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Authors:

First author Joke F. Lübbecke* ORCID: 0000-0002-7839-3284 GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany and Christian-Albrechts-Universität zu Kiel, Kiel, Germany jluebbecke@geomar.de
Second author Belen Rodríguez-Fonseca ORCID: 0000-0002-5261-7083 Departamento de Física de la Tierra y Astrofísica. Universidad Complutense de Madrid, Spain, and Instituto de Geociencias IGEO, CSIC-UCM brfonsec@fis.ucm.es
Third author Ingo Richter ORCID: 0000-0002-7765-5190 Japan Agency for Marine-Earth Science and Technology Yokohama, Japan richter@jamstec.go.jp
Fourth author Marta Martín-Rey ORCID: 0000-0001-6234-0447 CECI/CERFACS, Toulouse, France mmrey@cerfacs.fr
Fifth author Teresa Losada ORCID: 0000-0002-8430-1745 Departamento de Física de la Tierra y Astrofísica Universidad Complutense de Madrid, Madrid, Spain tldoval@fis.ucm.es

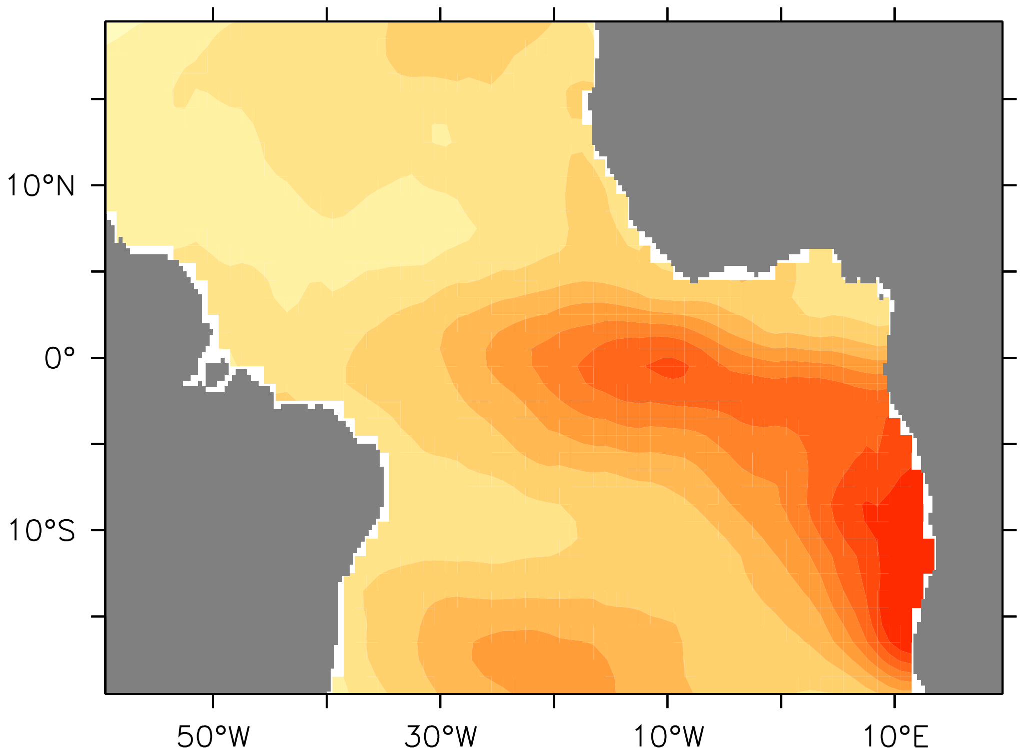
Sixth author
Irene Polo
ORCID: 0000-0002-6250-6109
Department of Meteorology
University of Reading, UK
i.polo@reading.ac.uk

Seventh author
Noel S. Keenlyside
ORCID: 0000-0002-8708-6868
Geophysical Institute, University of Bergen, Norway, and
Bjerknes Centre for Climate Research, Bergen, Norway
noel.keenlyside@gfi.uib.no

Abstract

Sea surface temperature (SST) variability in the tropical Atlantic Ocean strongly impacts the climate on the surrounding continents. On interannual time scales, highest SST variability occurs in the eastern equatorial region and off the coast of Southwestern Africa. The pattern of SST variability resembles the Pacific El Niño, but features notable differences, and has been discussed in the context of various climate modes, i.e. reoccurring patterns resulting from particular interactions in the climate system. Here, we attempt to reconcile those different definitions, concluding that almost all of them are essentially describing the same mode that we refer to as the "Atlantic Niño". We give an overview of the mechanisms that have been proposed to underlie this mode, and we discuss its interaction with other climate modes within and outside the tropical Atlantic. The impact of Atlantic Niño related SST variability on rainfall, in particular over the Gulf of Guinea and North Eastern South America is also described. An important aspect we highlight is that the Atlantic Niño and its teleconnections are not stationary, but subject to multi-decadal modulations. Simulating the Atlantic Niño proves a challenge for state-of-the-art climate models, and this may be partly due to the large mean state biases in the region. Potential reasons for these model biases and implications for seasonal prediction are discussed.

Graphical/Visual Abstract and Caption



Spatial pattern of the Atlantic Niño, the dominant climate mode in the tropical Atlantic on interannual time scales with impacts on precipitation over the surrounding continents.

Introduction

The tropical oceans are an important part of the climate system. Due to the excess solar radiation that they receive, a great amount of heat is stored in the tropics and distributed to higher latitudes by both atmospheric and oceanic circulations. The high surface temperatures of the tropical oceans also allow for strong interaction between the ocean and the atmosphere by deep atmospheric convection. Atmospheric wind forcing, in turn, strongly impacts sea surface temperature (SST) in the tropics, especially in the eastern equatorial Atlantic and Pacific, where it controls both the upwelling of cold water from below the sharp, shallow thermocline as well as the depth of the thermocline. SST anomalies in the tropics can thus have far-reaching effects. A prominent example is the El Niño-Southern Oscillation (ENSO) in the tropical Pacific, which can impact weather and climate worldwide.

In this review, we focus on the year-to-year variability in the tropical Atlantic. Similarly to the El Niño phenomenon in the Pacific, there are years when SSTs in the eastern equatorial and southeastern tropical part of the basin significantly depart from the climatological average over a period of several months. These warm and cold events, which we will refer to as Atlantic Niño and Atlantic Niña events, respectively, can have substantial impacts on the marine ecosystem and on rainfall over western Africa and north-eastern South America.

In the first section, we briefly describe the characteristics of interannual SST variability in the equatorial Atlantic and introduce the various climate modes that have been associated with it. We address the question of whether these modes are independent (i.e. result from different interactions of the climate system) or just different names for the same phenomenon. Furthermore, we discuss the different mechanisms proposed to generate SST anomalies in the eastern equatorial Atlantic. The second section is focused on the impacts of equatorial SST variations on precipitation over Western Africa, north-eastern South America and Mediterranean Europe. The interaction between ENSO in the Pacific and the Atlantic Niño mode is discussed in the third section. Many studies have investigated the aspects mentioned above - i.e. characteristics, generation mechanisms, impacts and teleconnections - but the results are not completely consistent among them. In the fourth section we suggest that some of these discrepancies arise from the multidecadal modulation of the Atlantic Niño and its teleconnections, which renders results sensitive to the study period. The last section is devoted to the simulation of equatorial Atlantic SST variability in state-of-the-art coupled climate models. We review potential sources of the mean-state tropical Atlantic biases common to most numerical models and examine to what extent they hamper realistic simulation of the variability. The conclusions section provides a summary as well as a discussion of various aspects.

INTERANNUAL SST VARIABILITY IN THE EQUATORIAL ATLANTIC AND ASSOCIATED CLIMATE MODES

Observed variability

SST variability in the equatorial Atlantic is dominated by the seasonal cycle (e.g. Ding, Keenlyside, & Latif, 2009). In boreal spring, the trade winds over the equator are weak, the Intertropical Convergence Zone (ITCZ) is located close to the equator and temperatures are almost uniformly high. In May, the ITCZ moves northward and the southeasterly trades intensify, which leads to a shoaling of the thermocline, enhanced upwelling and vertical mixing as well as intensified evaporation. As a result, a “cold tongue” develops in May and June east of about 20ºW and persists until September. This seasonal evolution of SST in the eastern equatorial Atlantic is illustrated in Figure 1d. A detailed description of the seasonal variation can be found in Dippe, Krebs, Harlaß, and Lübbecke (2018).

