Ocean-atmosphere interactions in the tropical Atlantic seasonal cycle and multidecadal variability of ENSO

Lander R. Crespo

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Abstract

The interaction between the ocean and atmosphere drives changes in the climate system in a wide variety of timescales. The strong annual cycle in the equatorial Atlantic, especially over the east, has been object of extensive research but the role of ocean-atmosphere interactions in driving the seasonal cycle remains to be fully understood in this region. The west African monsoon and the Atlantic cold tongue are the main phenomena controlling the seasonal variability in the equatorial Atlantic and a better understanding of their interaction is crucial for a complete comprehension of the dynamics of the annual cycle. Ocean atmosphere interactions are the main driver of ENSO, which is the leading mode of ocean-atmosphere variability at interannual timescales in the tropics. ENSO properties have experienced large changes in the last few decades but the drivers behind those changes are still in debate. The three studies presented in this thesis are based in climate model simulations. In the first and second papers the atmosphere and ocean components of NorESM model are used to investigate the dynamics of the seasonal cycle in the equatorial Atlantic. The third paper focuses on the identification of multidecadal modulation of ENSO properties by means of a strongly simplified model: the conceptual recharge oscillator model.

The first part of this thesis presents an in-depth study of the mechanisms of the seasonal cycle in the equatorial Atlantic with special focus on the quantification of the role of the coupling between the ocean and the atmosphere. My results show that thermodynamic coupling is the main driver of the seasonal cycle in the western equatorial Atlantic and indicate that the dynamical Bjerknes feedback plays a secondary role. In the east, ocean dynamics and the monsoon are the main drivers of the seasonal cycle in the ocean and atmosphere, respectively, with

ocean-atmosphere interactions contributing to the amplification of the annual cycle.

In the second part of this thesis, I study the changes in observed ENSO properties at multidecadal timescales. The large observed changes in ENSO in the recent decades are reproduced with a conceptual model based on the recharge and discharge of the Pacific equatorial upper ocean heat content. This indicates that dynamic coupling is the main driver of ENSO in the last decades with the thermocline feedback being the mechanism responsible of the amplification of the SST anomalies in the eastern equatorial Pacific.

List of scientific papers

Paper I: **The role of sea surface temperature in the atmospheric seasonal cycle of the equatorial Atlantic**
Lander R. Crespo, Noel Keenlyside and Shunya Koseki (2018) *published online in Climate Dynamics*, doi.org/10.1007/s00382-018-4489-4

Paper II: **What drives the seasonal cycle of the sea surface temperature in the equatorial Atlantic?**
Lander R. Crespo, Shunya Koseki, Noel Keenlyside and Yanchun He. *Manuscript in preparation.*

Paper III: **Multidecadal variability of ENSO in a recharge oscillator framework** Lander R. Crespo, Belen Rodríguez-Fonseca, Irene Polo and Noel Keenlyside. *Manuscript in preparation.*

Contents

1. Scientific background

This thesis investigates the dynamics of the seasonal cycle of the tropical Atlantic and the multi-decadal modulation of tropical Pacific ENSO. I will first introduce several studies on the seasonal cycle of the tropical Atlantic from an atmospheric (Section 1.1) and oceanic (Section 1.2) point of view, and review the relevance of the atmosphere-ocean coupling to the determination of the seasonal cycle. In Section 1.3, I will present observed changes of ENSO properties at decadal to multidecadal timescales and the drivers of those changes. I will also introduce the conceptual recharge oscillator model used in Paper III for simulating ENSO. The recharge oscillator is broadly considered the conceptual model that reproduces better ENSO properties and variability in the last decades.

1.1. The atmospheric seasonal cycle in the tropical Atlantic

In a large part of the global tropical oceans, the seasonal cycle in SST and rainfall distribution is determined by the seasonal cycle of the insolation. Both SST and rainfall are approximately symmetric about the equator, consistent with solar radiation distribution (Xie 1994). On the seasonal timescale, the location of maximum rainfall in these regions moves back and forth across the equator following the seasonal march of the sun. Over the eastern tropical Pacific and Atlantic, the seasonal cycle of the SST, low-level atmospheric circulation and deep convection show a strong annual cycle. This is in contrast to the weak semiannual cycle of the insolation in the top of the atmosphere (Wallace et al. 1989; Mitchell and Wallace 1992; Giese and Carton 1994). This mismatch between the semiannual cycle of the insolation and the annual cycle in SST might be an indicator of the important role of ocean-atmosphere interactions involving ocean adjustment processes. The tropical Pacific and Atlantic share many common features in their climatology, including the northward–displaced intertropical convergence zone (ITCZ), the prevailing easterly winds, the associated east-west gradient in the thermocline depth, and an equatorial cold tongue in the eastern side of the basin present from July to September (Mitchell and Wallace 1992).

