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2 **On the Atlantic-Pacific Niños connection:**
3 **A multidecadal modulated mode**
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22 **Abstract**

23 Atlantic and Pacific El Niño are the leading tropical oceanic variability phenomena at
24 interannual timescales. Recent studies have demonstrated how the Atlantic Niño is able to
25 influence on the dynamical processes triggering the development of the Pacific La Niña and
26 vice versa. However, the stationarity of this interbasin connection is still controversial.
27 Here we show for the first time that the Atlantic-Pacific Niños connection takes place at
28 particular decades, coinciding with negative phases of the Atlantic Multidecadal Oscillation
29 (AMO). During these decades, the Atlantic-Pacific connection appears as the leading
30 coupled covariability mode between Tropical Atlantic and Pacific interannual variability.
31 The mode is defined by a predictor field, the summer Atlantic Sea Surface Temperature
32 (SST), and a set of predictand fields which represent a chain of atmospheric and oceanic
33 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. 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.

Keywords: ENSO, Atlantic, Pacific, prediction, tropical variability, Atlantic Multidecadal Oscillation, Sea Surface Temperature

1. Introduction

El Niño-Southern Oscillation (ENSO) is the leading mode of interannual variability in the Tropical Pacific Ocean with worldwide impacts (Philander 1990; Bjerknes 1969). An analogous air-sea coupled mode takes place in the Tropical Atlantic basin, named as Equatorial Mode, zonal mode or Atlantic Niño (Zebiak 1993). These modes peak in different seasons, winter and summer respectively. Previous studies have demonstrated the connection between the interannual variability of the Atlantic and Pacific basins. Some authors have suggested the leadership of the Pacific Ocean, modifying the tropical Atlantic variability through Walker circulation or wave trains emanating from the equatorial Pacific (Saravanan and Chang 2000; Sutton et al. 2000; Huang et al. 2002; Münnich and Neelin 2005; Handoh et al. 2006a,b). On the other hand, the Atlantic Ocean also seems to influence the Tropical Pacific variability through an atmospheric bridge (Keenlyside and Latif 2007; Polo et al. 2008; Rodríguez-Fonseca et al. 2009; Wang et al. 2010; Kayano et al. 2011; Ding et al. 2012; Martín-Rey et al. 2012; Ham et al. 2013; Polo et al. 2014). Furthermore, Indian Ocean is also proposed as a precursor of ENSO development through changes in the winds over the western equatorial Pacific (Annamalai et al. 2005; Terray et al. 2005; Kug and Kang 2006; Izumo et al. 2010; Luo et al. 2010). Additionally, the contribution of extratropical regions to ENSO prediction has also been analysed (Terray 2011; Boschat et al. 2013; Dayan et al. 2013).

Regarding the tropical Pacific response to Atlantic SST, observational results and partially-coupled simulations in which the observed Atlantic Sea Surface Temperature (SST) is the

only external forcing, show that a summer Atlantic Niño (Niña) precedes the development of a Pacific La Niña (El Niño) during the boreal winter after the late 1960s (Rodríguez-Fonseca et al. 2009). For an Atlantic warm (cold) event, an alteration of the Walker circulation with anomalous ascending branch (descending motions) over the Atlantic and anomalous subsidence (ascending motions) over the Pacific is proposed as the atmospheric bridge connecting both basins. Sensitivity experiments with atmospheric general circulation models (AGCMs) and fully coupled general circulation models have confirmed this hypothesis (Losada et al. 2010; Ding et al. 2012 respectively).

More recently, using the simulated Pacific outputs of a partially coupled run with prescribed SSTs in the Atlantic, Martín-Rey et al. (2012) have demonstrated the existence of a leading SST variability mode in the Tropical Pacific in winter, which is forced by the equatorial Atlantic anomalous SSTs during the previous summer. This mode, which appears from the 1970s, coincides with the Pacific pattern associated with the Atlantic-Pacific Niños connection. In turn, its development is related to dynamical processes triggered by the Atlantic and in which the thermocline feedbacks are enhanced. Moreover, the ENSO events, which are not modulated by the Atlantic, appear to be more associated with thermodynamical processes.

A conceptual dynamical scheme of the Atlantic-Pacific connection is very important for its correct modelling and, thus, its correct prediction. For this reason, the oceanic mechanisms at work in the Tropical Pacific associated with the Atlantic influence, have been recently investigated by Polo et al. (2014). According to the former authors, for an Atlantic Niño

(Niña) the Walker circulation is altered linking both basins. The subsidence (ascending motions) over the Pacific creates surface wind divergence (convergence) around the dateline, strengthening (weakening) the trades to the west, in the warm pool region, and shallowing (deepening) the thermocline east of the divergence (convergence). This perturbation propagates to the east as a Kelvin wave, following the Gill-Matsuno (Matsuno 1966; Gill 1980; Suarez and Schopf, 1988) mechanism, favouring (inhibiting) the vertical entrainment and cooling (warming) the sea surface. Finally, the Bjerknes feedback is established intensifying the westward (eastward) currents and maintaining the cooling (warming) in the eastern equatorial Pacific (Bjerknes 1969).

Several recent studies have put forward the importance of the Atlantic for the correct ENSO forecast (Frauen and Dommenges 2012; Dayan et al. 2013; Bosch et al. 2013; Keenlyside et al. 2013;). Furthermore, the Atlantic-Pacific connection involves changes in the global climate variability since, in summer, both basins act together to modify the climate teleconnections (Losada et al. 2010, 2012; Rodríguez-Fonseca et al. 2011; Mohino et al. 2011).