We refer to year-to-year variations of this seasonal SST evolution as interannual anomalies. While their amplitude is small compared to the seasonal signal, they are able to impact convection, thereby producing changes in the Walker and Hadley cells as well as exciting extra-tropical teleconnection patterns. Thus, the fluctuations in SST can modify the winds and precipitation regime over South America, the Indian Ocean, Sahel and even Europe. Changes in ocean temperature and upwelling of nutrients can also have important consequences for the marine ecosystem.

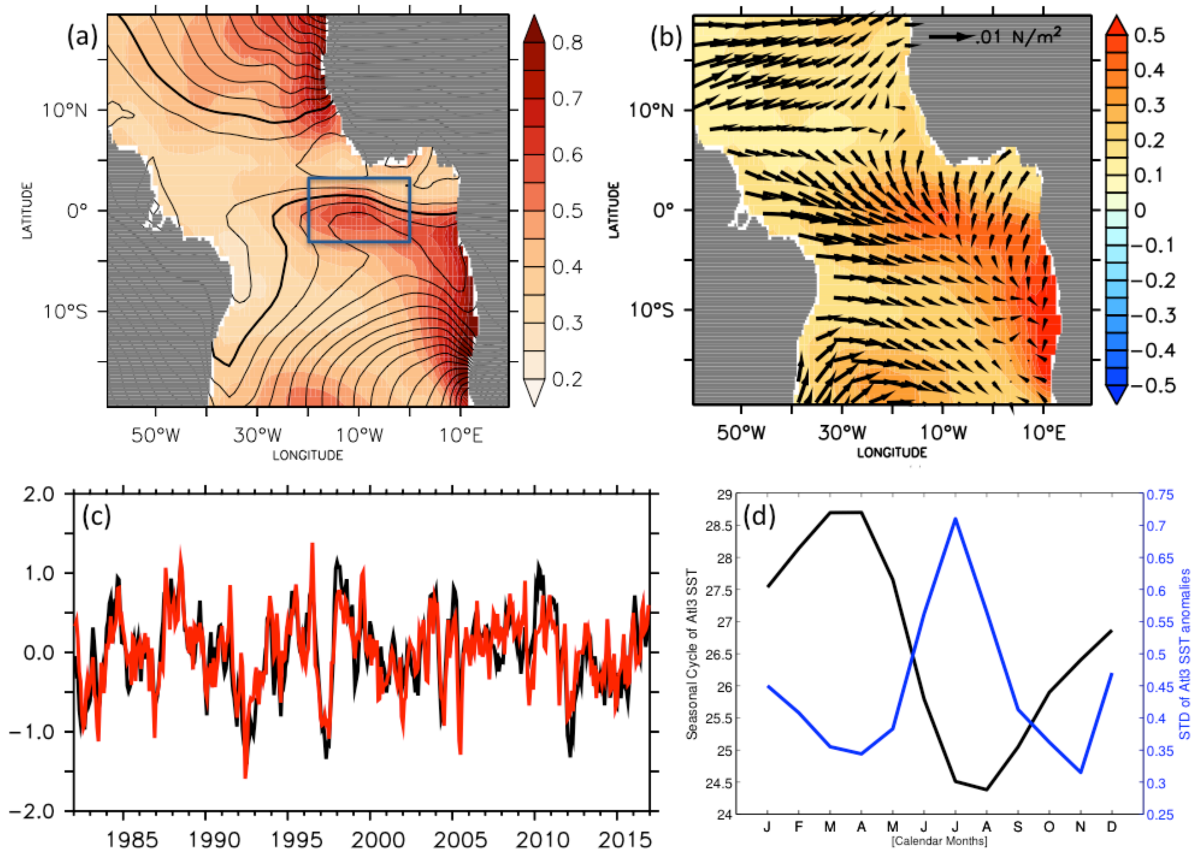


Figure 1: Pattern and time evolution of interannual SST variability in the tropical Atlantic *from monthly NOAA Optimum Interpolation (OI) SST (Reynolds, Rayner, Smith, Stokes & Wang, 2002) for the time period 1982 to 2016. (a) Standard deviation (shading) of interannual SST anomalies and annual mean climatological SST (contours). Contour interval is 0.5 ºC with 27ºC line in bold. (b) First EOF of interannual SST anomalies in the region 60ºW to 20ºE, 20ºS to 20ºN (shading) and associated wind anomalies (vectors). First EOF explains 32% of the variance. (c) Principal component of first EOF (black) and SST anomalies in ºC averaged over Atl3 region*

(20ºW – 0ºE, 3ºS – 3ºN, indicated as blue box in (a), red). (d) Seasonal cycle of Atl3 SST (black) and standard deviation of interannual SST anomalies (blue).

The spatial pattern of this variability is illustrated by the standard deviation of interannual SST anomalies and the first Empirical Orthogonal Function (EOF) in the equatorial Atlantic (Fig. 1a,b). The linear trend is removed from the time series to exclude the global warming signal. Both statistics clearly illustrate that the highest variability occurs in the cold tongue region in the eastern equatorial Atlantic as well as along the coast of Southwestern Africa. Note that the exact structure of the pattern depends on the time period chosen, as will be discussed in detail in the fourth section.

The variability is phase locked to the seasonal cycle, i.e. SST anomalies peak in boreal summer (Fig. 1d) when the thermocline is shallow and the surface-subsurface coupling is at its maximum (Keenlyside & Latif, 2007). Thus, equatorial SST anomalies can actually be understood as a modulation in timing and/or intensity of the seasonal development of the cold tongue (Burls, Reason, Penven, & Philander, 2012). This might also be an explanation for the remarkable symmetry between positive and negative SST anomalies. Both timing and amplitude of negative SST patterns evolve almost exactly as a mirror image of warm anomalies (Lübbecke & McPhaden, 2017).

Climate modes related to equatorial Atlantic variability

The dominant pattern of equatorial Atlantic SST variability introduced above has been described and discussed under various names in the literature. Already in 1980, Merle (1980) and Hisard (1980) described an “El Niño like” phenomenon in the tropical Atlantic with high SST anomalies in the eastern equatorial Atlantic and the Gulf of Guinea. The pronounced warm event that occurred in 1984 raised attention to this phenomenon and its impacts on rainfall over the adjacent continents (Philander, 1986; Carton & Huang, 1994). By comparing SST variability in the tropical Pacific and Atlantic Ocean, both from observations and in the framework of a simple dynamical model, Zebiak (1993) concluded that there exists an Atlantic equatorial coupled mode with dynamics similar to the El Niño-Southern Oscillation (ENSO), though more heavily damped. To characterize SST variability in the eastern equatorial Atlantic he defined the now regularly used ATL3 index as the SST anomaly averaged over the region 20ºW to 0ºE and 3ºS to 3ºN (indicated by the blue box in Fig. 1a).

Since the early 2000s, an increasing number of studies have addressed modes of SST variability in the equatorial Atlantic. Focusing on the interaction between climate variability modes in the tropical Atlantic, Servain, Wainer, Ayina, and Roquet (2000) referred to the variability as the **“Atlantic Equatorial Mode”**, and defined it from an EOF analysis of simulated monthly thermocline depth anomalies for the time period 1979 to 1993. Revisiting the study by Servain et al. (2000) for the time period 1949 to 2000, Murtugudde, Ballabrera-Poy, Beauchamp, and Busalacchi (2001) referred to the El Niño-like mode as the **“Zonal mode”**, emphasizing its east-west orientation. Ruiz-Barradas, Carton, and Nigam (2000) performed a rotated principal component analysis of SST, heat content, wind stress and diabatic heating for the time period 1958 to 1993. The second mode of this analysis, which they termed **“Atlantic Niño mode”**, was related to SST and heat content anomalies in the eastern equatorial basin and wind stress anomalies to the west of it. Stressing the location of the highest SST variability, the mode has also been called the **“Equatorial cold tongue mode”** (Haarsma & Hazeleger, 2007). Caniaux et al. (2011) defined indices for the extent, intensity, onset, and decay of the Atlantic cold tongue to characterize its variability, based on the surface area where SST is lower than 25ºC. Based on a Rotated-EOF (REOF) analysis of observed SST anomalies for 1950 to 1998, Huang, Schopf, and Shukla (2004) identified a **"Southern Tropical Atlantic (STA) pattern"** that is associated with SST anomalies centered at the Angolan coast and extending to the central equatorial Atlantic.