The tropical Pacific and Atlantic also present some remarkable differences of relevance for the determination of the climate variability. While in the eastern equatorial Pacific the seasonal cycle and the interannual variability have a similar strength, in the eastern tropical Atlantic the SST variability is much stronger in seasonal timescales with respect to interannual timescales (Xie and Carton 2013). The seasonal cycle in the ocean and the atmosphere, despite many similarities between both basins, is driven by different mechanisms. The thermocline plays a crucial role in the determination of the annual cycle in the Atlantic while in the Pacific it is only relevant at interannual timescales (Ding et al. 2009). In the Atlantic, as a consequence of the shape of the continents, land-atmosphere interactions can also play a determinant role in the determination of the seasonal cycle. A vast number of studies have been carried out on the role of the ocean-atmosphere interactions in the tropical Pacific, due to the large impact of ENSO on the global climate, but many aspects of the ocean-atmosphere interactions in the tropical Atlantic basin and their role in the seasonal cycle still remain to be investigated. In the following, I will describe the observed seasonal cycle in the equatorial Atlantic and provide some theories about the main drivers and dynamical mechanisms involved in the determination of the atmospheric seasonal cycle.

1.1.1 The observed seasonal cycle in the atmosphere

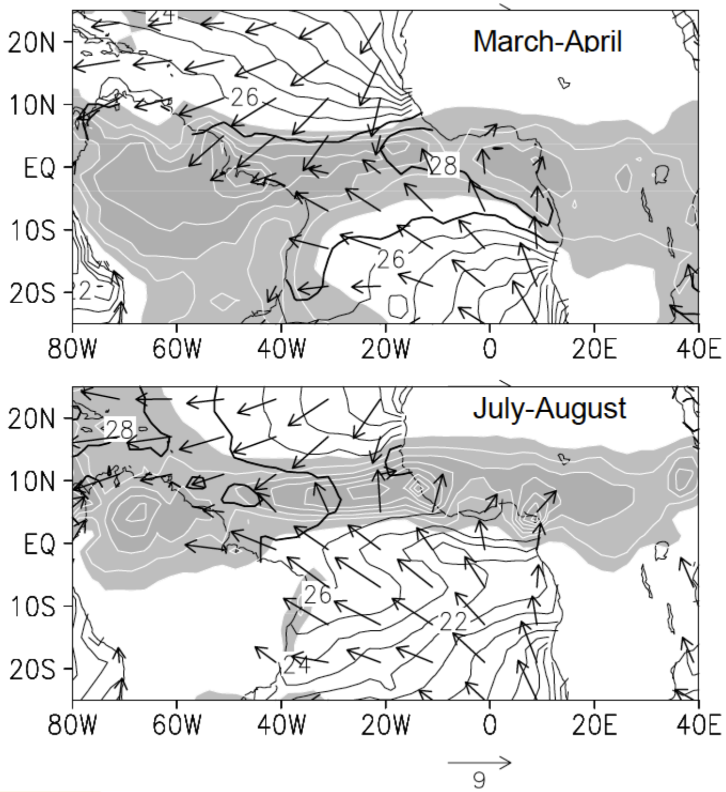

Fig. 1. Climatological distributions of rainfall (light shade > 2mm/day; dark shade > 6mm/day), SST (contours in ºC) and surface wind velocity (vectors in m/s) for March-April (upper panel) and July-August (lower panel), based on the Climate Prediction Center Merged Analysis of Precipitation (CMAP) and Comprehensive Ocean-Atmospheric Data Set (COADS). From (Xie and Carton, 2013).

The ITCZ exhibits large seasonal variations over the equatorial Atlantic with a clear distinction between a continental and an oceanic ITCZ. Over land, it nearly follows the seasonal march of the sun reaching its northernmost (southernmost) point in July to September (December to February) (Mitchell and Wallace, 1992). Over the ocean, the position of the ITCZ is tightly coupled to the SST patterns, with the rainband constrained to a band of warm SSTs (above 26ºC) (Xie and Carton 2013). In spring, the ITCZ is located close to the equator where the SSTs are maximal (see Fig. 1 upper panel). In May, when the equatorial Atlantic cold tongue (ACT) starts developing, the ITCZ migrates northward following the warm SSTs. Contemporaneously, the summer monsoon develops over Central America and West Africa pushing the oceanic ITCZ further north away from the equator. The ITCZ stays north of the equator until September when it reaches its northernmost point and starts slowly swinging back southward (see Fig. 1 lower panel).

