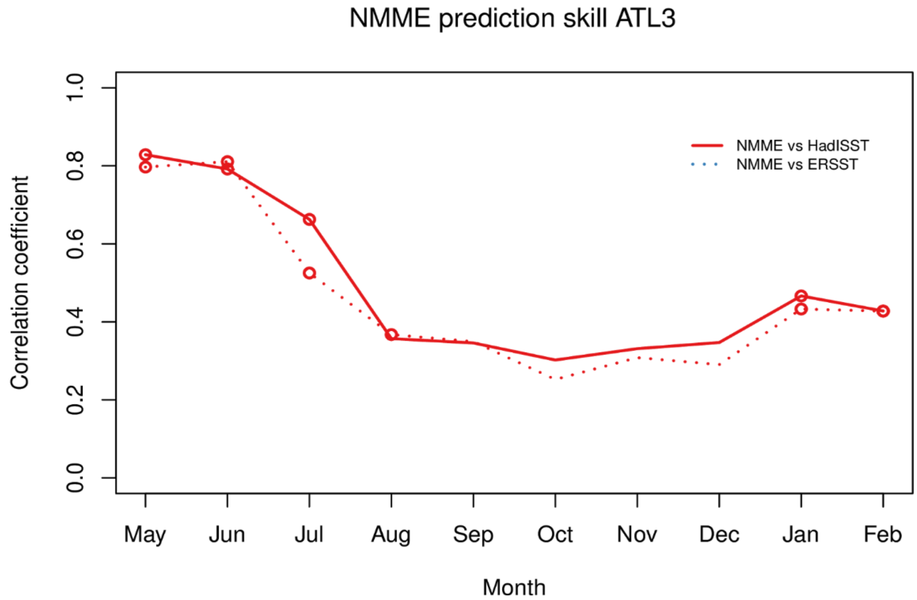

Figure 10: Prediction skill of the NMME2 multi-model mean forecasts initialized in May for ATL3, expressed as the correlation coefficient between the multi-model mean and two different observational datasets (HadISST and ERSST). Circles denote statistically significant correlations with a significance level of 5%.

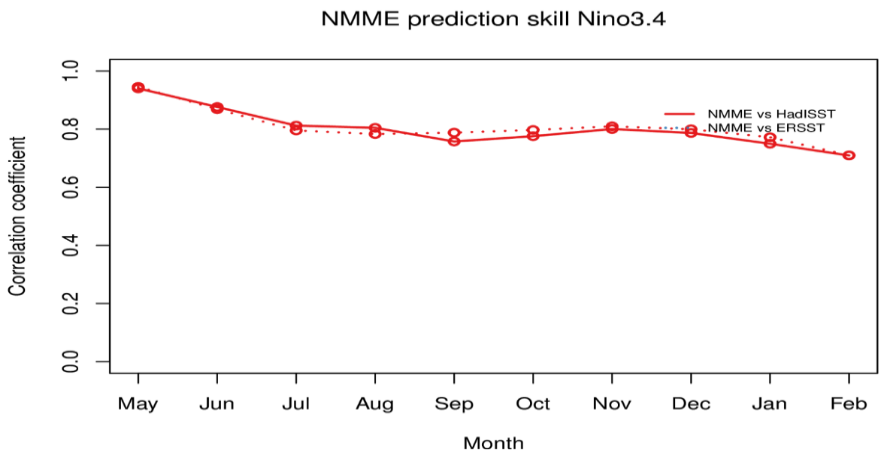

Figure 11: Prediction skill of the NMME2 multi-model mean forecasts initialized in May for Nino3.4, expressed as the correlation coefficient between the multi-model mean and two different observational datasets (HadISST and ERSST). Circles denote statistically

significant correlations with a significance level of 5%.

The prediction skill for the SST anomalies in the ATL3 and Nino3.4 regions (Figures 10, 11) show that in Nino3.4 there is the higher skill and for longer forecast time. In ATL3 the prediction skill falls after the third forecast month, is insignificant after the fourth forecast month, but reemerges in the ninth and tenth forecast month. The NMME2 multi-model mean captures the regression patterns of the observed MJJ ATL3 and observed OND Pacific SST (Figure 12), even if the regression in NMME3 is weaker and with lower statistical significance.

Details of this inter-basin connection, such as differences in phase dependencies, and exploration of the dynamical bridge between the two basins as suggested by Toniazzo (2010), will be further analyzed in the coming months.

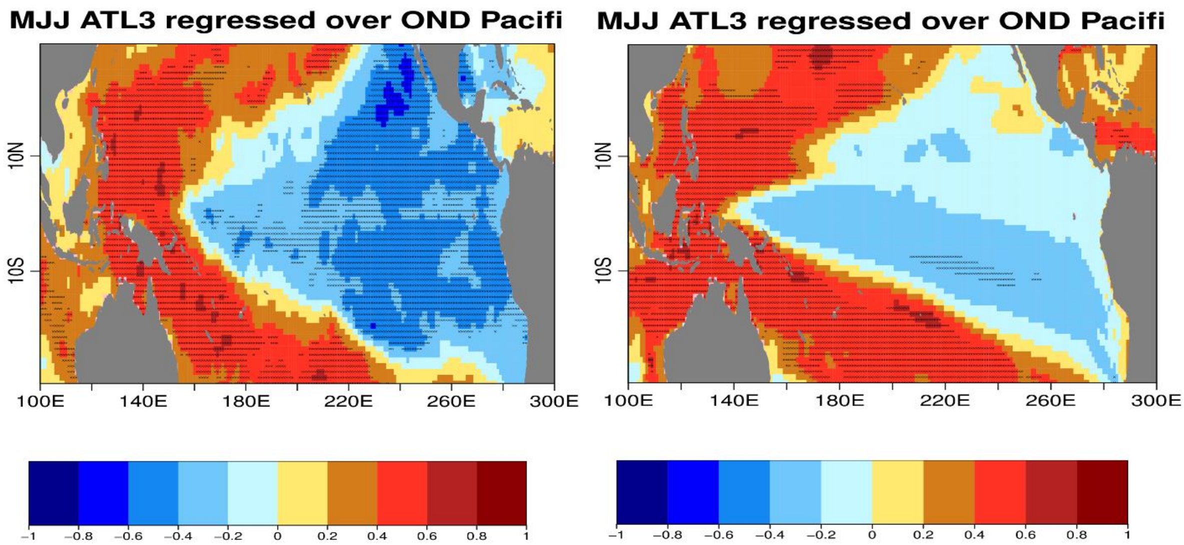

Figure 12: MJJ ATL3 index regressed over OND Pacifc SST for the period 1981-2010. Left: observations (HadISST), right: NMM2 multi-model ensemble, for forecasts initialized in 1st of May. Dotted points denote statistically significant correlations with a significance level of 5%.

3. Atlantic Equatorial Deep Jets

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Ascani et al. (2015), Matthießen et al. (2015) and Claus et al. (2016)

The Equatorial Deep Jets (EDJs) are a series of alternating, stacked zonal jets along the equator which steadily propagate downwards over time with a time scale of about 4.5 years in the Atlantic Ocean (Youngs and Johnson, 2015). The EDJs are often associated with linear equatorial basin modes (d'Orgeville, 2007; Youngs and Johnson, 2015) which implies that the observed downward phase propagation is associated with upward propagation of energy. Brandt et al. (2011) provides statistical evidence for the influence of the EDJs on surface climate by linking characteristic time scales of surface zonal velocity variability along the equator and equatorial SST variability with the time scale of the EDJs.