The variability patterns described by the above studies share many features: SST anomalies in the eastern equatorial cold tongue region that are centered just south of the equator; a southeastward extension of the equatorial SST anomalies toward the African coast; thermocline depth anomalies that roughly coincide with the SST anomalies; and zonal wind anomalies that tend to be maximum just south of the equator (Fig. 1b). The SST anomalies occur mainly on interannual time scales and are associated with precipitation anomalies in the Gulf of Guinea. The major difference among the descriptions is the balance between equatorial and southeastern SST anomalies, with some studies showing more pronounced SST anomalies in the southeast. Additionally, there are some minor differences in the structure of SST, thermocline and wind patterns. Potential reasons for these discrepancies across studies include different analysis periods and techniques, internal variability, and low-frequency modulation of the mode (see corresponding section below). In light of the commonalities among descriptions, and in recognition of the strong role of low-frequency modulation highlighted in this review, we suggest that all of the above studies really describe the same physical mode of variability. Many studies have pointed out the similarity to El Niño in the Pacific, and we thus use the term "Atlantic Niño" here.

There are other modes of climate variability in the tropical Atlantic that exhibit a pronounced signal in the area of the Atlantic Niño. Most studies on the Atlantic Niño focus on the cold tongue region, but, as mentioned above, its spatial configuration depicted in Figure 1 actually shows maximum SST variability also in an area along the southwest African coast. SST variability off Angola has been described separately already in the 1980s as an El Niño-like phenomenon and termed **"Benguela Niño"** (Shannon, Boyd, Bundrit, & Taunton-Clark, 1986). To characterize this variability, an Angola-Benguela area (ABA) index has been defined by Florenchie, Lutjeharms, Reason, Masson, and Rouault (2003) by averaging the SST anomalies over 20ºS to 10ºS and 8ºE to 15ºE. It has been shown that Atlantic and Benguela Niños are actually linked via equatorial and coastal Kelvin wave propagation (Florenchie et al. 2003; Lübbecke, Böning, Keenlyside, & Xie, 2010). Rossby wave propagation (Polo, Rodríguez-Fonseca, Losada, & García-Serrano, 2008) and an atmospheric bridge (Hu & Huang, 2007; Richter et al., 2010) might also contribute to the connection between these two regions. Even though most Benguela Niño and Niña events are linked to the equatorial Atlantic, warm and cold events off Angola can also be generated by local processes (Richter et al., 2010; Rouault, 2012) and the issue of whether Atlantic and Benguela Niños should be regarded as one mode is not fully resolved yet.

A **"South Atlantic Ocean Dipole"** (SAOD), characterized by opposite SST anomalies in the eastern equatorial (0ºS to 15ºS, 20ºW to 10ºE) and southwestern subtropical (25ºS to 40ºS, 10ºW to 40ºW) Atlantic, has been defined by Nnamchi, Li, and Anyadike (2011). This mode is very similar to the earlier described South Atlantic Subtropical Dipole (Venegas, Mysak & Straub, 1996, 1997; Haarsma et al., 2005; Colberg & Reason, 2007; Trzarska, Robertson, Farrara & Mechoso, 2007), and the question of whether they are independent of each other is still debated (Nnamchi, Kucharski, Keenlyside & Farneti, 2017). Regarding the connection to the equatorial Atlantic, Nnamchi et al.

(2016) indicated that when low-frequency SST variations are excluded, warm Atlantic Niño events almost always coincide with cooling in the southwestern subtropical Atlantic and argued that the Atlantic Niño could be viewed as the equatorial arm of the SAOD. If, however, the low-frequency component of the anomalies is retained, the Northeast and Southwest poles of the SAOD are not always anti-correlated, as in the period between 1960-1990 (Nnamchi et al., 2011; 2016). These results suggest some non-stationarity of the patterns and sensitivity to the definition of anomalies, as will be discussed below. Further research is required to resolve the debate on whether the SAOD and Atlantic Niño should be viewed as one mode.

There is also a possible link with the **"Atlantic Meridional Mode"** (AMM) that is associated with an interhemispheric gradient of anomalous SST (e.g. Ruiz-Barradas et al. 2000). The AMM, which tends to peak in boreal spring, influences the latitude of the Atlantic ITCZ (e.g. Xie & Carton, 2004) which, in turn, affects the equatorial surface winds (Richter et al., 2014) and could thus impact the Atlantic Niño. Servain, Wainer, McCreary, and Dessier (1999) demonstrated that a statistical relation exists, and Richter et al. (2017a) speculated on the underlying mechanism. There is also a dynamical ocean response to the off-equatorial winds related to the AMM in the form of discharge of ocean heat content (Zhu, Huang, & Wu, 2012) and triggering of oceanic waves (Foltz & McPhaden, 2010a). In this sense, wind-induced Rossby waves north of equator could be reflected at the western boundary as equatorial Kelvin waves, thereby impacting the eastern equatorial Atlantic SSTs (Foltz & McPhaden, 2010a).

As mentioned in the introduction, the interannual SST variability in the eastern equatorial Atlantic is closely phase locked to the seasonal cycle. It is most pronounced during the cold tongue season in boreal summer, and many studies actually use indices for June-July-August (JJA). Richter et al. (2017a) suggest that the phase locking is due to the seasonal migration of the ITCZ. Since the presence of deep convection over the equator enhances air-sea coupling, the northward migration of the ITCZ in early boreal summer reduces coupled feedbacks, which eventually leads to the decay of SST anomalies. Okumura and Xie (2006) noticed that there is a second peak of variability in November/December, and they called warm events that take place during boreal winter the **"Atlantic Niño II"**. They suggested that it occurs independently of the summer peak.

We conclude that there is one mode of boreal summer SST variability on interannual time scales in the southeastern tropical Atlantic that we will refer to it as Atlantic Niño. The two centers of variability in the cold tongue region and off Angola are closely connected, even though warm and cold events can also develop independently due to the influence of local forcing (described in more detail in the following subsection). The Atlantic Niño mode is robustly linked to opposite signed SST anomalies in the southwestern subtropical basin, a relation that has been described as a South Atlantic Ocean Dipole. It is also interacting with the Atlantic meridional mode, which is more active on longer time scales, peaking during boreal spring and controlled by thermodynamic feedbacks, through cross-equatorial wind stress anomalies. For the remainder of this paper, we will focus on the Atlantic Niño mode. Its forcing mechanisms, impacts, and long period modulations will be discussed in the following sections.

Generation mechanisms

Various mechanisms have been discussed for the generation of Atlantic Niño and Niña events. They are schematically summarized in Figure 2. Given its similarity to ENSO in the Pacific, an involvement of coupled air-sea feedbacks, namely the Bjerknes feedback (Bjerknes, 1969), appears likely. Keenlyside and Latif (2007) conducted an observation based regression analysis for both the equatorial Atlantic and Pacific to investigate the three components of the Bjerknes feedback, i.e. forcing of western basin wind anomalies by SST anomalies in the east, forcing of thermocline depth (or heat content) anomalies in the east by the wind anomalies in the west, and forcing of eastern basin SST anomalies by local thermocline depth anomalies. They concluded that all three components are active in the Atlantic, albeit weaker than in the Pacific. Deppenmeier, Haarsma, and Hazeleger (2016) arrived at similar results based on reanalysis data sets that they compared to CMIP5 model output. Using the Bjerknes stability index (Jin, Kim, & Bejarano, 2006), Lübbecke and McPhaden (2013) attributed the stronger damping of the Atlantic Niño mode to a weaker thermocline feedback. In Figure 1.b the wind stress anomalies associated with the first EOF of the interannual SST anomalies are shown, illustrating the weakening of the trade winds for the warm phase of the Atlantic Niño.