The seasonal cycle in the eastern equatorial Pacific and Atlantic presents many similarities, with SST, rainfall and surface winds exhibiting strong annual harmonics. The SST is maximal in spring when the ITCZ is closer to the equator, the southeast trade winds are weakest, the thermocline is deepest in the east and the insolation is maximal. In late spring, with the ITCZ moving northward following the seasonal march of the sun, the southeasterly winds intensify at the equator resulting in a shallower thermocline in the east. The combined effect of stronger evaporation, vertical mixing and intensified upwelling (Xie 1994) produces a rapid cooling in the SST that reaches its minimum in July in the Gulf of Guinea. Unlike in the Pacific, the annual cycle of the SST in the eastern equatorial Atlantic is highly asymmetric (see Fig. 2). The SST cools rapidly in only three months (from May to July) and warms slowly during the rest of the year reaching its maximum in April (see lower plot in the left panel in Fig. 2). The rapid cooling of the ocean is generally attributed to the sudden onset of the west African summer monsoon (WAM) and the associated abrupt intensification of the southerly winds in May in the Gulf of Guinea (see central plot in the left panel in Fig. 2). The intensified southerly winds produce upwelling (downwelling) slightly south (north) of the equator and enhance the evaporation resulting in a net cooling of the equatorial ocean (Philander and Pacanowski 1981). Over the cold tongue, the surface winds decelerate and accelerate over the warmer waters located north of the equator (Xie and Carton 2013) following the pressure adjustment mechanism (Lindzen and Nigam 1987). The zonal wind variations also play an important role in cooling the equatorial Atlantic SST by shoaling the thermocline in the east and inducing upwelling (Houghton 1983).

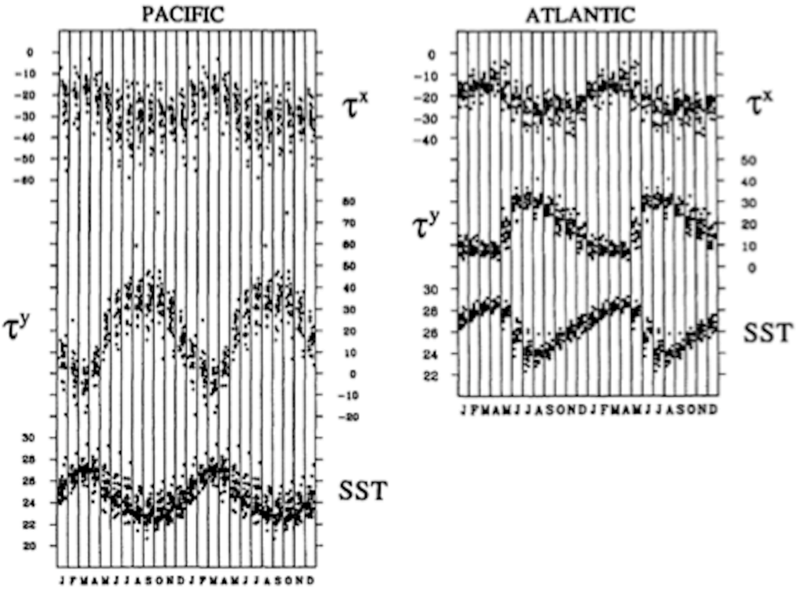

Fig. 2 (Left panel) Scatter diagram of the observed zonal wind stress to the west (4ºN-4ºS, 130º-110ºW), the meridional wind stress to the north (8ºN-0º, 120º-100ºW) of the Pacific cold tongue, and the cold tongue SST (ºC; 4ºN-4ºS, 104º-86ºW). (right panel) same as in the left panel but for the zonal wind stress in the western equatorial Atlantic (4ºN-4ºS, 34º-26ºW), the meridional wind stress in the Gulf of Guinea (6ºN-0º, 16ºW-4ºE), and the cold tongue SST (4ºN-4ºS, 16ºW-4ºE). Adopted from Mitchell and Wallace (1992).