To understand the driving mechanism of the EDJs, Ascani et al. (2015) set up an idealized model of the equatorial Atlantic and showed that both the EDJs and the Equatorial Intermediate Currents (EICs) are driven by deep intraseasonal variability (DIV). The DIV in turn is generated by the instability of the surface circulation in this model. The authors also found that the EICs are also driven by the EDJs via zonal self-advection of the EDJs.

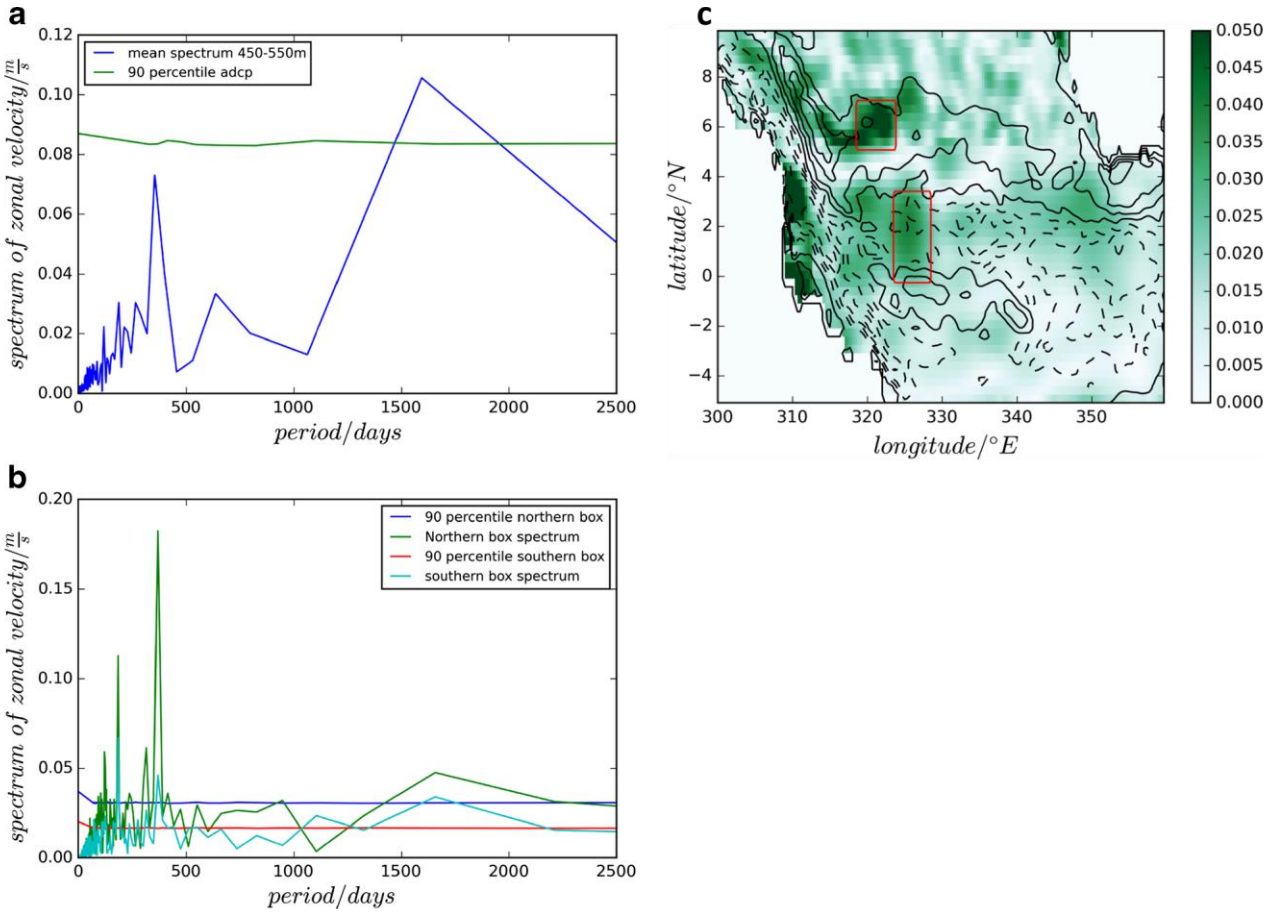

Figure 13: (a) Spectrum of the zonal velocity at 23°W on the equator from ADCP data (450–550 m depth, blue) and its 90 percentile (green line). (b) Spectra of the zonal velocity at the surface in the two boxes shown in (c) and their 90 percentile. (c) Plan view of the amplitude of the 4.5 year variability of the geostrophic zonal velocity at the surface from AVISO data as shown by the color shading. Contours show the time mean zonal velocity with an interval of 0.1 ms^{-1}, dashed contours showing westward, and solid contours eastward flow. The zero line is also shown by a solid contour.

The potential influence of the EDJs on the surface circulation has been investigated by Matthießen et al. (2015). The authors used a similar model setup as Ascani et al. (2015) and showed that the theoretical assumption of upward energy flux associated with the EDJs is true for their model. They further showed that variability of surface zonal velocity within the North equatorial Counter Current (NECC) and also closer to the equator is likely driven by the EDJs. The same pattern of surface velocity variability is also found in surface geostrophic velocity inferred from satellite observations, suggesting that the findings from the idealized box model also apply to the equatorial Atlantic Ocean (Figure 13).

Long-term, deep reaching zonal velocity observations at 23W on the equator were analysed by Claus et al. (2016). It was found that the zonal velocity variability is dominated by three distinct periods: the annual cycle, the semi-annual cycle and the EDJs. For each of these periods, the variability is associated with a resonant equatorial basin mode (see Figure 14). Assuming linear dynamics, a basin-wide reconstruction of the EDJs was inferred and it was confirmed that the EDJs are associated with upward energy propagation. It was further found that the EDJs are likely subject to relatively strong dissipation and have to be maintained against dissipation over a considerable depth range.

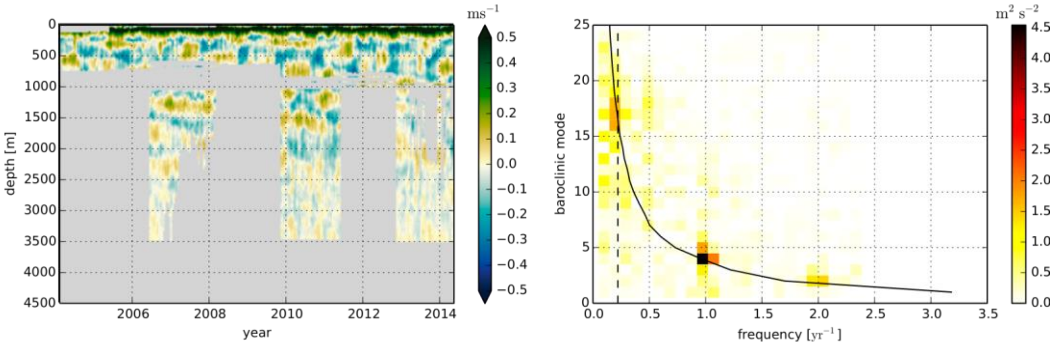

Figure 14: (left) Moored zonal velocity observations at 23°W on the equator. (right) Fitted energy spectrum of the zonal velocity data shown on the left panel for each baroclinic mode. The solid line marks the resonance frequency of the gravest equatorial basin mode and the dashed line corresponds to a period of 1650 days, which explains most variability in the interannual range.