Nevertheless, although some authors have indicated that this relation is stationary on time (Ding et al. 2012), other studies have only found the link after the 1970s (Rodríguez-Fonseca et al. 2009; Martín-Rey et al. 2012). This absence of stationarity has been observed using the summer Atl3 [20W-0; 3N-3S] and winter Niño3 [150W-90W; 5N-5S] indices for the whole 20th century, showing high correlation scores during the first and last decades of the 20th century (Polo et al. 2014). Also Guinean rainfall variability, which is highly

coupled with the Atlantic Niño, is related to ENSO phenomena only at the beginning and end of the 20th century (Joly and Voldoire 2010; Losada et al. 2012). These decades coincide with negative phases of the Atlantic Multidecadal Oscillation (AMO, Delworth and Mann 2000; Knight et al. 2006), suggesting the possible role of this decadal variability pattern in triggering the connection (Polo et al. 2014).

The influence of the AMO-like pattern on the Pacific mean state and variability has been already documented using General Circulation Models (GCMs, Dong et al. 2006; Fang et al. 2008; Hong et al. 2013). Furthermore, the Atlantic Ocean response from a substantial change in the Atlantic Meridional Overturning Circulation (AMOC) has also been investigated. In this way, from a weakening of the AMOC, a negative AMO-like SST pattern in the Atlantic appears together with changes in the tropical variability (Dong and Sutton 2007; Timmerman et al. 2007; Haarsma et al. 2008; Polo et al., 2013). Negative SST anomalies in the North Atlantic associated with a negative phase of the AMO seem to alter the large-scale tropical atmospheric circulation, changing the basic state in the tropical Pacific Ocean. This change is associated with a shallower thermocline depth and activates the thermocline and upwelling feedbacks, increasing ENSO variability (Federov and Philander 2000; An and Jin 2001; Dong and Sutton 2007). Similar analyses of the influence of a weakening of the AMOC onto the Atlantic basin have revealed a mean deepened equatorial thermocline, which leads to a decreasing in the Atlantic Niño variance (Haarsma et al. 2008; Polo et al. 2013). Additionally, the enhancement of the ENSO teleconnection onto the tropical Atlantic increases the tropical Atlantic variability in spring (Polo et al., 2013). Conversely, other recent study considering a weakening of the AMOC shows

changes in the Atlantic mean state but not in the Pacific background state, which increases the Atlantic equatorial variability during summer months, strengthening the Atlantic-Pacific connection (Svendsen et al. 2013). Thus, it is not clear how the changes in the tropical basins are connected in the real world.

Taking into account the current state of the discussion, we pose the following questions: Is the Atlantic-Pacific connection a mode of variability? If so, is this mode modulated at multidecadal timescales?

In case of finding positive answers, opportunity windows for the correct prediction of ENSO will be opened, enhancing the importance of the correct simulation of the tropical Atlantic climate variability (Ritcher et al. 2008, 2012; Wahl et al. 2011; Toniazzo et al. 2013; Voldoire et al. 2013).

Therefore, the aim of this study is to test if this Atlantic-Pacific connection is an internal mode of climate variability within the tropical regions, and to shed light on when does this pattern take place and how this connection appears or not modulated at multidecadal time scales.

The present study is divided in five sections. Section 2 describes the data and the methodology used in this study. The main results are presented in Section 3. In Section 3.1 we identify the coupled variability modes between the Tropical Atlantic and Pacific. In

section 3.2, the Atlantic influence on the coupled mode is investigated. Finally, the discussion and conclusions are displayed in Sections 4 and 5 respectively.

2. Data and Methodology

Observations and reanalysis

The observed tropical Pacific SST, wind stress and thermocline depth come from SODA reanalysis (Giese and Ray 2011). The 20°C isotherm depth has been considered as a proxy for the thermocline depth (z20). We have also used the observed tropical Atlantic SST from HadISST dataset (Rayner et al. 2003). The velocity potential at 200 and 950 hPa (hereafter, chi200 and chi950) has been calculated from the zonal and meridional wind obtained from 20th century reanalysis (Compo et al. 2011) using the Laplace equation, $\nabla^2\Phi = 0$ where

Φ is the velocity potential and verifies $u = \frac{\partial\Phi}{\partial x}$ and $v = \frac{\partial\Phi}{\partial y}$ being u and v the zonal and

meridional components of the wind. The period of study goes from 1871 to 2002.

Questions about the reliability of the data during the first decades of the 20th century remains a caveat. In early years, the observed SST is very sparse since the majority of the measures come from ships, which changed their commercial shipping routes along the time.

North Atlantic, western South Atlantic and North Indian Oceans are the regions with more density of measures. Nevertheless, the spatial coverage of tropical Atlantic and Pacific data

is completed around the 1960s (Deser et al., 2010). SST data comes from million of observations which have been carefully checked in order to generate corrected datasets.

However, corrections prior to about 1900 are less well known because of uncertainties in the mix of wooden and canvas buckets. Nevertheless, even in the 1870s, SST was little biased relative to land-surface air temperatures globally. Since 1941, observations mainly

(d) STD PACEQ HADISST 1871-2002

(e) STD PACEQ SIMATLVAR 1871-2002

(f) DIF STD PACEQ SIMATLVAR-HADISST 1871-2002

Figure 1. Seasonal Cycle and Standard deviation of the equatorial Pacific SST for HadISST and SIMATLVAR from 1871 to 2002 (a-b, d-e) Seasonal cycle and standard deviation of the equatorial Pacific SST for observations and model simulations (SimAtIVar). The monthly means (in K) have been detrended. (c,f) Difference between the simulated and observed seasonal cycle and standard deviation of the equatorial Pacific SST. A test of equal means/variances has been applied and the values exceeding 90% confidence level are shown.