The greatest particularity of the eastern equatorial Atlantic basin with respect to the Pacific is the asymmetry in the land distribution relative to the equator. The shape of the west African continent is a major driver of the observed cross-equatorial monsoonal surface winds over the equatorial Atlantic Ocean (Philander et al. 1996). The land surface temperature north of the Gulf of Guinea is much higher than the ocean surface temperature, leading to a minimum in surface pressure displaced northward over land instead of at the equator and hence, prevailing southerlies towards the landmass. These winds contribute to cool down the SST in the region, via evaporation and equatorial upwelling in the Gulf of Guinea, intensifying the land-ocean temperature contrast and pushing the ITCZ farther northward into the land (Giordani et al. 2013). The ITCZ is usually located over the warmest surface waters (above 26ºC) (Sabin et al. 2013; Roxy 2014; Koseki and Bhatt 2018) so these climatic asymmetries must be a consequence of land-sea contrast relative to the equator.

The dynamics of the seasonal cycle in the western equatorial Atlantic is significantly different from the eastern side. The seasonal north-south movements of the ITCZ are associated with seasonal changes in SST and the seasonality of the SST is a response of the wind changes that are largely controlled by the position of the ITCZ (Chang and Philander 1994). In that region, where the thermocline is deep, SST changes are controlled by the local ocean-atmosphere heat fluxes across the ocean surface, mainly by insolation and evaporation.

1.1.2. Drivers of the atmospheric seasonal cycle

Several theories exist about the drivers of the seasonal cycle in the equatorial Atlantic basin. The WAM and internal variabiliy in the atmosphere are widely considered the major drivers of the atmospheric variability in the eastern equatorial Atlantic at seasonal timescale (Sultan and Janicot 2003; Gallée 2004; Nicholson 2009). Other studies have additionally acknowledged the relevance of the tropical SST on the low-level circulation and precipitation in the region at different timescales (Janicot et al. 1998; Vizy and Cook 2001, Vizy and Cook 2002; Mohino et al. 2011). Remote SSTs from the Pacific and Indian Oceans can also affect the atmospheric seasonal cycle in the eastern equatorial Atlantic and west African continent (Goddard and Graham 1999; Camberlin et al. 2001; Paeth and Friederichs 2004; Mohino et al. 2011b; Rodríguez-Fonseca et al. 2015).

To what extent and how local SST impacts the eastern tropical Atlantic atmosphere through ocean-atmosphere interactions at seasonal timescales is still debated. Xie (1994) shows that the annual cycle in equatorial SST is coupled to the climatological location of the ITCZ in the northern hemisphere in both Atlantic and Pacific. The southerly cross-equatorial winds linked to the ITCZ drive seasonal changes in the SST. In the equatorial Pacific, air-sea interaction is the leading mechanism for the annual cycle, but in the tropical Atlantic the monsoons play a more important role due the narrow width of the basin and the presence of strong continental convective zones (Xie and Carton 2013). Li and Philander (1997) suggest that seasonal changes in the cross-equatorial surface winds over the Gulf of Guinea are mainly driven by the continental monsoon and its associated changes in land temperatures. The SST responds to those changes in surface winds, with local air-sea interactions playing a minor role. Biasutti et al. (2003) highlight the relevance of both ocean and land surface processes in determining the tropical Atlantic seasonal cycle. They find that the insolation determines the north–south displacement of continental convection and greatly modulates the intensity of precipitation over the tropical Atlantic Ocean. On the other hand, they show that the SST determines the location of the ITCZ over the oceans and influences continental precipitation in coastal regions and over the Sahel. Other studies suggest that the discrepancy between the annual cycle in the

SST and the semiannual cycle in the insolation is a product of ocean-atmosphere interactions (Okumura and Xie 2004; Druyan and Fulakeza 2015; Meynadier et al. 2016; Diakhaté et al. 2018). Mitchell and Wallace (1992) propose that the summer monsoons largely contribute to initiate the equatorial SST cooling in the east but that positive feedbacks between ocean and atmosphere are necessary for the intensification and westward expansion of the annual cycle of the SST. Okumura and Xie (2004) show that the ACT intensifies the southerly winds in the Gulf of Guinea and pushes the rainband farther north over the land strongly affecting the evolution of the WAM. They argue based on a momentum budget analysis that the annual cycle in equatorial zonal wind is driven by the continental monsoon and by the interaction with equatorial SST in the eastern and western equatorial Atlantic, respectively.

In the western equatorial Atlantic, there is an agreement that air-sea interactions play a dominant role on the determination of the seasonal cycle of the SST, surface winds and the ITCZ. Modelling studies show that the seasonal cycle of the winds strongly depend on the underlying SST in this region (Li and Philander 1997; Okumura and Xie 2004). The interannual variability of the ACT strongly influences the rainfall and the winds in the western equatorial Atlantic (Zebiak 1993; Chang et al. 2000; Keenlyside and Latif 2007; Richter et al. 2014).