4. Rainfall variability in the adjacent continental areas

The Pacific El Niño is the main source of variability at interannual timescales. It has been shown to affect rainfall variability in the continental areas adjacent to the Atlantic, its positive phase leading to negative rainfall anomalies over Southern Africa, Ethiopia, Northeast Brazil and West Africa and even to a reduction of the North Atlantic hurricane activity (Ropelewski and Halpert, 1987, 1989; Camberlin and Philippon 2002; Giannini et al. 2004; Rowell 2001; Bove et al. 1998). In the framework of PREFACE such influence has been further studied to better understand the mechanisms at play and the skill in models to reproduce the observed links. Dieppois et al. (2016) show that the shift in the Walker circulation linked to ENSO events interact with asymmetric ocean-atmosphere conditions between the South Atlantic and Indian Oceans leading to a modulation of rainfall over South Africa. However, the regional biases that the current generation of general circulation models show over Africa and the Indian Ocean hinder their capacity to simulate the right sign in the link (Dieppois et al. 2015). As for Ethiopia, Gleixner et al. (2016) show that the local subsidence and possibly also a reduction of the moisture inflow from the Atlantic ocean into Ethiopia associated with ENSO can explain the summer rainfall deficits observed during positive El Niño events.

However, the links of rainfall variability and ocean SST anomalies are not always stationary in time. Janicot et al. (2001) already showed that the impact of ENSO on West Africa was stronger after the 1970s. The possible non-stationarity in the teleconnections and the reasons for it have been further investigated in PREFACE. Rodríguez-Fonseca et al. (2015) review the links between rainfall variability over West Africa and SST anomalies, highlighting the change in the impact of the Atlantic El Niño on Sahel rainfall in the 1970s: before this decade the Atlantic El Niño lead to negative anomalies of rainfall over the Sahel due to a more southern location of the Monsoon, while, after the 1970s, the concomitant presence of a Pacific La Niña counteracted this effect leading to no signficant rainfall anomalies over the Sahel. Suarez-Moreno et al. (2017a, in revision) analyse rain-gauge data and suggest that the increased influence of the Pacific El Niño events on Sahel rainfall after the 1970s could be due to the change in the amplitude of the ENSO signal. Suarez-Moreno et al. (2017b, in revision) show that the Mediterranean – Sahel rainfall positive link was active in the first half of the 20th Century and in recent decades. They identify the North Atlantic multidecadal variability as the leading factor in modulating this link. Rodriguez-Fonseca et al. (2016) review the influence of ENSO on the North Atlantic and highlighted that the multidecadal ocean variability seems to modulate the presence of the teleconnections. Torralba et al. (2015) revisited the influence of Atlantic and Pacific El Niño events on North Eastern South American rainfall and found that after the 1970s, the combined effect of the Atlantic El Niño and the Pacific La Niña amplified the rainfall response.

4.1 Interannual to interdecadal variability of winter and summer southern African rainfall, and their teleconnections

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[3]Université de Bourgogne, Dijon, France
[4]University of Bergen, Bergen, Norway
(Dieppois et al. 2016)

Year-to-year variations in rainfall across Southern Africa have major consequences for human livehoods and ecosystems through their impact on drought, temperature, water supply, vegetation and agriculture. Interannual variability of summer Southern African rainfall is known to be primarily influenced by El Niño Southern Oscillation (ENSO), with dry/wet anomalies during El Niño/La Niña. Decadal fluctuations have also been found in summer Southern African rainfall. Of particular importance is the interdecadal 18.6 year Dyer-Tyson cycle. However, until now, discussions about potential mechanisms of these decadal fluctuations have been limited. For instance, most of the studies are based on comparisons between two periods of approximately 10-years, which are too short to capture the decadal signals (*i.e.*, roughly two ½ cycles). They are thus likely to describe changes in interannual variability between two decades that are not necessarily related to decadal signals. Using a time-space approach based on spectral analysis, this study aims to address these gaps, by defining the changing characteristics of summer South African rainfall, and their specific teleconnections for the main timescale of climate variability. As determined by wavelet analysis, the austral summer and winter rainfall indices exhibit three significant timescales of variability over the twentieth century: interdecadal (15–28 years), quasi-decadal (8–13 years), and interannual (2–8 years) (Figure 15).

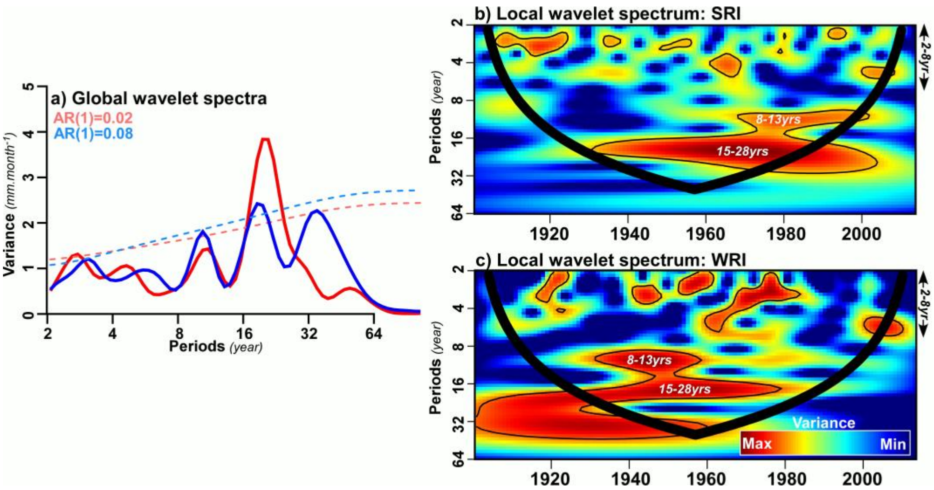

Figure 15: Time-scale patterns of variability in summer and winter southern African rainfall. ***a*** *Global wavelet spectra of the SRI (blue) and the WRI (red). The dashed blue and red lines indicate the red noise spectra with regard to the first order autoregressive (SRI–AR[1] = 0.02; WRI–AR[1] = 0.08).* ***b-c*** *Continuous wavelet power spectrum of the SRI and the WRI. Bold lines (the so-called cone of influence) delineate the area under which power can be underestimated as a consequence of edge effects, wraparound effects and zero padding; thin contour lines show the 95% confidence limits based on 1000 Monte-Carlo simulations of the red noise background spectrum.*

Teleconnections with global sea surface temperature and atmospheric circulation anomalies are established here but are different for each time scale. Tropical/subtropical teleconnections emerge as the main driver of austral summer rainfall variability. Thus, shifts in the Walker circulation are linked to the El Niño–Southern Oscillation (ENSO) and, at decadal time scales, to decadal ENSO-like patterns related to the Pacific Decadal Oscillation and the Interdecadal Pacific Oscillation. These global changes in the upper zonal circulation interact with asymmetric ocean-atmospheric conditions between the South Atlantic and South Indian Oceans; together, these lead to a shift in the South Indian Convergence Zone and a modulation of the development of convective rain-bearing systems over southern

Africa in summer. Such regional changes, embedded in quasi-annular geopotential patterns, consist of easterly moisture fluxes from the South Indian High, which dominate southerly moisture fluxes from the South Atlantic High. Austral winter rainfall variability is more influenced by midlatitude atmospheric variability, in particular the Southern Annular Mode. The rainfall changes in the southwestern regions of southern Africa are determined by asymmetrical changes in the midlatitude westerlies between the Atlantic and Indian Oceans.