EMMCA

Extended Multiple Maximum Covariance Analysis

X = Trop Atl SST JJAS	
Y=	Y1 = Trop Pac SST DJFM
	Y2= Trop Pac ustr JASO
	Y3= Trop Pac vstr JASO
	Y4= Trop Pac z20 JASO
	Y5= Trop Pac z20 SOND
	Y6= Trop Pac z20 DJFM
	Y7= Trop chi200 JJAS
	Y8= Trop chi200 DJFM
	Y9= Trop chi925 JJAS
	Y10= Trop chi925* DJFM

$X = X(n_s \text{ SST ATL}, n_t)$ ➤ SST ATL JJAS
 $Y1 = Y1(n_s \text{ SST PAC}, n_t)$ ➤ SST PAC DJFM
 $Y2 = Y2(n_s \text{ USTR PAC}, n_t)$ ➤ USTR PAC JASO
 $Y3 = Y3(n_s \text{ VSTR PAC}, n_t)$ ➤ VSTR PAC JASO
 $Y4 = Y4(n_s \text{ Z20J PAC}, n_t)$ ➤ z20 PAC JASO
 $Y5 = Y5(n_s \text{ Z20S PAC}, n_t)$ ➤ z20 PAC SOND
 $Y6 = Y6(n_s \text{ Z20D PAC}, n_t)$ ➤ z20 PAC DJFM
 $Y7 = Y7(n_s \text{ CHI200J}, n_t)$ ➤ chi200 JJAS
 $Y8 = Y8(n_s \text{ CHI200D}, n_t)$ ➤ chi200 DJFM
 $Y9 = Y9(n_s \text{ CHI925J}, n_t)$ ➤ chi925 JJAS
 $Y10 = Y10(n_s \text{ CHI925D}, n_t)$ ➤ chi925 DJFM

Covariance matrix C

$$C = X'(n_s \text{ SST ATL}, n_t) * (Y')^T(n_t, n_s \text{ vdl})$$

vdl=variables in specific spatial domains and lags :

Trop Pac SST DJFM, Trop Pac ustr JASO, Trop Pac vstr JASO,
Trop Pac z20 JASO, Trop Pac z20 SOND, Trop Pac z20 DJFM,
Trop chi200 JJAS, Trop chi200 DJFM, Trop chi925 JJAS, Trop chi925 DJFM

$$[Q, D, R] = \text{SVD}(C)$$

$$V = Q^T * (X')^T$$

Q: Spatial patterns

V: Expansion coefficients

$Q = [Q1 \text{ SST DJFM PAC}, Q2 \text{ USTR JASO PAC}, Q3 \text{ VSTR JASO PAC},$
 $Q4 \text{ Z20JASO PAC}, Q5 \text{ Z20SOND PAC}, Q6 \text{ Z20DJFM PAC}, Q7 \text{ CHI200JJAS},$
 $Q8 \text{ CHI200DJFM}, Q9 \text{ CHI925JJAS}, Q10 \text{ CHI925DJFM}]$

$V = [V1 \text{ SST DJFM PAC}, V2 \text{ USTR JASO PAC}, V3 \text{ VSTR JASO PAC},$
 $V4 \text{ Z20JASO PAC}, V5 \text{ Z20SOND PAC}, V6 \text{ Z20DJFM PAC}, V7 \text{ CHI200JJAS},$
 $V8 \text{ CHI200DJFM}, V9 \text{ CHI925JJAS}, V10 \text{ CHI925DJFM}]$

*For observations, the velocity potential at the surface has been computed for 950hPa

Figure 2. Schematic of the EMMCA applied in the present study. (Left) Scheme of the arrays for the predictor (X) and the set of predictand fields (Y) used in the Extended Multiple Maximum Covariance Analysis (EMMCA). (Right) Description of the different variables considered as predictor (summer Tropical Atlantic SST) and predictand fields (tropical velocity potential, Pacific wind stress, thermocline depth and SST) in specific lags and the methodology of the EMMCA.

Figure 3. Expansion coefficients of the leading mode of interannual variability from observations for the period 1872-2001. (a-c) Expansion coefficients and their 20-yr running standard deviation (thick line) of the leading mode obtained applying the EMMCA to the total period 1872-2001 for the predictor field, the summer (JJAS) tropical Atlantic SSTs, the set of the predictand fields and the tropical Pacific zonal wind in summer (JASO). (d) Running correlation in 20-yr windows between the expansion coefficient of the predictor and the expansion coefficient of the Pacific zonal wind stress (purple line). The statistical significant correlation exceeding 90% confidence level, according to a Monte Carlo test, is presented in dots. The 20-yr running mean of the Atlantic Multidecadal Oscillation index is also presented (green line).

Figure 4. 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 $^{\circ}\text{C}$, 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 $^{\circ}\text{C}$) 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.

Figure 5. Expansion coefficients of the leading mode of interannual variability from SimAtlVar for the period 1872-2001. Same as Figure 3 but for SimAtlVar

Figure 6. Leading Mode of the EMMCA for SimAtlVar. Same as Figure 4 but for SimAtlVar.

(a) MULTIDECADAL CHANGES ATLANTIC VELOCITY POTENTIAL AND PACIFIC SST VARIABILITY

(b) CORRELATION MAP AMO index - SST GLOB 1871-2001

(c) CORRELATION MAP AMO index - chi200JJAS 1871-2001

Figure 7. Multidecadal changes in the equatorial Atlantic velocity potential and Pacific SST variability (a) Purple line: changes in the standard deviation of Niño3 index in winter (DJFM) months with respect to the whole period. 20-yr running differences are computed and a F-test is applied to highlight the windows in which the differences are statistically significant at 90% confidence level. Red Line: the same as the purple line but for the summer (JJAS) velocity potential at 200hPa (chi200) in the western equatorial Atlantic (70W-35W, 5N-5S) from SimAtlVar. Green line: Atlantic Multidecadal Oscillation time series (defined as the annual SST anomalies averaged in North Atlantic region. The global warming signal has been previously removed; Villamayor et al. 2012) (b) Correlation map between the running 20-yr differences for AMO index (green line in (a)) and the global SST anomalies in 20-yr windows. (c) Same as (b) but for the running 20-yr differences for the chi200 in JJAS. Significant values at 90% confidence level according to a Monte Carlo test have been in shaded. Additionally, significant region which coincides in sign with those regions obtained correlating the red and purple lines from (a) over the global SST are also indicated with black markers.