1.1.3 SST variability and ocean-atmosphere interactions

The surface layer of the ocean is in contact with the atmosphere and interacts with it through heat, momentum and mass exchange. A good understanding of how SST impacts the atmosphere can enhance the representation of ocean-atmosphere interactions in the coupled models and largely improve the predictability of atmospheric processes. Due to its larger heat capacity, the processes in the ocean involve longer timescales than in the atmosphere. Therefore, it is often possible to detect changes in SST that will lead to changes in the atmosphere months in advance. In the following subsection, I will present a number of dynamical and thermodynamical processes relevant to determination of the SST.

1.1.3.1 Patterns of climate variability and their role in the seasonal cycle

In Paper I of this thesis we try to identify and quantify the impacts of the seasonal cycle of the equatorial SST on the atmospheric seasonal cycle in the tropical Atlantic. Thus, it is important to understand the processes involving SST that can affect the low-level atmospheric fields such as the surface wind fields through dynamical or thermodynamical air-sea feedbacks. Some of the most relevant patterns of variability can be divided into the equatorial zonal modes and the off-equatorial meridional modes that I will discribe in the following.

The equatorial zonal modes

In the equatorial regions, there are two zonal modes that can determine the variability of the SST and involve dynamical air-sea feedbacks between SST, zonal winds and thermocline: the deep thermocline remote mode (or “thermocline mode”) and the shallow thermocline local mode (or “SST mode”) (Neelin et al. 1998; Fedorov and Philander 2001). The thermocline mode is determined by vertical movements of the thermocline that affect the SST at interannual timescales while the SST mode depends on processes associated with zonal advection and entrainment across the thermocline and are generally active at shorter timescales.

In the Pacific, those two equatorial zonal modes are clearly separated and contribute to different processes at different timescales. Vertical thermocline displacements control the equatorial upwelling and drive interannual variability of SST, with the Bjerknes positive feedback (Bjerknes 1969; Zebiak 1993) playing a crucial role in the growth of the SST anomalies associated with ENSO. The seasonal variability of SST in the central and eastern Pacific is associated with the local thermocline mode, which involves a feedback in which the southerly winds induce upwelling that cools the SST to the south of the equator. The resultant meridional gradient intensifies the southerly winds amplifying the original SST gradients (“upwelling-SST feedback”; Chang and Philander 1994).

In the equatorial Atlantic, the seasonal (interannual) variabiity is stronger (weaker) than in the Pacific and involves different processes. The interannual variability in the equatorial Atlantic seems to primarily modulate the strength of the seasonal cycle (Burls et al. 2012). Keenlyside and Latif (2007) show that an equatorial zonal mode (known as the Atlantic Niño) is also present in the tropical Atlantic at interannual timescales with the Bjerknes feedback as a leading mechanism. The Atlantic Niño is considerably weaker in amplitude, occurs more frequently, and has a shorter duration than the corresponding mode in the Pacific (Wang et al. 2013; Lübbecke and McPhaden 2013; Lübbecke et al. 2018). These differences to the Pacific are likely due to the smaller size of the Atlantic basin, the different distribution of landmasses (Zebiak 1993; Keenlyside and Latif 2007). The amplitude of the seasonal variations of the thermocline is much larger in the Atlantic than in the Pacific, and comparable to the interannual variability (Merle

1980; Vauclair and du Penhoat 2001; Schouten et al. 2005). Therefore, it is logical to wonder whether the Bjerknes feedback might also play a relevant role in the equatorial Atlantic seasonal cycle. Ding et al. (2009) suggest that the relationship between SST, thermocline depth and surface zonal currents is more consistent with a thermocline mode than with a SST‑mode. Bunge and Clarke (2009) find that the annual cycle of the thermocline plays a determinant role in the seasonal cycle and that can be explained by two modes: a mode based on the recharge-discharge of the equatorial heat content and a thermocline tilt mode. Burls et al. (2011) propose that the seasonal cycle in the tropical Atlantic involves both the SST and the thermocline modes with Bjerknes and upwelling-SST air-sea feedbacks amplifying the initial SST anomalies.