4.2. Austral summer relationship between ENSO and Southern African rainfall in CMIP5 coupled models

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(Dieppois et al. 2015)

We study the ability of 24 ocean atmosphere global coupled models from the Coupled Model Intercomparison Project 5 (CMIP5) to reproduce the teleconnections between El Niño Southern Oscillation (ENSO) and Southern African rainfall in austral summer using historical forced simulations, with a focus on the atmospheric dynamic associated with El Niño. This study uses the monthly, land only, rainfall data from the Climatic Research Unit (CRU) 3.21 precipitation dataset to provide observations at 0.5 degree horizontal resolution. The monthly ERSST v3b data is used for global SST. We use NCEP/NCAR-1 (NCEP-1) reanalysis to infer monthly atmospheric dynamics. Overestimations of summer rainfall occur over Southern Africa in all CMIP5 models although, the CMIP5 experiments show a realistic seasonal rainfall cycle. Numerous weaknesses in the simulation of ENSO are still present in CMIP5. Abnormal westward extensions of ENSO patterns are a common feature of all CMIP5 models, while the warming of the Indian Ocean that happens during El Niño is not correctly reproduced. This impacts the teleconnection between ENSO and Southern African rainfall which is represented with mixed success in CMIP5 models. Large-scale anomalies of suppressed deep-convection over the tropical maritime continent and enhanced convection from the central to eastern Pacific are correctly simulated. However, regional biases occur above Africa and the Indian Ocean, particularly in the position of the deep convection anomalies associated with El Niño, which can lead to the wrong sign in rainfall anomalies in the northwest part of Southern Africa (Figure 16). From the near-surface to mid-troposphere, CMIP5 models underestimate the observed anomalous pattern of high pressure occurring over Southern Africa that leads to dry conditions during El Niño years. CMIP5 models have shortcomings in simulating eastward shift of the South Indian Convergence Zone during El Niño events.

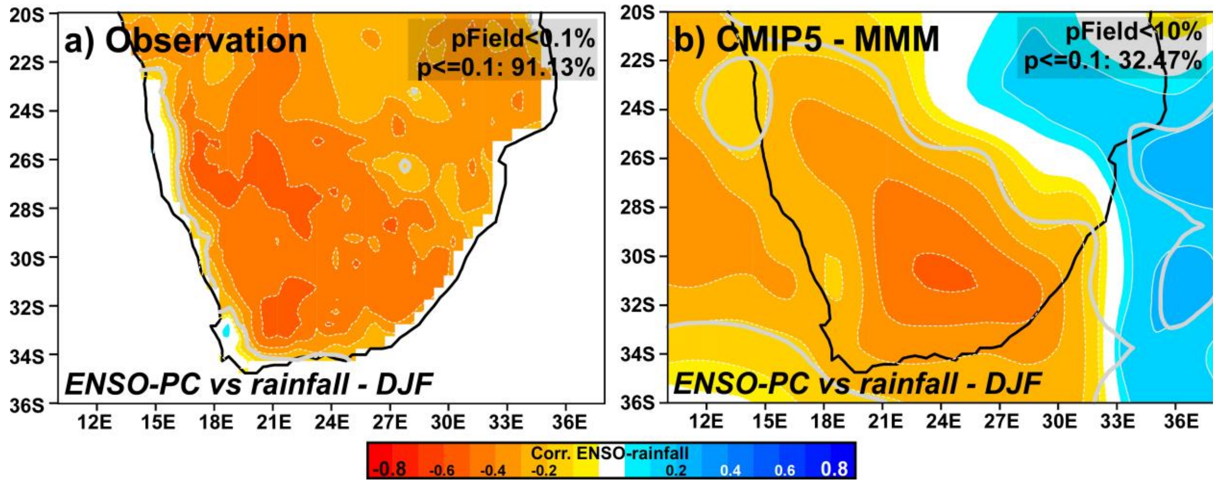

Figure 16: Observed and simulated summer-month correlations between ENSO components and South African rainfall. (a) Summer-month pointwise correlation between the ENSO component extracted by EOF and South African rainfall in the observation. (b) Idem for the CMIP5 multi-model mean -MMM.

4.3. On the structure of the large-scale circulation over central Africa and its adjacent Oceans

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In this study, we use atmospheric reanalyses (ERA-Interim, NCEP1, NCEP2) and an atmospheric general circulation model forced by SST (ECHAM version 5.3) to analyse the structure of the large-scale circulation over central Africa (07º–33ºE; 15ºS-10ºN) and its relation with adjoining oceans. To do so, we compute the meridional-mean zonal mass-weighted or Stokes streamfunctions (Cook 2003; Oort and Yienger 1996; Nguyen et al. 2013) to describe the Walker–type circulation over central Africa. To provide an important insight of the formation and evolution of large scale circulation, we present in figure 17, the seasonal cycle of the central Africa zonal overturning circulation. All year around, strong clockwise circulation predominates in central Africa and adjacent oceans, but at upper-levels, no eastward mass-weighted streamfunctions occur to balance the circulation. There is a dominant shallow zonal overturning circulation, thermally driven at a low level. The strong zonal temperature gradient between eastern Atlantic and western Indian Oceans, associated with strong sensible heating over the central Africa subcontinent, leads to unstable low-level atmosphere. This is likely to uplift the warm air (rising branch at ~25°E), resulting in a quasi-permanent low pressure system over central Africa. This zonal central Africa low pressure system is likely to trigger at near–surface, a monsoon–like circulation and convergence over central Africa, with moist air flowing from surrounding oceans at a low level. Between 800 and 750 hPa, the returning flow is westward, while over eastern Atlantic (at ~0°E), the air subsides, closing the circulation. The minimum and maximum of the central Africa overturning cell strength and expansion occur in May and August. However, there is no consistence in strength and extension of the circulation among datasets. For ERA-Interim (Figure 17), the mass-weighted streamfunctions indicate than the circulation is strengthening over central Africa and the eastern Atlantic troposphere, while it is slowing down over Indian Ocean confirming results by Tokinaka et al. (2011, 2012). In contrast, the eastern edge longitude of the central Africa zonal overturning cell is smaller in all datasets. There is no direct relationship between central Africa overturning cell intensity and central Africa rainfall at annual and monthly time scale.