Figure 8. Hindcast for the observed Niño3 SST in winter months (DJFM) for the periods 1871-1933, 1934-1969 and 1970-2001. Bars: Observed equatorial Pacific SST in Niño 3 region. Stems: Predicted equatorial Pacific SST in Niño3 region using the statistical hindcast from EMMCA information. Stars: Years in which there is a summer Atlantic Niño (Niña, expansion coefficient for Atlantic SST higher than ± 1 std) followed by observed and predicted Pacific La Niña (El Niño, Niño3 index higher than ± 0.5).

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2. Data and Methodology

Observations and reanalysis

The observed tropical Pacific SST, wind stress and thermocline depth come from SODA reanalysis (Giese and Ray 2011). The 20°C isotherm depth has been considered as a proxy for the thermocline depth (z20). We have also used the observed tropical Atlantic SST from HadISST dataset (Rayner et al. 2003). The velocity potential at 200 and 950 hPa (hereafter, chi200 and chi950) has been calculated from the zonal and meridional wind obtained from 20th century reanalysis (Compo et al. 2011) using the Laplace equation, $\nabla^2\Phi = 0$ where Φ is the velocity potential and verifies $u = \frac{\partial\Phi}{\partial x}$ and $v = \frac{\partial\Phi}{\partial y}$ being u and v the zonal and meridional components of the wind. The period of study goes from 1871 to 2002. Questions about the reliability of the data during the first decades of the 20th century remains a caveat. In early years, the observed SST is very sparse since the majority of the measures come from ships, which changed their commercial shipping routes along the time. North Atlantic, western South Atlantic and North Indian Oceans are the regions with more density of measures. Nevertheless, the spatial coverage of tropical Atlantic and Pacific data is completed around the 1960s (Deser et al., 2010). SST data comes from million of observations which have been carefully checked in order to generate corrected datasets. However, corrections prior to about 1900 are less well known because of uncertainties in the mix of wooden and canvas buckets. Nevertheless, even in the 1870s, SST was little biased relative to land-surface air temperatures globally. Since 1941, observations mainly

come from ship engine intake measurements, better insulated buckets and, latterly, from buoys (IPCC WG1). Therefore, SST data should be regarded as more reliable, also useful for projections at multi-decadal time-scales.

In particular, in the present study we have used Tropical Atlantic SST from HadISST dataset, which are based on in-situ observations and extend the data to more sparse oceanic regions applying reduced space optimal interpolation (RSOI, Kaplan et al. 1997) which use EOF technique (Rayner et al. 2003).

Also, SST data from version 2.2.4 of SODA reanalysis has been used for Pacific basin. This reanalysis considers for the boundary conditions and for the variables in the bulk formula, a new data set designed as 20CRv2 (Whitaker et al. 2004; Compo et al. 2006; 2008), hydrographic profiles from de Boyer et al. (2009) and SST observations from ICOADS (Woodruff et al. 2011). The variability of ENSO is well reproduced in the reanalysis although with stronger amplitude (Giese and Ray 2011).

Modelled data

The model used is SPEEDY model (Molteni 2003; Kucharski et al. 2006) coupled to an extended 1.5-layer reduced-gravity model (Kucharski et al. 2008; Chang et al. 1994) and the simulations are the same as in previous studies (Rodríguez-Fonseca et al. 2009; Martín-Rey et al. 2012; Polo et al. 2014) but extended from 1871 to 2002. The simulations consider the observed Atlantic SSTs (HadISSTs between 60N-60S) as the only external forcing and they are fully coupled in the tropical Indo-Pacific region [30N-30S], with climatological SST elsewhere being named as *SimAtlVar*. For the comparison analysis, the

oceanic and atmospheric variables previously mentioned for observations and reanalysis are considered, being also the period of study 1871 to 2002.

Seasonal cycle and variability of the equatorial Pacific SST

Both, modelled and observed seasonal cycle of the equatorial Pacific SST are characterized by the development of a cold tongue in the eastern basin during summer months (June-October), peaking in July-August for the whole period 1871-2002 (Figure 1a-b). Despite of the lower amplitude of the simulated SST, a good agreement between model and observations is shown in the offshore eastern equatorial Pacific (140W-80W) during this peak. Nevertheless, *SimAtlVar* presents an alteration of the seasonal cycle in comparison with the observations in the central-eastern part of the basin (Figure 1b). Figure 1c presents the difference between the observed and modelled seasonal cycle, which reveals the typical SST bias present in most climate models characterized by warmer SST anomalies in the central-east and cooler ones in the west Pacific from August to December (Figure 1c; Davey et al. 2002). The bias shows the opposite sign that the observed seasonal cycle, indicating how the observed seasonal cycle is damped in the simulation. An interesting feature is the lower changes between modelled and observed SST in the region 180E-100W in July (Figure 1c), suggesting the reduction of the bias in this region during the peak of the cold tongue.

Regarding variability, maximum values are located in the eastern equatorial Pacific (180-100W) for observations and model simulations during boreal autumn-winter (October to

March, Figure 1d-e). However, *SimAtlVar* also shows higher variability in western equatorial Pacific (120E-160E) along the year, peaking in late boreal autumn and winter (Figure 1e). Despite the lower amplitude, the model is able to capture the basic changes in the observed variability in the equatorial Pacific SST. Figure 1f indicates how the bias in variability is reduced in the western equatorial Pacific (west of the dateline) for the whole year. The results suggest that the simulation considering only the external Atlantic influence presents a reduction in the bias during the summer and also in its variability in the western Pacific along the whole year.

Thus, the next step is to compute for both models and observations, the Tropical Atlantic variability modes and study if these modes exert influences on the Pacific together with their associated modulations. The methodology is explained in the next section.

Methodology

Seasonal anomalies of 4-consecutive months, from January-February-March-April (JFMA) to December-January-February-March (DJFM), are computed subtracting the seasonal cycle of the total period of study. An interannual filter is applied in order to isolate the interannual variations from the low frequency ones (Bjerknes 1964; Stephenson et al. 2000). The filter consists in computing the difference between two consecutive years, highlighting in this way the high frequency signal of the field.