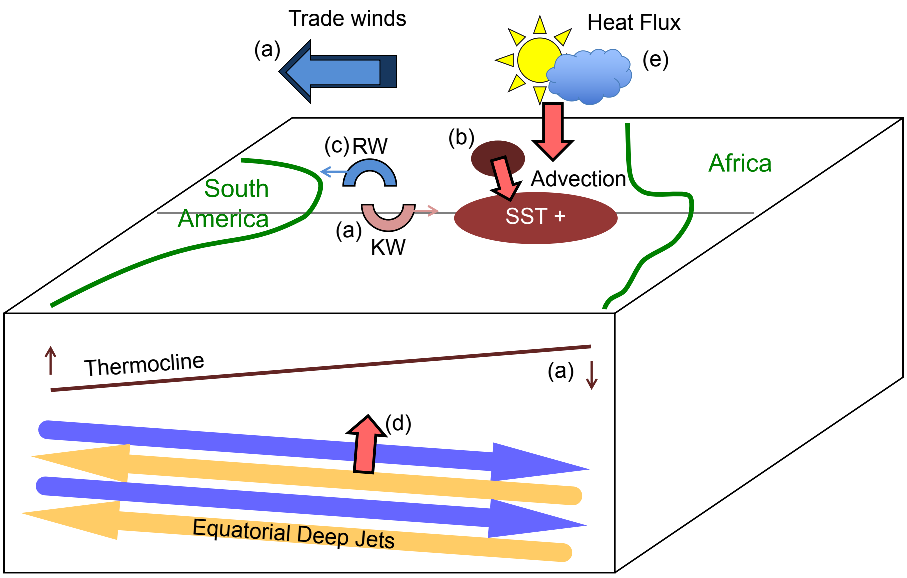


***Figure 2: Schematic of the different mechanisms suggested to generate Atlantic Niño events**: (a) the Bjerknes feedback including a weakening of the trade winds and adjustments of the thermocline slope via the propagation of equatorial Kelvin waves, (b) meridional advection of temperature anomalies, (c) Rossby wave reflection, (d) Equatorial deep jets, and (e) net surface heat flux anomalies.*

The second component of the Bjerknes feedback, i.e. the forcing of heat content anomalies in the east by wind stress anomalies in the western tropical Atlantic involves the eastward propagation of equatorial Kelvin waves. When these waves reach the eastern boundary, they are partially reflected into westward propagating Rossby waves and partially transmitted along the African coast as coastally trapped waves (Polo, Lazar, Rodriguez-Fonseca, & Arnault, 2008). When the southward propagating waves reach the Angola-Benguela Front at about 17ºS where the thermocline outcrops, they can cause pronounced SST anomalies, the so called Benguela Niños (Florenchie et al., 2003; 2004; Rouault, Illig, Bartholomae, Reason, & Bentamy, 2007; Lübbecke et al., 2010; Bachelery, Illig, & Dadou, 2015). Local wind forcing can also contribute to these events (Richter et al., 2010).

Richter et al. (2013) noted that some Atlantic Niño events cannot be explained by wind stress variations consistent with the Bjerknes feedback. Typically, a warm SST anomaly in the eastern equatorial Atlantic would be associated with a weakening of the trade winds in the western basin, but some warm events occur when the winds are actually anomalously strong. Richter et al. (2013) called these events “non-canonical” and suggested that they might be driven by meridional advection of temperature anomalies from north of the equator. Another explanation for non-canonical events involves the reflection of Rossby waves at the western boundary (Foltz & McPhaden 2010b; Burmeister, Brandt, & Lübbecke, 2016; Lübbecke & McPhaden, 2012). In both cases, a cross-equatorial SST gradient induces a wind stress curl anomaly that causes a thermocline depth and related subsurface temperature anomaly to the north of the equator. In the mechanism suggested by Richter et al. (2013), this temperature anomaly is directly advected to the equator by mean meridional currents while it propagates westward as a Rossby wave and then eastward as a reflected equatorial Kelvin wave in the mechanism suggested by Foltz & McPhaden (2010a,b).

The reversal of Atlantic Niño anomalies has also been linked to equatorial wave dynamics similar to those in the Pacific (Zebiak, 1993), and recharge-discharge of equatorial heat content could be important as well (Bunge & Clarke, 2009, Jansen, Dommenget, & Keenlyside, 2009). However, turbulent heat fluxes may play a dominant role in the decay of Atlantic Niño and Niña events once the coupled feedbacks weaken in boreal summer (Polo, Lazar, Rodriguez-Fonseca, & Mignot, 2015). A secondary role of ocean dynamics is supported by the character of the SST variability, which is largely consistent with an AR-1 process (Latif & Grötzner 2000; Nnamchi et al. 2016).

The mechanisms described above involve fluctuations in the wind field over the equatorial Atlantic. Part of these wind stress anomalies are excited by SST changes in the equatorial Atlantic itself, as part of the Bjerknes feedback. They can, however, also be generated remotely, e.g. as a response to ENSO (Latif & Grötzner, 2000; Handoh, Bigg, Matthews, & Stevens, 2006) or variations in the South Atlantic subtropical high (Polo et al., 2008b; Lübbecke, Burls, Reason, & McPhaden, 2014), or just occur as stochastic wind variability (Richter et al. 2014).

A novel mechanism for the generation of eastern equatorial SST variability, intrinsic to the ocean and independent of atmospheric forcing, has been brought forward by Brandt et al. (2011a). These authors argued that equatorial deep jets, vertically alternating deep zonal jets of short vertical wavelength, propagate their energy upwards and thereby affect SST.

In contrast to all the mechanisms involving ocean dynamics, Nnamchi et al. (2015, 2016) suggested that thermodynamic feedbacks excited by stochastic atmospheric perturbations (driving surface heat fluxes), can explain a large part of the SST variability in the eastern equatorial Atlantic. In response to this newly proposed thermodynamic mechanism, recent studies (Dippe, Greatbatch, & Ding, 2017; Jouanno, Hernandez, & Sanchez-Gomez, 2017) have addressed the relative importance of dynamic vs. thermodynamic processes. They conclude that dynamics and in particular the Bjerknes feedback are the dominant driver for Atlantic Niño events and that the strong warm bias that is present in the tropical Atlantic in most coupled climate models (see section on simulation) can lead to an overestimation of thermodynamical drivers in those models. However, heat flux variations can explain a significant amount of the SST variability in the eastern equatorial Atlantic.

IMPACTS

The Atlantic Niño strongly influences climate over the African and American continents, but it also has an important contribution to variability in the tropical Indian and Pacific Oceans, and over Europe.

Tropics

The impact on rainfall over the Gulf of Guinea (GG) is direct because the warm SSTs reduce low level wind flow inland, leading to positive precipitation anomalies over the GG and adjacent coastal region (see Rodríguez-Fonseca et al., 2011; 2015; Brandt et al, 2011b for a review). The opposite holds for cold SSTs over the GG. Over the West African region (WA), comprising the Guinea Coast and the Sahel, a monsoon develops during boreal summer, due to the strong sea level pressure gradient between the equatorial Atlantic Ocean and the continental regions. Research activity within the framework of the European Union program AMMA has generated an extensive literature on the influence of SSTs on West African Monsoon (WAM) variability (Fontaine & Janicot, 1996; Ward, 1998; Polo et al., 2008b; Kucharski et al., 2009; Losada et al., 2012a; Rodríguez-Fonseca et al., 2011; Mohino et al., 2011; Rodríguez-Fonseca et al., 2015; Brandt et al., 2011b). The Atlantic Niño peaks in boreal summer, when the monsoon season starts in West Africa (Sultan & Janicot, 2000), affecting the interannual variability of the whole WAM. Sensitivity experiments in which an Atlantic Niño is prescribed as the only external factor show how the positive phase of the Atlantic Niño produces a dipolar response over WA, with a reduction of rainfall over the Sahel and an increase over Guinea (Losada et al., 2010a). Although the impact of the Atlantic Niño on Guinean rainfall variability is stationary in time, its influence over the Sahel is not, with significant changes during the 20th century (see Fig. 1 in Losada et al., 2012a; Joly & Voldoire, 2010). Although it could be argued that this is be due to a relatively weak influence of the Atlantic Niño north of 10ºN (Giannini, Saravanan, & Chang, 2005), several studies point to the counteracting effect of concomitant SST anomalies in the tropical Pacific and Indian basins (Losada et al., 2012a; Mohino et al., 2011).

Precipitation variability in northeastern South America (NESA) is driven by the two leading modes of SST variability in the tropical belt: the Atlantic Niño (Zebiak, 1993) and ENSO (Philander, 1990). Nobre and Shukla (1996) illustrated how a warming of the equatorial Atlantic produces a delay in the northward migration of the ITCZ and, thus, changes in rainfall over NESA. Even though the Atlantic Niño mode peaks in boreal summer, i.e., after the rainy season in the NESA in MAM, related anomalies can already occur in boreal spring (e.g. Losada et al., 2010b; Mohino et al., 2011; Martín-Rey, Polo, Rodríguez-Fonseca, Losada, & Lazar, 2018). The position of the ITCZ plays an important role in the connection of rainfall anomalies over NESA and Sahel region (Rao, Giarolla, Kayano, & Franchito, 2006). When the ITCZ is displaced to the south (north), higher than normal rainfall occurs in NESA (the Sahel). This result has been highlighted in previous studies, which also deem the ITCZ as the main driver of the rainfall variability in NESA (Moura & Shukla, 1981; Sperber & Palmer, 1996; Uvo, Repelli, Zebiak, & Kushnir, 1998; Giannini, Saravanan, & Chang, 2004). SST anomalies over the tropical Atlantic can cause a strengthening (weakening) of the interhemispheric SST gradient, as shown in Harzallah, Rocha de Aragao, and Sadourny (1996), Chiang, Kushnir, and Zebiak (2000), and Cazes-Boezio, Robertson, and Mechoso (2003). These authors suggest that the dipole rainfall pattern over the NESA region is related to variations in the latitudinal position of the ITCZ that are in turn driven by the SST anomalies. The response to concomitant SST anomalies in the Pacific and Atlantic basins is of the same sign over NESA, producing an enhancement in the response when both basins act together (Torralba, Rodríguez-Fonseca, Mohino, & Losada, 2015).