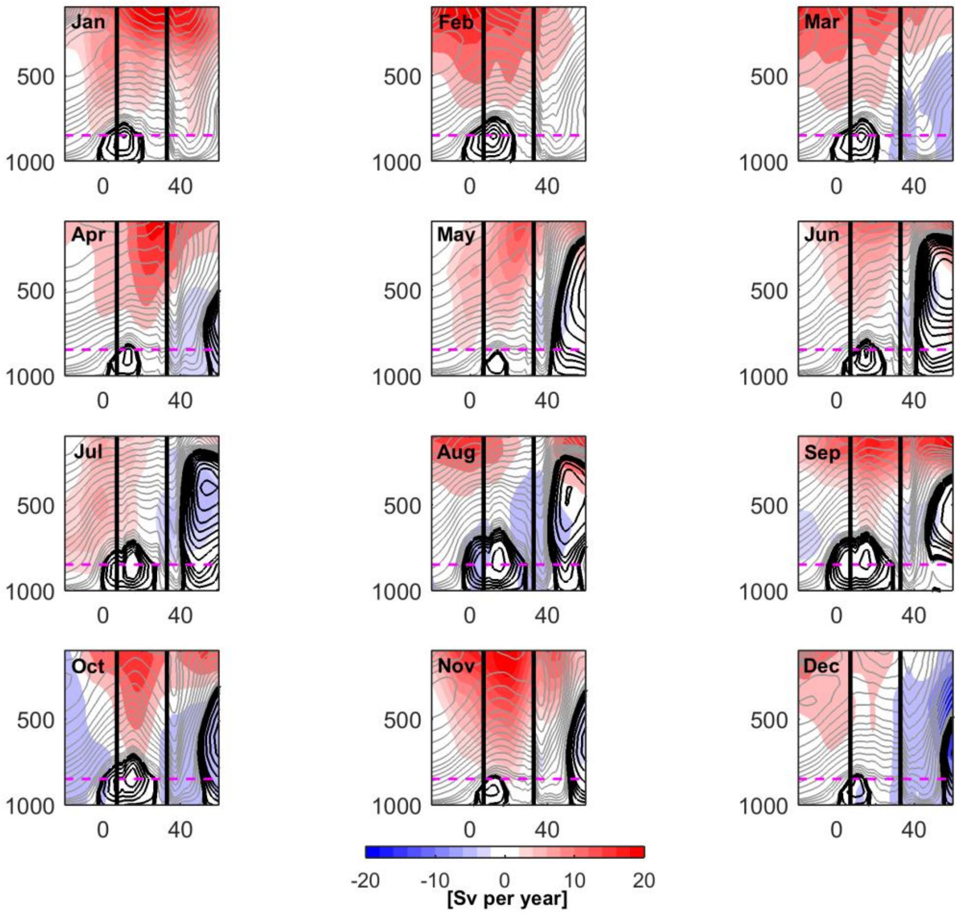

Figure 17: Seasonal cycle of the meridional-mean zonal mass-weighted streamfunctions (ψ) values in ERA-Interim during the 1979–2015 period. Positive (negative) values are indicated with grey (black) contours, representing clockwise (counterclockwise) circulations. Mass-weighted streamfunctions trend is shown in shading. The thick solid black contours correspond to values where ψ = 0. Contour interval for ψ is in Sverdrup (1 Sv = 1×10^9 kg s^{-1}). Contours intervals are 10Sv when ψ < 100Sv and 100Sv when ψ is between 1000 and 1500 Sv. The magenta solid line delineates the 850- hPa pressure level.

To capture any potential contribution of the moist air masses transport to the vertical overturning circulation in the atmosphere (Czaja and Marshall 2006; Pauluis et al. 2008; 2010), we represent the central Africa zonal overturning in isentropic coordinates (not shown). It emerges that over adjacent oceans, the air mass is transported eastward at higher moist static energy level and westward at lower moist static energy level, while air masses over central Africa are transported mainly eastward. This highlights that the surrounding oceans are the main suppliers of atmospheric moisture over central Africa, with cooler and warmer moist air flowing from Atlantic and Indian Oceans respectively. The adjacent oceans play a crucial role in regulating the westward and eastward propagation of central Africa zonal overturning cell. In fact, based on the near-surface temperature gradient between the relatively cold eastern Atlantic and relatively warm western Indian Oceans and given than less atmospheric water vapour reside over central Africa than over the oceans, the unsaturated air uplifts dry adiabatically at ~25°E. The resulting low surface pressure, over central Africa, triggers a converging monsoon-like circulation at low-level. At the same time, aloft 750- hPa, the warm air flows westward, before subsiding over Atlantic Ocean. However, the seasonal displacement of the zonal ITCZ location is strongly related to the low surface pressure over central Africa, which in turn, is controlled by the zonal atmospheric energy transport. The zonal atmospheric energy transport is good measure of the central Africa overturning cell, in terms of its strength, width and edge longitudes and the ECHAM5.3 simulation provides a support to this mechanism.

4.4. The El Niño effect on Ethiopian rainfall

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(Gleixner et al. 2016)

While El Niño is known to cause failure of Kiremt (boreal summer) rainfall in Ethiopia, the mechanisms are not fully understood. Here we use the ECHAM5 Atmospheric General Circulation Model to investigate the physical link between Pacific SST anomalies and Kiremt rainfall. We compare ECHAM5 simulations forced with reconstructed SST data, to gauge-based rainfall observations and atmospheric reanalysis for the time period of 1961–2009. We perform composite analysis and sensitivity experiments driven only with equatorial Pacific SST anomalies. Our results show warm SST anomalies in the equatorial Pacific drive a corresponding large-scale circulation anomaly with subsidence over Ethiopia in dry Kiremt seasons. Horizontal wind fields show a slow-down of the whole Indian monsoon system with a weaker Tropical Easterly Jet and a weaker East African Low-Level Jet in these summers. These changes can be seen as an anomalous circulation cell over northern Africa with westerlies at 100–200 hPa and easterlies below 500 hPa. Surface easterlies might reduce the moisture inflow from the Atlantic and Congo basin into Ethiopia. This and the general subsidence over the region could explain the reduction in Kiremt rainfall. Our results suggest up to 50% of the Kiremt rainfall anomalies is driven by equatorial Pacific SST variability.

4.5. Variability and Predictability of West African Droughts: A review of the role of sea surface temperature anomalies

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(Rodríguez-Fonseca et al. 2016)

The Sahel experienced a severe drought during the 1970s and 1980s after wet periods in the 1950s and 1960s. Although rainfall partially recovered since the 1990s, the drought had devastating impacts on society. Most studies agree that this dry period resulted primarily from remote effects of SST anomalies amplified by local land surface–atmosphere interactions. This paper reviews advances made during the last decade to better understand the impact of global SST variability on West African rainfall at interannual to decadal time scales. At interannual time scales, a warming of the equatorial Atlantic and Pacific/Indian Oceans results in rainfall reduction over the Sahel, and positive SST anomalies over the Mediterranean Sea tend to be associated with increased rainfall. At decadal time scales, warming over the tropics leads to drought over the Sahel, whereas warming over the North Atlantic promotes increased rainfall. Prediction systems have evolved from seasonal to decadal forecasting. The agreement among future projections has improved from CMIP3 to CMIP5, with a general tendency for slightly wetter conditions over the central part of the

Sahel, drier conditions over the western part, and a delay in the monsoon onset. The role of the Indian Ocean, the stationarity of teleconnections, the determination of the leader ocean basin in driving decadal variability, the anthropogenic role, the reduction of the model rainfall spread, and the improvement of some model components are among the most important remaining questions that continue to be the focus of current international projects.

4.6. Interdecadal variations in the SST-driven rainfal predictability

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[1]IGEO, Madrid, Spain
[3]KIT, Karlsruhe, Germany
(Suárez-Moreno et al. 2017a submitted)

During boreal summer, climate variability in the Sahel is dominated by the West African monsoon. Rainfall variability in this region is driven by global sea surface temperature anomalies in tropical and extratropical ocean basins. In this framework, Pacific and Atlantic tropical variability have been found to play a pivotal role, controlling the surface land-ocean gradients and the upper level dynamics associated with the West African Monsoon. Moreover, the Mediterranean Sea exerts a prominent influence, altering the low-level moisture transport across the Sahara to the south, which converges in the Sahel with the southwesterly monsoonal flow. Nevertheless, previous studies have found how the impacts associated with these oceanic forcings teleconnections have changed or even disappeared during some decades. The underlying dynamics responsible of these non-stationarities have not yet been addressed so far. This work takes a step forward in understanding the SST-forced seasonal rainfall variability in the Sahel, carrying out a better characterization of its potential predictability. A network of rain-gauge stations across West Africa is used to better assess the non-stationarity of the SST-Sahel link. A dynamical hypothesis is posed under different oceanic background states, according to which the associated configurations of the atmospheric general circulation favors some SST-driven teleconnections and inhibit others: For the eastern Mediterranean connection, a cooling in the east north Atlantic could be responsible of disrupting the classic teleconnection mechanism Mediterranean-Sahel. When it comes to the tropical Atlantic, the different mechanisms between periods of high and low connection are based on the counteracting effect from the tropical Pacific observed after the 1970s. Regarding the tropical Pacific, the non-stationarity of the teleconnection is due to the varying amplitude of the ENSO signal between after the 1970s. The results of this study become crucial in improving the seasonal forecast of Sahel rainfall.