Maximum Covariance Analysis (MCA) is used as the statistical discriminant analysis methodology to calculate the principal directions of maximum covariance between the

predictor (SSTs) and the variables to predict (Bretherton et al. 1992, Cherry 1997). MCA considers two fields, X and Y, named as predictor and predictand field respectively, and applies a Singular Value Decomposition (SVD) to the covariance matrix. SVD calculates linear combinations of the time series of X and Y (named as expansion coefficients, hereinafter U and V) that maximize the covariance among them. U and V are computed by the diagonalization of the covariance matrix $C=X*Y^T$ by SVD. The singular vectors R and Q are the resultant eigenvectors from the diagonalization, which are the spatial configurations of the main mode of covariability. The associated loadings on the time domain are the expansion coefficients U and V respectively. Finally, the eigenvalues are a measure of the percentage of variance explained by each mode. The percentage of explained covariance for each mode k is given by the square covariance fraction, calculated as a function of the eigenvalues. Additionally, to evaluate how much the expansion coefficients U and V are related to each other, we calculate the correlation coefficient for each mode.

In the meteorological context, the two matrices associated to the predictand and predictor fields (X and Y respectively) are dimensioned in the time (n_t) and space domain (n_x and n_y for X and Y respectively), although the spatial domain can be more complex depending on the needs, as it is the case of the present study. In this case, the study involves atmospheric and oceanic mechanisms in which more than two variables are connected. In particular, we want to analyse the Atlantic influence on the Pacific variability, in which, as indicated by a set of papers (Polo et al., 2008, Rodríguez-Fonseca et al., 2009; Ding et al., 2012; Martín-Rey et al., 2012; Ham et al. 2013) the summer Tropical Atlantic SST appears as the predictor field. As proposed by Polo et al. (2014), this predictor connects both basins

through changes in the Walker circulation, impacting on tropical Pacific wind stress, thermocline depth and SST through an atmospheric bridge. For this reason, we consider that the predictand field X includes, in one matrix, all the fields involved in the connection, which in turn act at different lags. Thus, the MCA is applied using multiple lags and variables, so we have named it as Extended Multiple Maximum Covariance Analysis (hereafter EMMCA). The variables involved in the interbasin connection are Tropical Atlantic SSTs in summer (JJAS) as predictor field and the following predictand fields: Tropical velocity potential fields at the surface (925 or 950 hPa) and upper levels (200 hPa) in summer and winter months (JJAS-DJFM), tropical Pacific wind stress in summer (JASO), thermocline depth from summer to winter (JASO-SOND-DJFM) and Tropical Pacific SST in winter (DJFM).

A scheme of the EMMCA calculation is presented in Figure 2, as a mix of the methodologies exposed in Polo et al (2005) in which multiple variables are included in the analysis and Polo et al. (2008) in which multiple predictors are included in the analysis. Nevertheless, in this work, we just include one variable as predictor field and multiple lags (similar to Garcia-Serrano et al., 2008) and variables as predictand ones. Thus, the X matrix is the predictor and has (n_x, n_t) dimensions, but the Y matrix has dimensions (n_y^{vdl}, n_t) where vdl indicate the specific combinations of variables (v), lags (l) and spatial domains (d) for all the variables to predict, all having the same time length, in agreement with the mechanism described in Polo et al. (2014).

Once EMMCA is applied, the spatial and temporal patterns for the individual Pacific variables are obtained projecting the original predictand matrix Y for the variable i , $Y(n_y^i, n_t)$ over the total expansion coefficient U_k obtained as outputs of the EMMCA:

$$r_i = U_k * Y(n_y^i, n_t)^T \quad [1]$$

The robustness of the results is assessed by applying a Monte Carlo test. It is a non-parametric test, which consists in permuting the initial time series to create a random distribution of the sample. The results are compared with those obtaining by chance and significant values that exceed 90% confidence level are shown in this paper. We have also used a parametric test, F-test, which considers the equality of variances as the null hypothesis. Significant values at 90% confidence level are also shown.

In the next section, the results obtained when EMMCA is applied are described for both model and observations. Notice that a simple correlation of the Atl3 index onto the variables would lead to similar results, although with lower correlation scores, especially in the observations (not shown). However, The EMMCA methodology allows us to express the pattern as a robust climate coupled covariability mode and to perform a Niño3 hindcast from the output parameters in order to assess the predictability of the ENSO from the equatorial Atlantic SST (see later in the results).

3. Results

3.1 Identification of the leading covariability mode and analysis of its stationarity

Firstly, the whole available time period of data (1871-2002) is considered in the EMMCA analysis. The leading covariability mode explains 35.2% of the total variance and shows the link between the Tropical Atlantic and Pacific interannual variability, in particular summer Atlantic Niño (Niña) and a winter Pacific Niña (Niño). The results show how the summer Atlantic Niño appears associated with an alteration of the Walker circulation, with ascending branch over the Atlantic and descending motions over the central Pacific in relation to an Atlantic warming, creating surface wind divergence in summer months over this Pacific region (not shown). The evolution of the z20 suggests that the anomalous surface wind could trigger an oceanic Kelvin wave propagating eastward and impacting on the Pacific SST in winter months, according to the mechanism proposed by Polo et al. (2014).

The existence of this mode and the relation found between the predictand variables and the predictor could be indicating the presence of the Atlantic-Pacific connection (Rodríguez-Fonseca et al., 2009) during the whole century and, thus, a stationary behaviour. Nevertheless, it has been found how the amplitude of the standardized expansion coefficients varies on time, indicating the different loading amplitudes of the mode in some decades than in the others (Figure 3). In particular, the variability of the expansion coefficient (thick line) for tropical Atlantic SST seems to be modulated by a positive decadal trend that could be associated with the global warming (Figure 3a; Kucharski et al.

2011). Nevertheless, the expansion coefficient for the set of Pacific variables involved in the mode shows a multidecadal modulation with higher loadings during the first decades of the 20th century and after the 1970s (Figure 3b).