The off-equatorial meridional mode

The above described dynamical air-sea feedbacks involving thermocline displacements are important in upwelling regions and at the equator but do not dominate the SST variability in off-equatorial and subtropical regions (Wang et al. 2013). In these regions where the thermocline is deeper, the dynamical interaction between ocean and atmosphere is weak. Instead, thermodynamical ocean-atmosphere interactions involving surface heat flux play a more relevant role. (Xie and Philander 1994) propose a mechanism in which a positive feedback between wind speed, surface evaporation and SST (WES feedback) takes place for increasing the cross-equatorial SST gradient (Chang and Philander 1994; Chang et al. 1997). In this mechanism, let us consider a positive SST anomaly north of the equator and a negative anomaly to the south. The well-organized meridional SST gradient induces a northward surface flow across the equator that is deflected westward by the Coriolis force in the southern hemisphere and eastward in the northern hemisphere. This increases the wind speed over the negative southern SST anomaly, cooling it further through surface evaporation, and decrease the wind speed over the positive northern SST anomaly, warming it further. The net effect is a positive feedback on the original SST anomaly and an amplification of the meridional SST gradient (see Fig. 3). The so-called meridional SST mode is largely determined by the WES feedback that involves air-sea interactions in the north-south direction (Saravanan and Chang 2013; Chiang and Vimont 2004). Previous studies indicate that thermodynamic coupling might play a dominant role in the tropical Atlantic (Chang et al. 1997; Xie and Carton 2013). In the Pacific basin, ENSO dominates the climate variability with a strong Bjerknes feedback but in the Atlantic, with a weaker Bjerknes feedback, the relevance of WES feedback is at least comparable. Consequently, in the tropical Atlantic, both the zonal and the meridional mode are equally important for the growth of SST anomalies, with Bjerknes and WES feedback amplifying the zonal and meridional SST gradients, respectively.

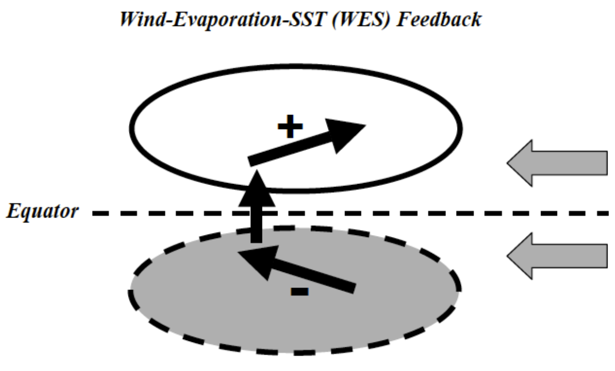

Fig. 3. Schematic of the WES feedback: anomalies of SST in contours (negative dashed) and surface wind velocity in black vectors. The gray vectors on the right signify the background easterly trades. From (Xie 2004).

1.1.3.2 Equatorial SST fronts and wind convergence

As discussed in previous sections, many studies show that the SST variability has a significant impact in the tropical Atlantic seasonal cycle. But, which dynamical mechanisms drive the SST field affecting the low-level atmosphere? Several mechanisms can explain how the atmosphere responds to the SST field forcing. Takatama et al. (2012) decompose the wind convergence budget into three major contributions involving SST fronts: i) the downward momentum mixing mechanism (Wallace et al. 1989; Chelton et al. 2001; Zermeño-Diaz and Zhang 2013) ii) the pressure adjustment mechanism (Lindzen and Nigam 1987; Feliks et al. 2004) and iii) a horizontal advection term. In the downward momentum mechanism the downward momentum transport intensifies over warm SSTs and acts to accelerate the surface wind (Chelton et al. 2001). In the pressure adjustment mechanism (also known as Lindzen and Nigam mechanism) the SST modifies the temperature in the atmospheric boundary layer and creates SLP anomalies. The resultant SLP gradient produces wind convergence (divergence) over warm (cold) SSTs (Lindzen and Nigam 1987) (see schematics of both mechanisms in Fig. 4). Takatama et al. (2012) show that the contribution of the horizontal advection to the wind convergence is negligible in comparison to downward momentum mixing and pressure adjustment terms.

Many of the relevant studies on the relationship between SST fronts and low-level atmospheric wind convergence focus in strong convergence regions at mid-latitudes such as the Gulf Stream (Sweet et al. 1981; Wai and Stage 1989; Minobe et al. 2008, 2010; Takatama et al. 2012) and the Kuroshio and its extension (Tokinaga et al. 2006; Koseki and Watanabe 2010). However, there are also a few relevant studies in the tropics and specifically in the equatorial Atlantic showing that downward momentum mixing and pressure adjusment mechanisms dominate in the western and eastern equatorial Atlantic, respectively (Zermeño-Diaz and Zhang 2013; Richter et al. 2014; Diakhaté et al. 2018). Diakhaté et al (2018) find that meridional SST and SLP gradients are closely related to meridional winds over the Gulf of Guinea. Contrastingly, the surface wind convergence in the western equatorial Atlantic is not related to the underlying SST and SLP gradients but rather to convective heating anomalies (Richter et al. 2014; Diakhaté et al. 2018) following the Gill-Matsuno response (Wang and Li 1993; Back and Bretherton 2009).