4.7. The north Atlantic key role in driving the Mediterranean impact on the Sahel

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(Suárez-Moreno et al. 2017b submitted)

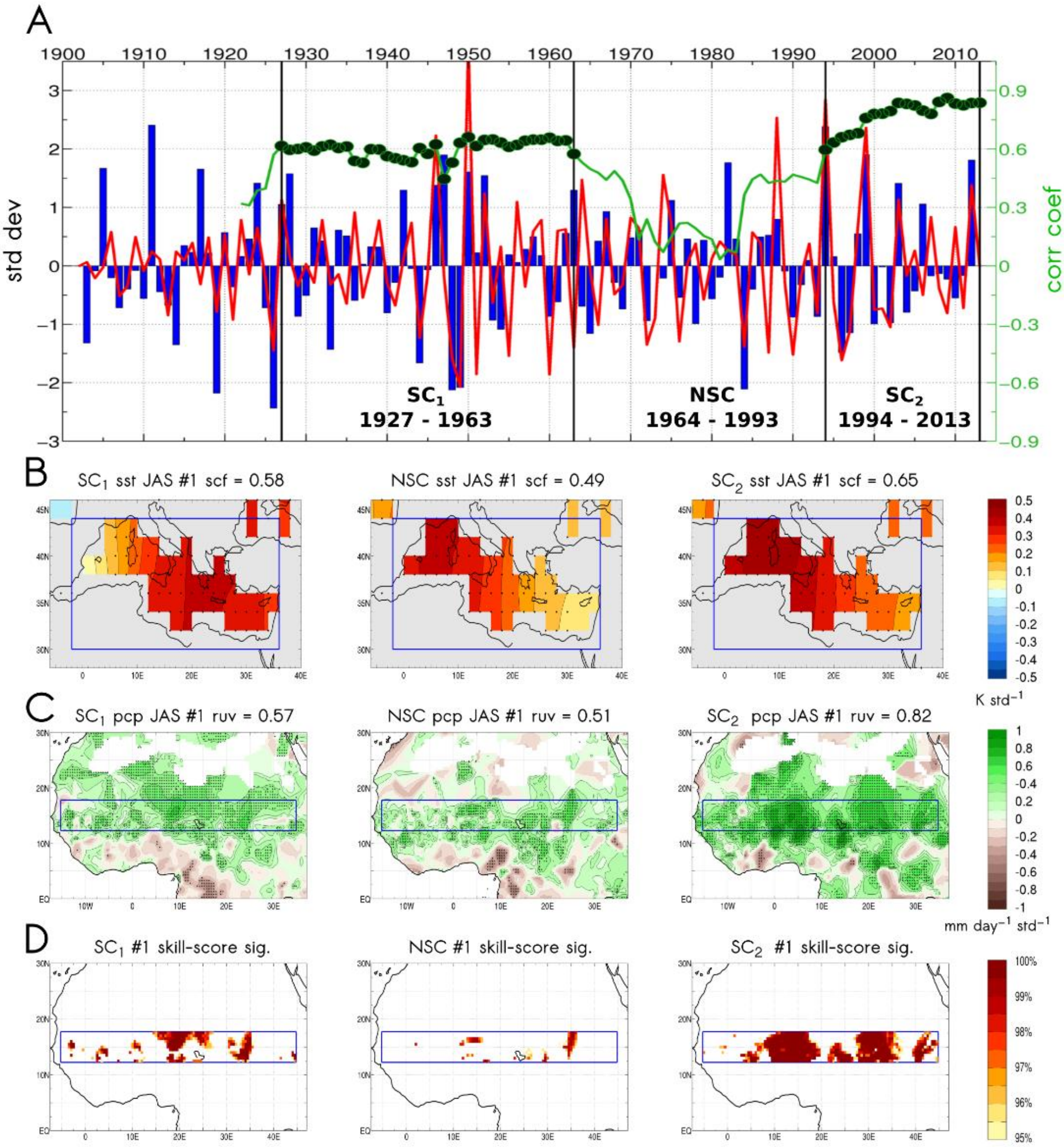

Figure 18: July-to-September (JAS) leading MCA mode calculated from Mediterranean SSTA defined in 2ºW-36ºE; 30ºN-44ºN and standardized anomalous Sahel rainfall defined in 15ºW-35ºE; 12ºN-18ºN. (A) Time series of the standardized expansion coefficients for SSTA (U, blue bars) and anomalous rainfall (V, red line) corresponding to the whole 1902-2013 period (values on the left vertical axis). 21-years (for each year and the previous twenty) sliding window correlation scores between U and V (green line) and corresponding statistically significant values (green shaded circles) (values on the right vertical axis). From this figure, three different periods are identified: the first significant correlation period (SC_1, 1927-1963), a non-significant correlation period (NSC, 1964-1993) and the second significant correlation period (SC_2, 1994-2013). (B) Homogeneous SSTA (K std^{-1}) maps calculated by regressing U onto the Mediterranean SSTA. (C) Heterogeneous anomalous rainfall (mm day^{-1} std^{-1}) maps obtained by regressing U onto regional anomalous Sahel

rainfall (D) Skill-score in terms of Pearson correlation coefficient score between cross-validated hindcasts and observations for anomalous rainfall in the Sahel. Shaded values denote the significance level (%) in the regions of positive skill. From (B) to (C): Leading MCA mode and skill-score for SC_1 period (left column), NSC period (central column) and SC_2 (right column). The squared-covariance fraction (scf) and correlation between expansion coefficients (ruv) are shown in figure titles. Blue contoured boxes indicate the selected spatial domains in the MCA analysis. Stippling denotes statistical significance at 95% assessed using the Monte Carlo method (1000 permutations).

Sea surface temperatures anomalies drive rainfall variability in the Sahel from interannual to multidecadal time scales. Both the harsh drought experienced from the early 1970s to the 1990s and the later recovery trend have been associated with the combination of thermal anomalies in tropical and extratropical ocean basins. In this context, the Atlantic and Mediterranean multidecadal variability have been found to play a leading role in explaining low-frequency variability of Sahelian rainfall. While the former was linked to the Sahel big drought, the anthropogenic warming of the Mediterranean has been addressed as a key factor in the recent recovery trend. Moreover, the Mediterranean impact on the Sahel has been widely described at interannual time scales, even though the non-stability of this link has been overlooked. Through the analysis of observations we find the Mediterranean SST-forced response of Sahel rainfall to be active in the first half of the 20th century and recent decades, and declining during the big drought (Figure 18).

On the basis of observational evidence and a set of numerical experiments performed with the LMDZ Atmosphere General Circulation model, we identify the North Atlantic multidecadal variability as the leading factor in modulating the year-to-year Mediterranean-Sahel teleconnection. A robust mechanism in which warm anomalies in the North Atlantic amplify the Sahel rainfall response to Mediterranean warm events is identified, addressing the key role of the Saharan heat low in driving the teleconnection. Our results represent a step forward in improving seasonal predictability of monsoonal rainfall in the Sahel.