Additionally, the 20-yr running correlation between the expansion coefficients for the summer Atlantic SST and the predictand fields also exhibits a multidecadal modulation with significant correlations at the beginning and end of the 20th century (not shown). In particular, the moving correlation in 20-yr windows is shown for the summer Atlantic SST and zonal Pacific wind stress expansion coefficient in Figure 3d. Significant correlation seems to occur under negative phases of the Atlantic Multidecadal Oscillation (AMO), suggesting the non-stationary behaviour of the interbasin connection. The correlation score between AMO and running correlation curve, in Figure 3d, reaches -0.52.

To corroborate the possible non-stationarity of the mode, the EMMCA analysis has been computed separately for periods associated with positive (1934-1969) and negative (1871-1933 and 1970-2001) phases of the AMO (Figure 4a-r).

The results reveal how the Atlantic Niño-Pacific Niña mode (and vice versa, Figure 4a-f and Figure 4 m-r) appears as the leading coupled covariability mode at the beginning and end of the 20th century (explaining the 36.84 % and 36.79% of the total variance), but not in the decades in-between (Figure 4g-l). Thus, for negative phases of the AMO, when the connection takes place, the Atlantic SST anomalies (Figure 4a and 4m) cover the entire tropical basin [20N-20S, 70W-20E], enhancing the deep convection over the equatorial Atlantic (Figure 4b and 4n), modifying the Walker circulation and impacting on the Pacific

Ocean during summer season (Figure 4b-c and 4n-o). The anomalous surface wind divergence peaks in the central Pacific (160W-120W), shallowing the thermocline depth and triggering the Kelvin wave which impacts on the SST during winter months (Figure 4d-f,p-r), according to the mechanism proposed by Polo et al. (2014). A Pacific La Niña-like pattern is completely developed in DJFM (Figure 4f and 4r) and it is associated with a see-saw pattern in the velocity potential field (not shown).

However, for the period 1934-1969 and coinciding with a positive AMO phase, an Atlantic Niño appears associated with no defined SST pattern in the Tropical Pacific basin (34.06% of the total variance, Figure 4g-l). Also, the associated Atlantic Niño presents a different spatial configuration, with positive anomalies in the eastern side and negative ones in the subtropical South Atlantic (Figure 4g). The change in the spatial structure of this mode, as well as, in its impacts, has also been documented in previous studies (Losada et al. 2010 and 2012; Mohino et al. 2011). Nevertheless, during the positive AMO years, the Atlantic Niño does not appear associated with Walker circulation changes and interbasin atmospheric teleconnections. Although an atmospheric response to the equatorial warming is observed over the Atlantic, it does not modify the atmospheric circulation over the Pacific region (Figure 4h). Significant wind convergence is presented at surface levels but it is independent of Atlantic forcing and is not able to impact on the winter Pacific SST (Figure 4h and 4l).

3.2 The Atlantic influence in the Pacific variability

In this section, the real influence of the Atlantic on this mode is checked by repeating the analysis of section 3.1 with the simulated data obtained when prescribing the observed SST over the Atlantic and coupling the Indo-Pacific basin.

Atlantic contribution to the coupled mode

To evaluate the Atlantic contribution to ENSO development, the EMMCA has also been performed for model simulations, *SimAtlVar*, considering the observed Atlantic SST as the only external forcing (Rodríguez-Fonseca et al. 2009; Martín-Rey et al. 2012). Model results reproduce the leading Atlantic-Pacific mode, explaining 26.52% of the total variance, for the entire period 1871-2002 and the multidecadal modulation of the amplitude of the expansion coefficients (Figure 5). The running correlation between the expansion coefficients of the predictor and predictand fields presents higher values at the beginning and end of the 20th century (not shown). Indeed, the correlation between summer Atlantic SST and zonal Pacific wind stress suffers a sharp decrease during the 1910s-1940s from correlation scores of 0.8 to 0.2 suggesting the weakening of the Atlantic-Pacific mode in this period (Figure 5d).

Validation of the model EMMCA shows that almost all expansion coefficients are significantly similar than the observational ones, with significant correlation scores of 0.97 and 0.33 between the expansion coefficients for the Tropical Atlantic SSTs and total Tropical Pacific variables respectively.

The correlation maps show the Atlantic-Pacific mode during the first and last decades of the 20th century (explaining 29.68% and 29.82% of the total variance, respectively), giving robustness to the observational finding (Figure 6a-r vs Figure 4a-r). Our model results confirm the alteration of the Walker circulation as a response of an Atlantic Niño (Niña) during those decades, coinciding with negative AMO phases (Figure 6b,n). Nevertheless, the subsidence (ascending motions) over the central Pacific is displaced westward with respect to the observations, showing the surface wind divergence (convergence) around 180-150W (Figure 6b and Figure 6n), where the thermocline shallows (deepens) and triggers the upwelling (downwelling) Kelvin wave propagating to the east reaching the South American coast in winter months (Figure 6c-e and 6o-q). The zonal displacement of the surface divergence (convergence) originates a lag in the impact on the SST with respect to the wind forcing: significant cooling (warming) is only shown in the southeastern Pacific, while the warm (cold) horseshoe is already developed in winter months (Figure 6f and 6r). This delay in the creation of the cold (warm) tongue has also been documented in previous studies, suggesting that although the wind anomalies in the western Pacific contributes to generate the warming (cooling) in this region, the feedbacks processes in the simulation are not so effective to cool (warm) the eastern Pacific, resulting in a slower Bjerknes feedback mechanism (Polo et al. 2014).

On the contrary, under positive AMO phases the Atlantic Niño is able to alter the Walker circulation over the tropical Atlantic basin with a descending branch over the Indian Ocean but with no impact on the Pacific basin, in agreement with observations (33.18% of the total variance, Figure 4h and Figure 6h). Surface wind convergence is located around the

dateline and significant warm SST anomaly pattern appears in the central-eastern Pacific during winter months (Figure 6l). As no significant changes are observed in the thermocline depth and neither in the Walker circulation over the Pacific, the anomalous wind stress and SST development could be associated with a local forcing (Figure 6h-k).