Several studies have assessed the impact of the Atlantic Niño over the Indian Ocean. They suggest that anomalous convection over the equatorial Atlantic can lead to anomalous subsidence and reduced rainfall over the Indian monsoon region (Kucharski, Bracco, Yoo, & Molteni, 2007; 2008; Losada et al., 2010b; Losada & Rodríguez-Fonseca, 2016). This teleconnection is thought to be mediated by atmospheric equatorial Kelvin waves that arise from a Gill-type response (Gill, 1980) to the heating in the tropical Atlantic (Kucharski et al., 2009). Such remote influences, which can vary over time due to changes in the structure of the Atlantic Niño mode (Losada & Rodríguez-Fonseca, 2016), could also modulate SST variability in the Indian Ocean (Kajtar, Santoso, England, & Cai, 2017), modify the relationship between ENSO and the Indian monsoon during certain decades of the 20th Century (Kucharski et al., 2007), as well as the influence of the Atlantic Niño on the Pacific (Losada & Rodríguez-Fonseca, 2016).

Extratropics

The atmospheric diabatic heating associated with warmer conditions in the tropical Atlantic region in summer is able to alter upper level divergence and generate atmospheric Rossby waves that, via their interaction with the background flow, can influence extratropical regions, including the Mediterranean sector in early winter (Cassou, Deser, Terray, Hurrell, & Drévillon, 2004; García-Serrano, Losada, Rodríguez-Fonseca, & Polo, 2008). According to some studies, warming during the decaying phase of the Atlantic Niño can modify the atmospheric circulation over Europe through a circumglobal teleconnection pattern (Haarsma & Hazeleger, 2007; García-Serrano, Losada, & Rodríguez-Fonseca, 2011). Other studies highlight a possible contribution of equatorial Atlantic SST anomalies to the North Atlantic Oscillation (Drévillon, Cassou, & Terray, 2003; Peng, Robinson, Li, & Hoerling, 2005).

Losada, Rodríguez-Fonseca, and Kucharski (2012) and Mohino and Losada (2015) demonstrated that Atlantic Niños can increase precipitation over Europe and the Mediterranean Sea during the summer months through extratropical Rossby waves for present climate and future scenarios, respectively. These impacts, however, may be modulated by SST anomalies in the Indo-Pacific sector, causing a decrease of precipitation over the Iberian Peninsula and southern France during certain decades (Losada et al., 2012b).

INTER-BASIN TELECONNECTION WITH THE INDO-PACIFIC REGION

While the robust remote impact of ENSO on the tropical North Atlantic (TNA) has been widely recognized (Enfield & Mayer, 1997; Saravanan & Chang, 2000), during recent years a growing body of research has emphasized the equatorial interbasin teleconnection and the ability of the equatorial Atlantic interannual variability to influence ENSO (Rodríguez-Fonseca et al., 2009; Ding, Keenlyside, & Latif, 2012; Polo, Martín-Rey, Rodríguez-Fonseca, Kucharski, & Mechoso, 2015). In the following subsections, the two-way Atlantic Niño-ENSO relationship is described.

ENSO to Atlantic Niño teleconnection

Wang (2006) first reported a global tropical mode, detected in the observations from the 1970s, composed of SST anomalies of opposite sign in the tropical Atlantic and Pacific oceans. This inter-basin SST gradient implies a change in the global Walker circulation. Handoh, Matthews, Bigg, and Stevens (2006) and Handoh et al. (2006b) proposed an additional mechanism for the ENSO-Tropical Atlantic teleconnection via atmospheric waves. The Pacific-North America (PNA) and South America patterns (PSA), emanating from the tropical Pacific, can modify the Subtropical High Pressure Systems and consequently the surface winds and SST variability of the tropical Atlantic basin.

Based on the Walker teleconnection, Latif and Grötzner (2000) reported a positive connection between events, with ENSO driving a six months later Atlantic response through its impact on wind stress over the western equatorial Atlantic. This wind anomaly over the western equatorial Atlantic generates subsurface anomalies that propagate eastward as a Kelvin wave, setting up favorable conditions for the development of an Atlantic Niño event. In contrast, Münnich and Neelin (2005) found a negative correlation between these interannual events, with ENSO preceding Atlantic Niñas by only one season. These discrepancies in the ENSO forcing could be associated with the periods used in those studies (1903 to 1994 vs. 1982 to 2003) which feature different tropical Atlantic mean states (Tokinaga & Xie, 2011) and ENSO variance (Münnich & Neelin, 2005; Dong, Sutton, & Scaife, 2006). Furthermore, Chang, Fang, Saravanan, Ji, & Seidel (2006), based on GCM sensitivity experiments, investigated the contribution of thermodynamic versus dynamic processes in the tropical Atlantic response to ENSO. They concluded that, in the absence of ocean dynamics, the tropical Atlantic becomes warmer due to the tropospheric warming. However, when the dynamical influence of surface wind stress on the equatorial Atlantic is included, anomalous surface cooling develops and is amplified through the Bjerknes feedback (Chang et al., 2006). A different mechanism that could explain the inconsistent response of the equatorial Atlantic SST to El Niño events was investigated by Lübbecke and McPhaden (2012). According to their results, the strength of the ENSO impact on the TNA SST anomalies is crucial for the generation of the equatorial SST signal during the following summer. Strong positive TNA SST anomalies are accompanied by westerly wind anomalies north of the equator that excite downwelling Rossby waves. These Rossby waves are reflected at the western boundary as equatorial Kelvin waves that reach the eastern equatorial Atlantic during boreal summer, when they tend to damp the initial wind-induced equatorial cooling and sometimes even lead to a warming.

According to the atmospheric wave mechanism, strong and prolonged Pacific El Niño events induce changes in the Walker circulation and the PSA wave train that cause easterly wind anomalies in the western equatorial Atlantic (Rodrigues, Haarsma, Campos, & Ambrizzi, 2011; Lee, Enfield & Wang, 2008). These anomalous winds are able to activate the Bjerknes feedback and strengthen the cold tongue in boreal spring and summer. However, during short and weak Pacific El Niño events, westerly wind anomalies are present in the western equatorial Atlantic accompanied by warm anomalies in the eastern equatorial and tropical South Atlantic. Consequently, a positive phase of the South Atlantic subtropical dipole (SASD) develops during boreal winter (Rodrigues et al., 2011). The connection between ENSO and the SASD has been further investigated by Rodrigues, Campos, and Haarsma (2015) who showed that central Pacific ENSO events are linked to the SASD via the PSA and associated variations in the South Atlantic subtropical High. Eastern Pacific ENSO events, on the other hand, do not show this connection to the SASD.

In summary, while the TNA consistently warms in response to an El Niño event in the Pacific, the response in the eastern equatorial Atlantic is less robust, owing to different competing mechanisms and modulations on multi-decadal time scales. These fluctuations in the ENSO-TA connection have been discussed in the literature during the past decades and could be considered the result of inter-decadal climate modulations. In this sense, Chiang et al. (2000) indicated that the boreal spring Pacific and Atlantic ITCZ were connected at the beginning and end of the 20th century, probably associated with warmer conditions in the tropical Pacific. Moreover, the ENSO characteristics and impacts have been modified and reinforced during certain decades (Fedorov & Philander, 2000; Dong et al., 2006; López-Parages & Rodríguez-Fonseca, 2012). Finally, preconditioning of the tropical Atlantic mean state and variability seem to be also a key factor to mediate the ENSO impact on inter-annual tropical Atlantic variability (Chang et al., 2006; Martín-Rey et al., 2018).

Atlantic Niño to ENSO teleconnection

As stated in the section on impacts, the Atlantic Niño has been found to directly influence Guinean rainfall variability, thus affecting the diabatic heating in the atmospheric column. The upper level divergence in the western equatorial Atlantic could potentially affect the Pacific through the Walker circulation. The influence of the Atlantic Niño on the Pacific has been demonstrated using sensitivity experiments in which observations were prescribed over the Atlantic and a free coupled ocean model was run over the tropical Indo-Pacific basin (Rodríguez-Fonseca et al. 2009; Ding et al. 2012, Polo et al., 2015a). The results suggest that Atlantic Niños (Niñas) lead to easterly (westerly) surface wind anomalies over the western equatorial Pacific, triggering upwelling (downwelling) equatorial Kelvin waves and the development of a Pacific La Niña (El Niño) event (Rodríguez-Fonseca et al., 2009, Losada et al., 2010b, Polo et al., 2015a). The dynamics involved in this connection are consistent with the Recharge Oscillator model (Jin, 1997), as demonstrated by Jansen et al. (2009).