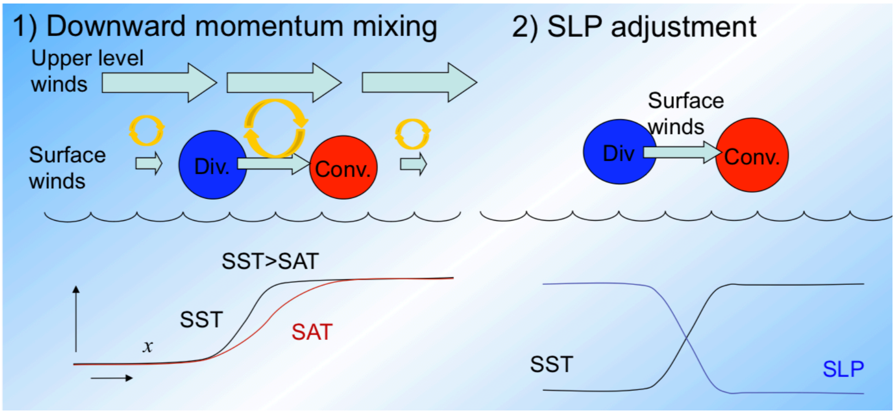

Fig. 4. Schematics of the (1) downward momentum mixing mechanism and (2) pressure adjustment mechanism. Courtesy of Shoshiro Minobe.

In Paper I we do not compute the complete wind convergence budget but only the term related to the pressure adjustment mechanism following the approach of Minobe et al. (2008). They propose that in the regions with an active Lindzen-Nigam mechanism, it is possible to identify a linear relationship between wind convergence and SLP Laplacian and between the inverse of the SST Laplacian and SLP Laplacian.

1.2. The oceanic seasonal cycle in the tropical Atlantic

The ocean is an important contributor to the seasonal variability of the climate system in the tropical Atlantic. In this section I will introduce the main concepts and theories behind the seasonal cycle of the ocean. In Paper II we explore which are the main drivers of the seasonal cycle of the equatorial Atlantic SST and what is the relative role of the coupling with the atmosphere and of ocean dynamics.

1.2.1 The observed seasonal cycle in the ocean

The variability of the equatorial Atlantic Ocean is dominated by the seasonal cycle (Xie and Carton 2013). In most of the global oceans the SST varies seasonally following the seasonal march of the sun. However, in the equatorial Atlantic Ocean the SST presents a strong annual cycle in contrast to the weak semiannual cycle in the insolation (Mitchell and Wallace 1992). The surface winds also exhibit a marked annual cycle except the zonal wind in the central and eastern equatorial Atlantic that exhibits a semiannual cycle. The thermocline depth has large seasonal variations in the equatorial Atlantic so it is expected that ocean dynamics are an important driver of the seasonal variability of the SST. The seasonal variability in the thermocline is closely related to the surface wind forcing and thus an annual (semiannual) cycle is present in the west (east) following the zonal wind stress forcing (Fig. 5.a,b). The thermocline is deeper in the west than in the east in the annual mean as a consequence of the prevailing easterly trade winds at the equator. In May, the thermocline depth presents a minimum in the west (as a result of weaker trade winds) that propagates eastward via equatorial Kelvin waves and reaches the Gulf of Guinea in boreal summer coinciding with the development of the cold tongue. Nevertheless, the thermocline has a semiannual cycle in the eastern equatorial Atlantic in contrast to the strong annual cycle present in the SST (Philander and Pacanowski 1986) (see Fig. 5c). The nature of the strong annual cycle in the SST in the eastern equatorial Atlantic remains an unanswered question. There is no agreement in the literature on what drives the seasonal cycle of the SST and why it differs from the cycle of ocean dynamics, surface zonal wind stress and insolation in this region. The complete explanation of the seasonal cycle of the SST might require of the collective contribution of ocean dynamics, insolation and ocean-atmosphere interactions.