Despite its simplicity, the model is able to simulate the atmospheric and oceanic processes at work in this connection. The good agreement between modelled and observational results could be due to the fact that the Atlantic influence on ENSO development is based on equatorial dynamics associated with thermocline feedbacks, which are well resolved in the model (Polo et al. 2014). Additionally, the Atlantic modulated -ENSO phenomena seem to follow Wyrтки's theory: a wind perturbation in the central-western equatorial Pacific builds up water in the western Pacific which propagates eastward as a Kelvin wave favouring the creation of SST anomalies in the eastern equatorial Pacific (Wyrтки 1975). Therefore, an AGCM coupled to a simplified 1.5 layer ocean model is able to simulate the change in the thermocline depth, as a consequence of the anomalous winds coming from the Atlantic, which in turn, propagates to the east as a Kelvin wave reaching the coast and favouring the SST anomalies related to ENSO phenomena (Figure 6), according to the Wyrтки's hypothesis.

4. Discussion

Our study evidences that, during certain decades, there is a leading tropical coupled covariability mode that links the Atlantic and Pacific interannual variability. Thus, a summer Atlantic Niño is associated with a Pacific La Niña during the next winter, and vice

versa. This relation is found using both observations and model simulations with prescribed Atlantic SSTs and coupled over the Indo-Pacific region. Although the relation between the Atlantic-Pacific Niños has been demonstrated in previous studies (Keenlyside and Latif 2007; Rodríguez-Fonseca et al. 2009; Ding et al. 2012; Martín-Rey et al. 2012), here, for the first time the Atlantic-Pacific connection is presented as a leading mode of coupled covariability, which appears modulated at multidecadal timescales. The decades in which the mode shows up coincide with negative phases of the Atlantic Multidecadal Oscillation (AMO), putting forward the possible modulation of this mode by this multidecadal variability pattern.

4.1 Multidecadal modulation

In order to shed light on the role of the AMO in the tropical Atlantic and Pacific variability, the multidecadal changes of the variability in winter equatorial Pacific SST (Niño3 region) and summer western equatorial Atlantic convergence at upper levels (in terms of the velocity potential) are computed using model simulations which consider the observed Atlantic SSTs as the only external forcing (Figure 7a).

As the main difference between the Atlantic SST pattern related and unrelated with ENSO (Figure 4b vs Figure 4a,c) is located in the western equatorial Atlantic, we have analysed the changes in the divergent component of the upper-level flow in this region. These changes are significant during negative phases of the AMO, suggesting how the AMO is able to modify the amplitude of the anomalous convection and, thus, impacting on the Pacific SSTs (Figure 7). Figure 7a shows how this enhancement (weakening) of Niño3

variability takes place during the first and last (middle) decades of the 20th century, coinciding with negative (positive) AMO phases in which the South Atlantic is warmer (cooler) than normal. Indeed, the correlation map obtained between the time evolution of the curves from Figure 7a and the anomalous global SSTs resembles clearly an AMO-like pattern: the inter-hemispherical pattern associated with the AMO (Figure 7b, shaded) is well reproduced when using the time series obtained by the model (purple and red lines) over the global SSTs (Figure 7b dotted areas). This similarity corroborates the AMO influence on the Pacific SST variability reported in previous studies (An and Jin 2001; Dong et al. 2006; Timmerman et al. 2007; Hong et al. 2013; Polo et al. 2013). Additionally, for the first time, we suggest that the changes in the mean state of the Atlantic Ocean as an AMO response could modify the convergence at the upper levels of the western equatorial Atlantic, favouring and changing the variability of the atmospheric bridge which links the Atlantic and Pacific basins (red line, Figure 7a and Figure 7c).

Nevertheless, the role of the mean state and variability of the Atlantic SST in the Atlantic-Pacific connection remains unclear. On the one hand, some authors suggest that changes in the Atlantic mean state could enhance the equatorial Atlantic SST variability in summer strengthening the Atlantic-Pacific connection (Svendsen et al. 2013). Also, modifications of the Atlantic and Pacific mean state associated with the global warming could also contribute to favour the interbasin connection (Kucharski et al. 2011). On the other hand, a mean deepened thermocline depth, which implies a decrease of the Atlantic variance, has been reported in recent studies (Haarsma et al. 2008; Polo et al. 2013). Additionally, spatial pattern of the Equatorial mode changes depending on the period considered (Figure

4-6, first row) with different impacts on the ENSO phenomenon and coinciding with opposite phases of the AMO. Further sensitivity studies must be done in order to isolate the role of the mean state on the interannual variability and the interannual variability of the Atlantic Ocean and their impact on the Pacific basin.

4.2 Statistical hindcast of Niño3 SST

One way to examine to the role of the Atlantic in the Pacific is to test the ENSO prediction using the information from EMMCA (Figure 8). A statistical hindcast is calculated for each of the three periods of study: 1871-1933, 1934-1969 and 1970-2001, associated with positive and negative phases of the AMO. The selected year i to predict is previously removed from the sample, and the EMMCA is applied to the new sample with dimensions $X(n_x, n_t - i)$ and $Y(n_y, n_t - i)$ for predictor and predictand fields respectively. A Psi function, which contains the information between the predictor (X) and predictand fields (Y), has been obtained. The Psi function and the predictor are used to hindcast the predictand fields:

$$Y(n_y, n_t) = Psi(n_y, n_x) * X(n_x, n_t) \quad [2]$$

Here, we show the hindcast for Niño3 SST in winter months for periods of negative AMO phases, coinciding with the appearance of the Atlantic-Pacific mode, and period of positive AMO phase (Figure 8). The observed SST is well predicted in the first and last decades of the 20th century, showing significant correlation scores at 90% confidence level (Figure 8a,c), while this value decreases to almost zero in AMO positive decades (Figure 8b). This

result evidences that the AMO negative periods are opportunity windows for ENSO forecast using the summer tropical Atlantic SST as the predictor field.

5. Summary and Conclusions

The present study has demonstrated for the first time that the Atlantic-Pacific Niños connection is a leading mode of interbasin covariability, which appears modulated at multidecadal timescales coinciding with phases of the AMO.