4.8. The non-stationary influence of the Atlantic and Pacific Niños on North Eastern South American rainfall (NESA).

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Rainfall variability over the tropical Atlantic region is dominated by changes in the surface temperature of the surrounding oceans. In particular, the oceanic forcing over Northeast of South America (NESA) is dominated by the Atlantic interhemispheric temperature gradient, which leads its predictability. Nevertheless, in recent decades, the SST influence on rainfall variability in some tropical Atlantic regions has been found to be non-stationary, with important changes of the Atlantic and Pacific influence on Sahelian rainfall, which appear to be modulated at multidecadal timescales. In this work, we revisit the SST influence over Northeast of South America including the analysis of the stationarity of this relationship at interannual timescales. Principal Component Analysis has been applied to the interannual component of rainfall during the March-April-May season.

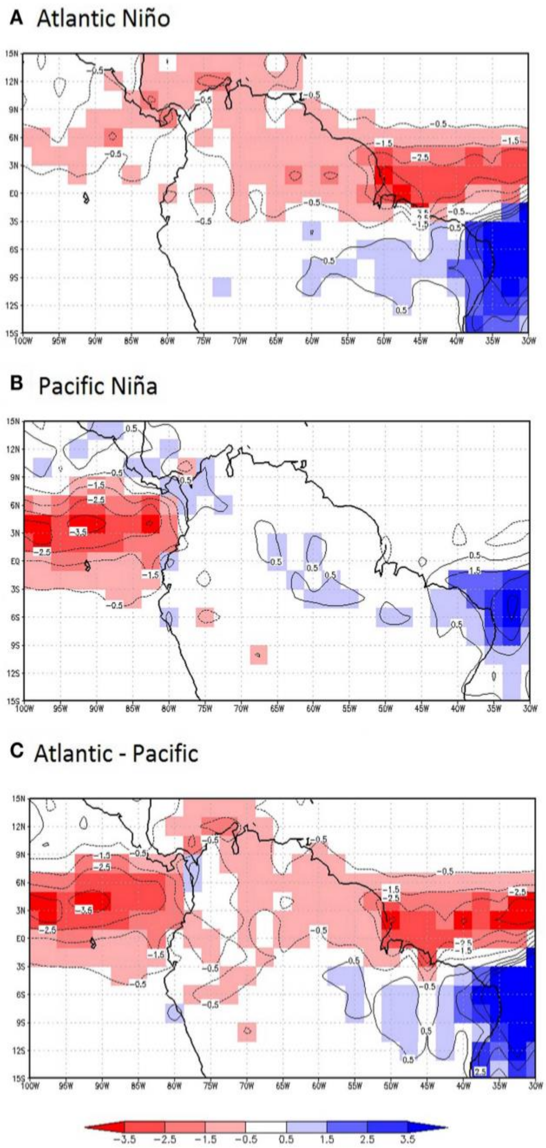

Figure 19: Rainfall anomalies for the Atlantic Niño simulation. (B) Rainfall anomalies for the Pacific Niño simulation. (C) Rainfall anomalies for the simulation in whole Tropical region (Atlantic Pacific). Contoured areas represent the values of the rainfall, expressed in mm/day, while the regions with correlations significant at the 95% level are shaded.

Based on observations, our results show how the SST forcing on the first mode of rainfall variability, which is a dipole-like pattern generated by the changes in the seasonal migration of the Intertropical Convergence Zone, is different depending of the considered period. The response to the SST anomalies in the Pacific basin is opposite to the Atlantic one and affects different areas. The Atlantic Niño influences rainfall variability at the beginning of the XX century and after 1970, while the Pacific Niño plays a major role in the variability of the rainfall in the Northeast of South America from 1970 onwards. The combined effect of both basins after the 1970s amplifies the anomalous rainfall response. This result is confirmed by the analysis of three sensitivity experiments performed with the UCLA AGCM: In the first experiment the SST anomalies prescribed are those from whole tropical region (Atlantic and Pacific) and they are added to the climatological SST values for the period 1979–2005, which is considered as the reference period. In these experiments, an Atlantic Niño appears together with a Pacific La Niña. In the second experiment the SST anomalies in the Tropical Atlantic (corresponding to an Atlantic Niño) are retained and they are added to the SST climatology in the Atlantic basin for the reference period. In the third experiment the anomalies in the Tropical Indo-Pacific are considered (Corresponding to a Pacific La Niña) and they are added to the mean SST values, for the reference period in the Indian and Pacific basins. The combined effect of the two basins produces a dipole-like pattern similar to the leading mode of variability. The positive anomalies in the north of equatorial region in the Atlantic coast of NESA region related to the Atlantic Niño are strengthen by the effect of the Pacific Niña which produce and increase of rainfall in the study region (Figure 19). Thus, over the NESA, the Atlantic-Pacific Niños connection adds their individual effects on rainfall. This novel result is very important for predictability issues and to better assess the SST influence on rainfall in the region.

4.9. A review of ENSO Influence on the North Atlantic.

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The atmospheric seasonal cycle of the North Atlantic region is dominated by meridional movements of the circulation systems: from the tropics, where the West African Monsoon and extreme tropical weather events take place, to the extratropics, where the circulation is dominated by seasonal changes in the jetstream and extratropical cyclones. Climate variability over the North Atlantic is controlled by various mechanisms. Atmospheric internal variability plays a crucial role in the mid-latitudes. However, El Niño-Southern Oscillation (ENSO) is still the main source of predictability in this region situated far away from the Pacific. Although the ENSO influence over tropical and extra-tropical areas is related to different physical mechanisms, in both regions this teleconnection seems to be non-stationary in time and modulated by multidecadal changes of the mean flow. Nowadays, long observational records (greater than 100 years) and modeling projects (e.g., CMIP) permit detecting non-stationarities in the influence of ENSO over the Atlantic basin, and further analyzing its potential mechanisms. The present article reviews the ENSO influence over the Atlantic region, paying special attention to the stability of this teleconnection over time and the possible modulators. Evidence is given that the ENSO–Atlantic teleconnection is weak over the North Atlantic. In this regard, the multidecadal ocean variability seems to modulate the presence of teleconnections, which can lead to important impacts of ENSO and to open windows of opportunity for seasonal predictability.

5. Madden Julian Oscillation and tropical Atlantic

The Madden Julian Oscillation (MJO) is the main mode of tropical variability at intra-seasonal time scales (Madden and Julian 1994). It consists of a tropical disturbance that propagates eastward around the tropics from the western Indian ocean to the western Pacific ocean with a periodicity of around 30-90 days. The MJO has a wide range of impacts, affecting precipitation and atmospheric circulation around the tropics. Previous works have highlighted an influence of the MJO on convection anomalies over regions of the Tropical Atlantic like West Africa (e.g. Matthews 2004; Mohino et al. 2012). In the framework of PREFACE Niang et al. (2017) have evaluated the skill of AGCMs to simulate the impact of the MJO on convection and rainfall over West Africa. They show that the convection signal over West Africa tends to be weaker in models than in observations. However, the timing of the transitions between positive and negative rainfall anomalies associated with MJO is adequately reproduced by models. Tseng et al. (2014) use a one-column high resolution ocean model coupled to an atmospheric general circulation model to show that resolving the upper-ocean warm layer leads to a great improvement in the characteristics of the simulated MJO. Chang et al. (2015) further used such enhanced version of the model to investigate the impact of global warming in the MJO. They show that in a warmer climate the MJO is expected to increase its intensity and frequency, showing a more circumglobal propagation tendency.