The seasonality of Atlantic and Pacific Niños plays an important role in the connection: the 6-months lag between the peak of equatorial Atlantic and Pacific SST variability allows the relatively weak Atlantic Niño to kick the equatorial Pacific during a time when SSTs are close to neutral there. Thus the equatorial Atlantic may play an important role in the development of ENSO. Consistently, several studies have demonstrated that the skill in ENSO forecast is enhanced when the information of the tropical Atlantic SSTs is included (Frauen & Dommenget, 2012; Dayan, Vialard, Izumo, & Lengaigne, 2014; Keenlyside, Ding, & Latif, 2013).

MULTI-DECADAL MODULATIONS IN THE ATLANTIC NIÑO VARIABILITY AND ITS TELECONNECTIONS

The Atlantic-Pacific connection has been shown to be stronger during certain decades of the 20th century (Martín-Rey, Polo, Rodríguez-Fonseca, & Kucharski, 2012; Martín-Rey, Rodríguez-Fonseca, Polo, & Kucharski, 2014; Martín-Rey, Rodríguez-Fonseca, & Polo, 2015). Multi-decadal changes in the background state of the ocean (Martín-Rey et al., 2014; 2018) and in the spatial configuration of the Atlantic Niño pattern (Losada & Rodríguez-Fonseca, 2016) are possible reasons for this non-stationary behavior. Here we review literature on multi-decadal modulation of the equatorial Atlantic and follow with a discussion of the caveats.

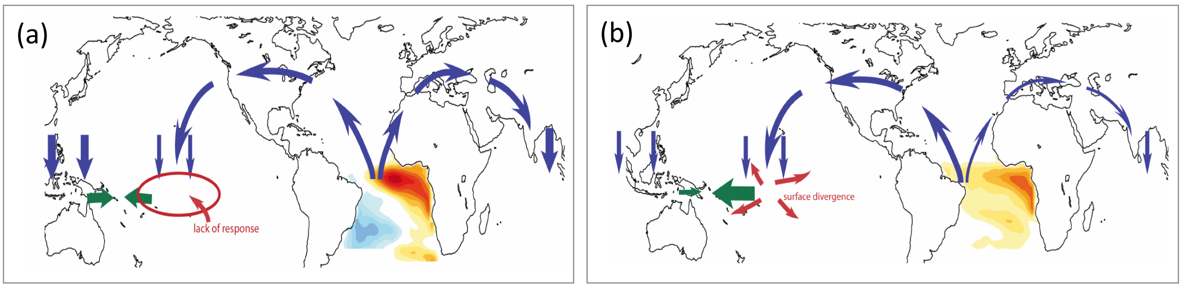


Figure 3: Decadal change of the Atlantic Niño pattern and its impact. *SST anomalies of the Atlantic Niño pattern during boreal summer before (a) and after (b) the 1970s and a schematic representation of the respective impact on the Pacific and Indian Ocean.*

Regarding the changes of the Atlantic Niño, it has been shown that different spatial patterns emerge depending on the time period (Fig. 3) together with changes in its periodicity, explained variance, and associated impacts (Losada & Rodríguez-Fonseca, 2016; Martín-Rey et al., 2018; Nnamchi et al. 2011). Before the 1970s, the Atlantic Niño presents positive SST anomalies restricted to the eastern equatorial Atlantic and an anomalous cooling in the western South Tropical Atlantic (STA, Fig. 3a). This dipolar-like structure is consistent with the boreal summer footprint of the SAOD (Nnamchi et al. 2011; 2016). However, after the 1970s the Atlantic Nino features more of a basin-wide pattern, with positive anomalies covering the entire equatorial Atlantic (Fig. 3b). The connection to the STA is somewhat controversial with some analysis identifying a robust and stationary link (Nnamchi et al. 2016), and other finding that the link disappears (Nnamchi et al. 2011; Martin-Rey et al. 2018). These discrepancies appear to result from the different filtering, considered domain and statistical analysis applied.

The westward extension of the warm tongue in the Atlantic Niño spatial configuration after the 1970s is responsible for the impact over the Indo-Pacific region and the associated shift in deep convection (Losada and Rodríguez-Fonseca, 2016). The authors pointed to the Indian sector response to the Atlantic Niño as a key factor modulating the Atlantic Niño-ENSO teleconnection: before the 1970s, the subsidence over the Maritime Continent produced by the Atlantic Niño is strong enough to counteract the impact of the Pacific Walker circulation on surface winds, thus precluding the Atlantic Niño-ENSO teleconnection to occur.

Martín-Rey et al. (2014), using observations and partially-coupled simulations, found evidence that the Atlantic-Pacific Niños connection shows up as an air-sea coupled mode of tropical variability during certain decades (Fig. 4). In some periods (blue dots in Fig. 4), associated with Atlantic Nino events, there is more anomalous precipitation over the western Atlantic which induce low-level divergence over the Pacific (following the mechanism described by Rodríguez-Fonseca et al. (2009) and Polo et al. (2015a)). The emergence of this connection was suggested to coincide with negative phases of the Atlantic Multidecadal Oscillation (AMO; Kushnir, 1994; Kerr, 2000), a basinwide low-frequency SST variability pattern in the Atlantic that can be identified in the 20th century instrumental records.

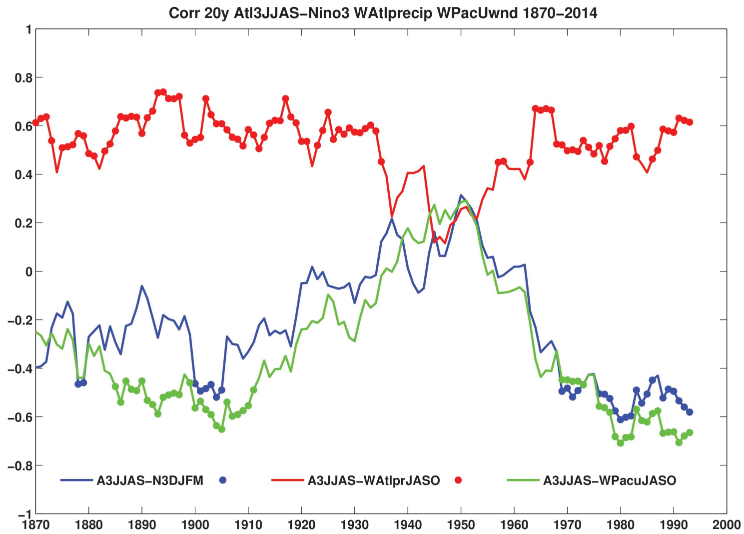


Figure 4: Decadal modulation of Atlantic – Pacific relationship. *Running correlation of 20-yr windows between the boreal summer (JJAS) SST anomalies in Atl3 region [20ºW-0ºE, 3ºN-3ºS] and the following boreal winter (DJFM) SST anomalies in Niño3 [150ºW-90ºW, 5ºN-5ºS] (blue line), boreal summer (JASO) precipitation in western equatorial Atlantic [70ºW-35ºW, 5ºN-5ºS] (red line) and boreal summer (JASO) zonal surface wind in western equatorial Pacific [140ºE-180º, 5ºN-5ºS] (green line). Dots denoted significant correlations according to a t-test at 95% confidence level.*

In fact, the Atlantic Niño spatial configuration itself may be modulated by the AMO. The changes in the TA modes of variability during positive and negative AMO phases was recently studied by Martín-Rey et al. (2018). The modifications in the Atlantic Niño were in agreement with those reported by Losada and Rodríguez-Fonseca (2016). A perturbation in the Atlantic Subtropical Highs during the preceding winter and spring, associated with the AMO, could be responsible for the changes in the mode. The mean state variations related to a shallower thermocline during negative AMO periods were responsible for an increased SST variability in the eastern equatorial Atlantic. Consequently, during negative AMO phases, a hitherto undocumented SST pattern, exhibiting maximum loadings in the equatorial Atlantic, appears as a second variability mode (Martín-Rey et al. 2018). It is characterized by an anomalous warm (cold) horse-shoe surrounding an eastern equatorial cooling (warming) and appears to be remotely forced by ENSO.