Warm (cool) SST anomalies over the equatorial Atlantic in summer are related to ascending (descending) motions over the Atlantic and subsidence over the Pacific, where an upwelling (downwelling) Kelvin wave is generated propagating eastward and impacting on the Pacific SST in winter months, favouring the development of La Niña (El Niño). This mechanism, which has been reported by Polo et al. (2014) is a mode of interbasin variability and has been isolated in this work, explaining almost the 30% of the total variance.

The associated leading mode of the Tropical Atlantic SST variability, the Atlantic Niño, presents different spatial patterns depending on the decades considered: anomalous SSTs covering the entire Tropical Atlantic basin are observed under negative AMO phases, while a dipolar structure is presented for AMO positive periods (Figure 4a,g,m and Figure 6a,g,m). The main difference between them is located in the western Equatorial Atlantic (70W-35W, 20N-20S); it is warmer during the first and last decades of the 20th century (Figure 4a,m and Figure 6a,m). These decades coincide with negative AMO periods, where

the southern Atlantic is warmer than normal, the western equatorial Atlantic atmosphere is more perturbed and could help to connect the Atlantic and Pacific basins at multidecadal time scales. Also, there is an increase of Pacific SST variability during these periods, favouring the occurrence of the Atlantic-Pacific Niños mode.

We suggest that the multidecadal internal variability of the ocean is able to modulate the Atlantic-Pacific connection through changes in the western equatorial Atlantic convection and Pacific SST variability (Figure 7). This finding provides a step forward in the improvement of the seasonal and decadal forecast. The statistical hindcast of the Niño3 SST from the mode information has revealed that the Pacific SST can be reproduced with the information of the Tropical Atlantic SST in negative AMO periods (Figure 8).

On the one hand, the Atlantic-Pacific connection increases ENSO predictability (Frauen and Dommenges 2012; Dayan et al. 2013; Bosch et al. 2013). But, on the other hand, the correct simulation of the AMO could in turn favour the periods in which this predictability is observed. Further analyses with coupled models are needed in order to check the modulation role of the Atlantic mean state in triggering the Atlantic-Pacific connection.

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825 **Figure Caption**

826 **Figure 1. Seasonal Cycle and Standard deviation of the equatorial Pacific SST for**
827 **HadISST and SIMATLVAR from 1871 to 2002.**(a-b, d-e) Seasonal cycle and standard
828 deviation of the equatorial Pacific SST for observations and model simulations
829 (*SimAtlVar*). The monthly means (in K) have been detrended. (c,f) Difference between the
830 simulated and observed seasonal cycle and standard deviation of the equatorial Pacific SST.
831 A test of equal means/variances has been applied and the values exceeding 90% confidence
832 level are shown.

833
834 **Figure 2.Schematic of the EMMCA applied in the present study.** (Left) Scheme of the
835 arrays for the predictor (X) and the set of predictand fields (Y) used in the Extended
836 Multiple Maximum Covariance analysis (EMMCA). (Right) Description of the different
837 variables considered as predictor (summer Tropical Atlantic SST) and predictand fields
838 (tropical velocity potential, Pacific wind stress, thermocline depth and SST) in specific lags
839 and the methodology of the EMMCA.

840
841 **Figure 3. Expansion coefficients of the leading mode of interannual variability from**
842 **observations for the period 1872-2001.** (a-c) Expansion coefficients and their 20-yr
843 running standard deviation (thick line) of the leading mode obtained applying the EMMCA

to the total period 1872-2001 for the predictor field, the summer (JJAS) tropical Atlantic SSTs, the set of the predictand fields and the tropical Pacific zonal wind in summer (JASO). (d) Running correlation in 20-yr windows between the expansion coefficient of the predictor and the expansion coefficient of the Pacific zonal wind stress (purple line). The statistical significant correlation exceeding 90% confidence level, according to a Monte Carlo test, is presented in dots. The 20-yr running mean of the Atlantic Multidecadal Oscillation index is also presented (green line).

Figure 4. 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 m²/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.

Figure 5. Expansion coefficients of the leading mode of interannual variability from SimAtlVar for the period 1872-2001. Same as Figure 3 but for SimAtlVar.

Figure 6. Leading Mode of the EMMCA for SimAtlVar. Same as Figure 4 but for *SimAtlVar*.

Figure 7. Multidecadal changes in the equatorial Atlantic velocity potential and Pacific SST variability (a) Purple line: changes in the standard deviation of Niño3 index in winter (DJFM) months with respect to the whole period. 20-yr running differences are computed and a F-test is applied to highlight the windows in which the differences are statistically significant at 90% confidence level. Red Line: the same as the purple line but for the summer (JJAS) velocity potential at 200hPa (chi200) in the western equatorial Atlantic (70W-35W, 5N-5S) from SimAtlVar. Green line: Atlantic Multidecadal Oscillation time series (defined as the annual SST anomalies averaged in North Atlantic region. The global warming signal has been previously removed; Villamayor et al. 2012) (b) Correlation map between the running 20-yr differences for AMO index (green line in (a)) and the global SST anomalies in 20-yr windows. (c) Same as (b) but for the running 20-yr differences for the chi200 in JJAS. Significant values at 90% confidence level according to a Monte Carlo test have been in shaded. Additionally, significant region which coincides in sign with those regions obtained correlating the red and purple lines from (a) over the global SST are also indicated with black markers.

Figure 8. Hindcast for the observed Niño3 SST in winter months (DJFM) for the periods 1871-1933, 1934-1969 and 1970-2001. Bars: Observed equatorial Pacific SST in Niño 3 region. Stems: Predicted equatorial Pacific SST in Niño3 region using the statistical hindcast from EMMCA information. Stars: Years in which there is a summer Atlantic Niño (Niña, expansion coefficient for Atlantic SST higher than ± 1 std) followed by observed and predicted Pacific La Niña (El Niño, Niño3 index higher than ± 0.5).