5.1. Impact of the Madden Julian Oscillation on the summer West African monsoon in AMIP simulations

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Niang et al. (2017)

At intraseasonal timescales, convection over West Africa is modulated by the Madden Julian Oscillation (MJO). In this work we investigate the simulation of such relationship by 11 state-of-the-art atmospheric general circulation models runs with prescribed observed sea surface temperatures. In general, the Atmospheric Model Intercomparison Project simulations show good skill in capturing the main characteristics of the summer MJO as well as its influence on convection and rainfall over West Africa. Most models simulate an eastward spatiotemporal propagation of enhanced and suppressed convection similar to the observed MJO, although their signal over West Africa is weaker in some models (Figure 20). In addition, the ensemble average of models' composites gives a better performance in reproducing the main features and timing of the MJO and its impact over West Africa. The influence on rainfall is well captured in both Sahel and Guinea regions thereby adequately producing the transition between positive and negative rainfall anomalies through the different phases as in the observations. Furthermore, the results show that a strong active convection phase is clearly associated with a stronger African Easterly Jet (AEJ) but the weak convective phase is associated with a much weaker AEJ. Our analysis of the equatorial waves suggests that the main impact over West Africa is established by the propagation of low-frequency waves within the MJO and Rossby spectral peaks. Results from the simulations confirm that it may be possible to predict anomalous convection over West Africa with a time lead of 15–20 day.

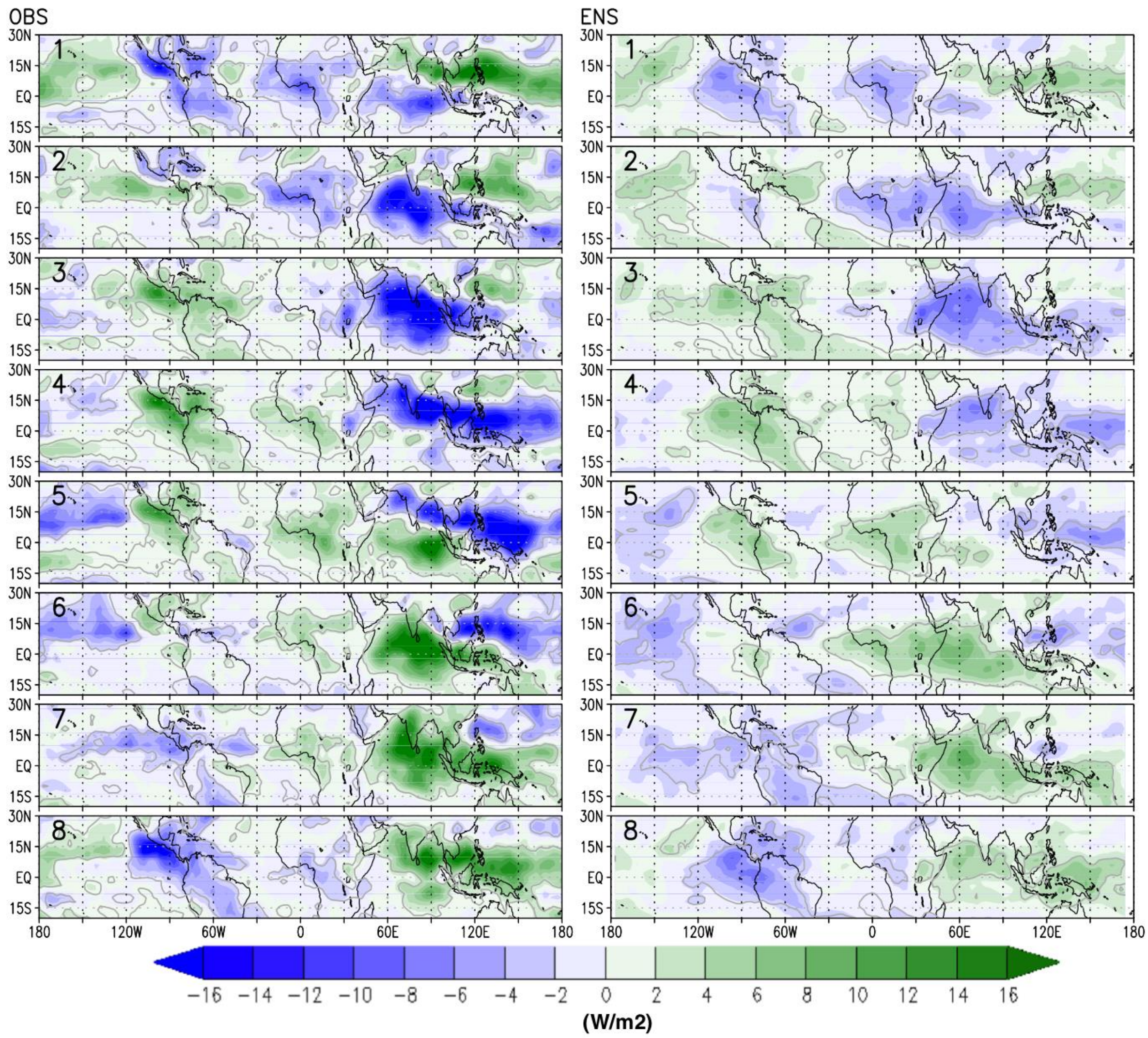

Figure 20: Summer composites of deseasonalized anomalies of OLR according to the eight phases associated with the MJO, from observations (left) and the ensemble average of AMIP composites (right). The ensemble composite is obtained as the average of the 11 models composites, which are previously phase-adjusted). The units are W/m^2. The grey contours represent the 95 % significant regions obtained from a two-tailed t test .

5.2. Resolving the upper-ocean warm layer improves the simulation of the Madden-Julian oscillation.

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(Tseng et al. 2015)

Here we show that coupling a high-resolution one-column ocean model to an atmospheric general circulation model dramatically improves simulation of the Madden-Julian oscillation (MJO) to have realistic strength, period, and propagation speed. The mechanism for the simulated MJO involves both frictional wave-convective conditional instability of the second kind (Frictional wave-CISK) and air–sea convective intraseasonal interaction (ASCII). In particular, better resolving the fine structure of upper ocean temperature, especially the warm layer, produces more vigorous atmosphere–ocean interaction and strengthens intraseasonal variations in both SST and atmospheric circulation. This helps organize and strengthen deep convection, inducing a stronger Kelvin-wave like perturbation and frictional near-surface convergence to the east. In addition, the warmer SST ahead of the MJO also acts to destabilize the boundary layer and enhance frictional convergence. These lead to a more realistic eastward-propagating MJO. A suite of sensitivity experiments were performed to show the robustness of the mechanisms and to demonstrate: (1) that mean state differences are not the main contributors to the improved simulation of our coupled model; (2) the role of SST variability in enhancing frictional convergence and intraseasonal variations in precipitation, and (3) that the simulation is significantly degraded when the first ocean model layer is thicker than 10 m. Our coupled model results are consistent with observations and demonstrate a simple but effective means to significantly improve MJO simulation and potentially also forecasts.

5.3. The Madden-Julian Oscillation in a warmer world

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(Chang et al. 2015)

Global warming's impact on the Madden-Julian Oscillation (MJO) is assessed using one of the few models capable in reproducing its key features. In a warmer climate predicted for the end of the century, the MJO increases in amplitude (by ~30%) and frequency, showing a more circumglobal propagation tendency. The MJO spatial extent becomes enhanced, deeper, and more zonally extended but meridionally confined. A stronger vertical tilting structure in diabatic heating, moisture, and convergence fields is seen. Our findings indicate that these changes result from an intensification of the frictional wave-conditional instability of the second kind mechanism via the coupling of dynamical and thermodynamic response to the warming. The warming and moistening of the mean state contribute to the enhanced deep convective heating, driving a stronger-forced Kelvin wave-like perturbation. This reinforces the frictional low-level convergence, leading to larger shallow convective heating and therefore to a faster development and enhancement of the deep convection in the MJO.

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