The above-mentioned studies suggest the modulation by low-frequency variability modes (i.e. the AMO) as a possible explanation for the discrepancies found in the Atlantic Niño structure and teleconnections. Changes in the global background state and the alteration of atmospheric teleconnections could cause the diversity of Atlantic Niño patterns and impacts along the observational record. Note, however, that these results should be interpreted with caution. On the one hand, there is measurement uncertainty, particularly for data from the pre-satellite era, and due to the fact that only 2.5 cycles of the AMO are currently available. On the other hand, the AMO might have a direct influence on the Pacific and Indian Oceans, and thus perceived changes in the equatorial Atlantic-Indo Pacific teleconnection might be due to this.

In addition to the multidecadal modulations discussed above, the Atlantic Niño mode is expected to change as a result of global warming, but large uncertainties exist. Tokinaga and Xie (2011) found that SST variability in the eastern equatorial Atlantic weakened over the time period 1950 to 2009, and they attribute this to a general warming of the basin that is most pronounced in the cold tongue region in boreal summer. Their dynamical explanation also involves a weakening of the trade winds, which deepens the thermocline. In contrast, Servain, Caniaux, Kouadio, McPhaden, and Araujo (2014) reported a strengthening of the trade winds over the whole tropical Atlantic (30ºN to 20ºS, 60ºW to 15ºE) for the time period 1964 to 2012, which is most pronounced in the coastal upwelling regions. It should be noted that Tokinaga and Xie (2011) focused on trends in boreal summer while Servain et al. (2014) did not stratify their analysis. Further contributions to the diverging trend estimates may come from differences in the analysis periods, the trend estimation techniques, and, of course, the underlying datasets. While Servain et al. (2014) based their analysis on the SERV pseudo wind stress, they compared several wind products, among them the WASWinds from Tokinaga and Xie (2011). None of them showed a decrease for the basin-wide average for 1964 to 2012, but there is a large range between the long-term trends of the different wind products with SERV winds showing a trend three times stronger than WASWinds. Also, regional patterns can differ a lot between different time periods. Given the difficulty of consistently measuring ocean surface wind speed over long periods and given the pronounced multidecadal variability in the region, continued monitoring will be crucial to obtain confident trend estimates. Lübbecke, Durgadoo, and Biastoch (2015) proposed that increased inflow of warm Indian Ocean water through Agulhas leakage might have contributed to the tropical Atlantic warming, even in the light of stronger trade winds.

Under global warming conditions, the strength of the Atlantic Meridional Overturning Circulation (AMOC) is hypothesized to decrease. Note that the AMO, whose influence on the Atlantic Niño has been discussed above, has actually been suggested to be a fingerprint of the AMOC (Latif et al., 2004). Water hosing experiments that mimic the increased freshwater influx due to melting Greenland ice sheets obtain an equilibrium SST response reminiscent of the negative phase of the AMO (Vellinga & Wood, 2002; Knight, Allan, Folland, Vellinga, & Mann, 2005; Zhang & Delworth, 2005). These simulations suggest that the circulation and temperature of the tropical Atlantic will react to those changes (e.g. Haarsma, Campos, Hazeleger, & Severijns 2008; Chang et al., 2008), which will have consequences for the Atlantic Niño mode (Polo, Dong, & Sutton, 2013). In the model simulations adjustment, there is a lag of several years between the slowdown of the AMOC and the mean state changes in the tropical Atlantic (e.g. Chang et al., 2008; Wen, Chang, & Saravanan, 2011). This might allow to monitor changes in tropical Atlantic variability after an observed reduction of the AMOC in the recent decades (Robson, Hodson, Hawkins, & Sutton, 2014; Jackson, Peterson, Roberts, & Woods, 2016). Finally, regarding the teleconnections of the Atlantic Niño under global warming conditions, Mohino and Losada (2015) found a weakening in the impact on the Asian monsoon, together with an eastward shift in the Rossby waves triggered by the warming of the tropical Atlantic that would change the extratropical impacts of the Atlantic Niño mode.

Understanding the origins of the non-stationarities of the Atlantic Niño remains a challenge. The first and most important obstacle is the short available observational period (~100 years). Previous studies, focused in the equatorial Pacific, showed that tropical variability is subject to substantial internal variability (Wittenberg, 2009). Thus, in order to fully characterize the variability of the system, multi-millennial time series might be required. This constraint implies that the observed changes in the Atlantic Niño pattern could be just due to internal variability.

SIMULATION OF TROPICAL ATLANTIC CLIMATE AND ATLANTIC NIÑO VARIABILITY

Essentially all current state-of-the-art general circulation models (GCMs) exhibit large errors in simulating the mean climate of the tropical Atlantic. In observations SSTs are warmest on the western side of the basin, and there is a pronounced tongue of cold water in the east that extends southeast towards the Benguela region. The precipitation and surface wind patterns are relatively closely related to the SST: the Atlantic ITCZ, a rain band extending from the North Brazilian coast to the African coast, is roughly collocated with the warmest SST and occurs in a zone of surface wind convergence. In contrast, climate models tend to simulate the warmest SST in the eastern equatorial Atlantic with corresponding errors in rainfall and surface winds (Richter & Xie, 2008). Seasonally, the error in equatorial SST is largest in boreal summer (Fig. 5a) and reflects the poor ability of climate models to capture the development of the equatorial cold tongue (Fig.5b,c). The error has been attributed to erroneously weak zonal trade winds in boreal spring that are amplified by the Bjerknes positive feedback, and lead to a severe underestimation of the boreal summer equatorial cold tongue and delay in its onset by 1-2 months (Richter & Xie, 2008). The trade wind error is apparent in stand-alone atmospheric model simulations and appears related to the representation of tropical convection and vertical mixing in the lower-troposphere (Richter, Xie, Behera, Doi, & Masumoto, 2012; Richter, Xie, Wittenberg, & Masumoto, 2012; Zermeño-Diaz & Zhang, 2013). These errors can be reduced by changes in convection schemes and model resolution (Tozuka, Doi, Miyasaka, Keenlyside, & Yamagata, 2011, Harlaß, Latif, & Park, 2015; 2017) and have also been linked to misrepresentation of oceanic processes such as vertical mixing (Hazeleger & Harsma, 2005; Jochum et al., 2012; Song, Lee, Wang, Kirtman, & Qiao, 2015).

The Angola-Benguela upwelling area (ABA) is dynamically linked to the equatorial Atlantic cold tongue (as discussed in the first section) and is marked by similar, albeit more severe, warm biases in GCMs (Fig. 5a). Some studies have indeed found evidence for a dynamical link between equatorial and ABA biases (Richter et al., 2012b; Xu, Chang, Richter, & Kim, 2014). There are other important factors, however, including an erroneous southward displacement of the Angola-Benguela Frontal zone (Xu, Li, Patricola, & Chang, 2014; Koseki et al. 2017), a region characterized by a sharp meridional SST gradient, and the common inability of GCMs to reproduce the persistent low-level cloud cover typically observed in the region (Zuidema et al., 2016, and references therein). Richter (2015) provides a full review of GCM errors in this as well as other coastal upwelling regions.

The Atlantic Niño peaks in boreal summer, exactly the season when climate models exhibit the largest climatological errors in the tropical Atlantic. Nevertheless, some climate models are able to simulate Atlantic Niño variability exhibiting similarities to observations in terms of SST spatial structure, amplitude, and seasonality (Richter et al., 2012a; Nnamchi et al., 2015), as well as oceanic upwelling (Polo et al., 2015b). In some of these models SST variability is overestimated, which Yang, Xie, Wu, Kosaka, and Li (2017) have linked to excessive spring SST variability in the northern equatorial Atlantic, triggering the Bjerknes feedback. As mentioned above, thermodynamic ocean-atmosphere interaction is able to explain the first order properties of south tropical Atlantic variability. This type of variability appears to be dominant in climate models from the earlier Coupled Model Intercomparison Project Phase 3 (CMIP3), and may explain why these models simulate Atlantic Niño variability poorly (Breugem, Hazeleger, & Haarsma, 2008). Nevertheless, even some of these models simulate variability with amplitude similar to observations (Nnamchi et al., 2015), despite not even representing the Bjerknes positive feedback (Deppenmeier et al., 2016) or ocean dynamics (Nnamchi et al., 2015). The erroneously deep thermocline and insufficient upwelling (Richter & Xie, 2008) likely contribute to the diminished role of ocean dynamical processes in these models (Deppenmeier et al., 2016; Dippe et al., 2017).

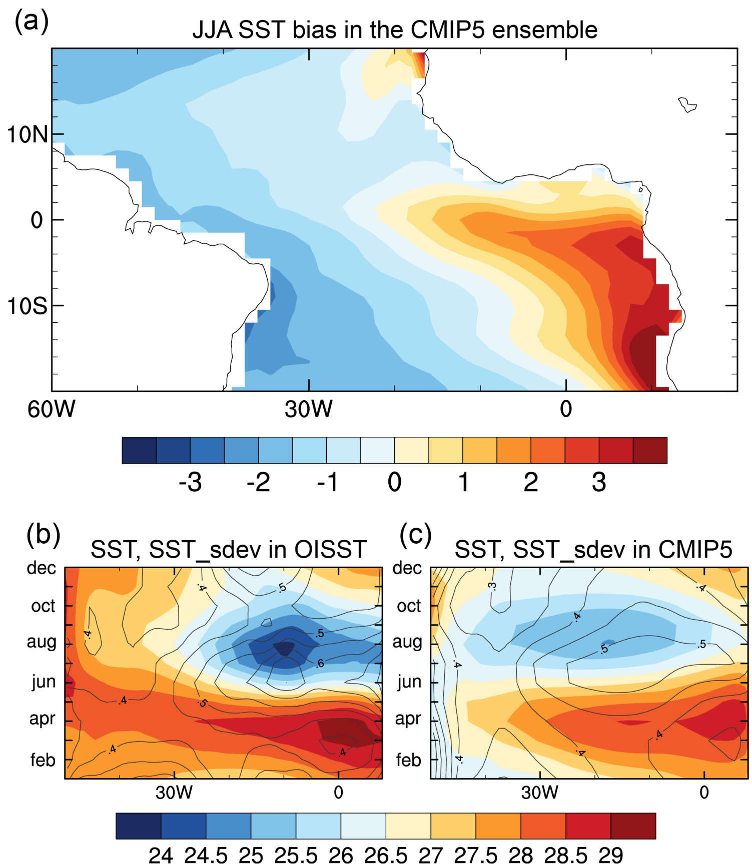


Figure 5: Simulation of tropical Atlantic SST in climate models. *(a) SST bias (K) in an ensemble mean of models from the CMIP5 experiment piControl. The reference data is NOAA Optimum Interpolation (OI) SST for the period 1982-2016. (b) and (c) Longitude-time sections of SST (degC; shading) and its standard deviation (K; contours), averaged between 3S-3N for OISST (b) and CMIP5 (c).*

The simulation of Atlantic Niño variability is improved in the more recent CMIP5 models. In particular, models that simulate a more realistic mean state, also simulate a leading mode of variability in boreal summer that closely matches the observed pattern (Fig. 1) with a similar explained variance (Richter et al., 2012a). In models with larger errors, the Atlantic Niño may appear as the second mode of variability explaining less variance than observed. The variability tends to peak in July and August (i.e., approximately 1-2 months later than observed), and also the relation to westerly wind anomalies in boreal spring is mostly inconsistent with observations. In models, wind in the western Atlantic tends to precede SST anomalies in the east by 2-3 months, while in observations the lag is typically only 1 month. These differences are probably related to the delay in the northward shift of the Atlantic ITCZ in climate models and in the onset of the equatorial cold tongue.

Seasonal prediction of equatorial Atlantic variability continues to pose a challenge. An earlier intercomparison study by Stockdale, Balmaseda, and Vidard (2006) found that dynamical prediction models struggled to match persistence forecasts and were often outperformed by statistical models. A recent study by Richter, Doi, Behera, & Keenlyside (2017) suggests that the situation has not changed fundamentally over the intervening decade. Skillful seasonal dynamical prediction relies on knowledge of the initial state, deterministic evolution of this initial state on seasonal time scales (i.e., the existence of a predictable signal), and a numerical model that can adequately represent the relevant dynamics. Most GCMs suffer from severe mean state biases in the tropical Atlantic and it may therefore seem obvious that these biases are a major reason for the poor prediction skill in the equatorial Atlantic. No study to date, however, has conclusively shown this and it is therefore possible that the poor prediction skill of current models is due to insufficient knowledge of the initial state or inherent predictability limits. The inherent predictability depends, to a large extent, on the strength of coupled air-sea feedbacks (in particular the Bjerknes feedback) governing the evolution of the system on seasonal timescales. Several observational and modeling studies suggest that the Bjerknes feedback is active in the equatorial Atlantic but significantly weaker than in the Pacific (Keenlyside & Latif, 2007; Jansen et al., 2009; Lübbecke and McPhaden, 2013; Deppenmeier et al., 2016). In this context it is also noteworthy that the idealized model of Zebiak and Cane (1987) did not produce a self-sustained oscillation in the equatorial Atlantic (Zebiak, 1993), in contrast to the Pacific. The relatively weak coupling strength in the equatorial Atlantic would suggest lower predictability than in the Pacific. Additionally, there is evidence that internal atmospheric processes play a relatively large role in the variability of equatorial Atlantic surface winds (Richter et al., 2014) and that coupled feedbacks are cut short by the strong seasonal phase locking of variability due to the annual migration of the ITCZ (Richter et al., 2017a). Considering the very modest improvement in prediction skill over the last decade despite continued model development, dramatic prediction skill improvement through bias reduction does not seem very likely, though some improvement should be possible.

Regarding the simulation of the Atlantic-Pacific teleconnection by state of the art coupled models, Ott, Romberg, and Jakobeit (2015) analyzed the two-way Atlantic Pacific connection in pre-industrial control simulations and found that the reliability of the teleconnection depends on the bias in the Benguela upwelling region and the equatorial Pacific.

Conclusion

This paper reviews interannual SST variability in the tropical Atlantic Ocean. This variability occurs predominantly in the eastern equatorial basin and along the southwestern African coast and is phase-locked to boreal summer. We argue that most of the climate modes that have been associated with this pattern actually describe the same mode of variability and we suggest to use the term "Atlantic Niño" mode as this name captures the similarity to El Niño in the Pacific. The Atlantic Niño is closely connected to the Benguela Niño, which is characterized by SST anomalies off Angola and Namibia and the South Atlantic Ocean Dipole, which has been defined by opposite SST anomalies in the eastern equatorial and southwestern subtropical Atlantic. Further research is needed to fully resolve the question of whether these modes are all part of one phenomenon.

Even though there are differences between the Pacific and Atlantic Niño phenomena, they share many characteristics and also the dominant positive feedback mechanism, namely the Bjerknes feedback. Other processes have been suggested to contribute to the generation of Atlantic Niño events: off-equatorial Rossby waves being reflected into equatorial Kelvin waves at the western boundary, meridional advection of temperature anomalies, net surface heat flux and forcing from the deep ocean by equatorial deep jets. These might be thought to give rise to different flavors of Atlantic Niño. The Atlantic Niño mode and Pacific ENSO interact with each other via changes in the Walker circulation and atmospheric wave trains. While the influence from the equatorial Pacific onto the equatorial Atlantic is not straightforward due to a number of competing feedbacks, Atlantic Niño events tend to favor the development of Pacific La Niña events and vice versa for opposite sign of the anomalies during certain time periods.

Atlantic Niño and Niña events exert a strong influence on precipitation over the adjacent continents. Warm events are associated with reduced rainfall over the Sahel and increased rainfall over the coast of Guinea as well as, via the influence on the ITCZ, over Northeast Brazil. It is important to note that the characteristics of the Atlantic Niño mode and its impacts and teleconnections are not stationary in time. Multi-decadal modulations appear related to the phase of the AMO and are potentially influenced by changes in the AMOC. This non-stationarity can have important implications in the context of the seasonal to decadal prediction, and its consideration in forecast systems may lead to their improvement.

Most current climate models suffer from a mean-state warm bias in the eastern equatorial and southeastern tropical Atlantic, and a cold bias in the western equatorial and northern tropical Atlantic. These biases affect the ability of models to realistically simulate equatorial Atlantic variability but there are models that produce relatively realistic variability patterns despite mean state biases. While tropical Atlantic biases have been a long-standing problem, there has been some moderate progress from CMIP3 to CMIP5 and recent studies show some promising approaches to further reduce mean state biases. It is not clear, however, to what extent bias reduction will translate into improved prediction skill because internal variability of the system may be another important limiting factor.

Despite many improvements in our understanding of tropical Atlantic SST variability, a number of open questions remain. Assessing all the factors that contribute to the generation of warm and cold events in the eastern equatorial Atlantic, understanding the multidecadal modulation and longer term trends of the Atlantic Niño mode, realistically simulating the tropical Atlantic mean state and variability and providing predictions that will benefit countries impacted by precipitation changes associated with this variability are and will be subjects of tropical Atlantic climate research.

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