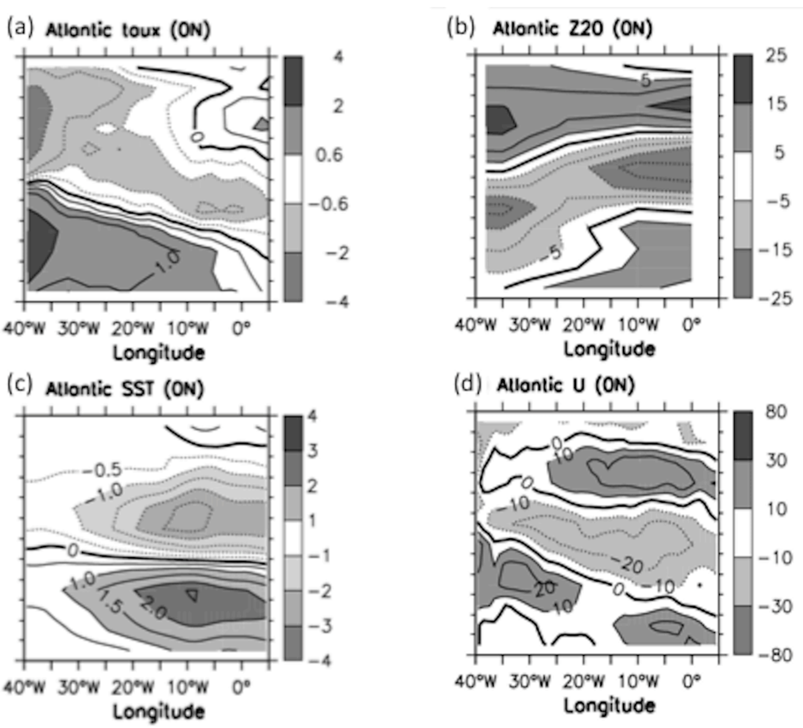

Fig. 5 Seasonal cycle of (a) zonal windstress, (b) thermocline depth, (c) SST and (d) zonal surface currents in the equatorial Atlantic. From Ding et al. (2009).

There are other relevant aspects of the seasonal cycle in the equatorial Atlantic Ocean that can play a role in the seasonal cycle of the SST.

Altimeter observational data show that the sea surface height (SSH) propagates eastward at the equator but westward off the equator (Schouten et al. 2005). They suggest that equatorial wave theory is behind this phenomenon. However, Bunge and Clarke (2009) find that the theoretical Kelvin wave phase speeds do not match the observed velocity of the eastward propagation of SSH, and they propose that an equatorial heat content recharge-discharge mechanism (analogous to that of Jin (1997a,b) recharge oscillator for ENSO) is behind it. Ding et al. (2009) show that eastward propagation of the SSH is well described by equatorial waves when considering the contribution of both wind-forced Kelvin and Rossby waves and the boundary reflections of those waves.

Another unresolved aspect is why the observed surface currents and SSH exhibit a strong semiannual cycle while the surface winds have a weak semiannual cycle. Ding et al. (2009) argue that this occurs as a result of the resonant excitation of the basin mode in the equatorial Atlantic whose period is close to semiannual. In paper II, we explore the drivers of the dynamics of the seasonal cycle of the equatorial Atlantic SST with special focus on the role of ocean-atmosphere interactions.

1.2.2 Drivers of the seasonal cycle of equatorial Atlantic SST

The coupling between the ocean and the atmosphere is an important contributor to the climate variability in the tropics. Ocean-atmosphere interactions can be divided into dynamical and thermodynamical coupling. They involve exchange of momentum and heat between the ocean and the atmosphere, respectively. Dynamical coupling plays a dominant role in the tropical Pacific being the driver of ENSO; the most important tropical ocean-atmosphere coupled mode for global climate. The surface winds transfer momentum from the atmosphere to the ocean through the wind stress which modifies the surface currents and subsequently the vertical structure of the upper ocean by inducing changes in the thermocline depth. The changes in the thermocline modify the SST field through modulating the temperature of upwelled and entrained subsurface cold waters. The Bjerknes feedback (Bjerknes 1969) is the main mechanism based on dynamical ocean-atmosphere coupling that leads to growth of initial SST anomalies in ENSO (see Section 1.1.3.1 and 1.3.1 for a more detailed explanation of the Bjerknes feedback). Thermodynamic coupling can also play a significant role in ocean-atmosphere interactions. The WES mechanism (see section 1.1.3.1) is one of the main mechanisms of thermodynamic coupling and involves a feedback between surface wind speed, evaporation and SST.

In the tropical Atlantic dynamic coupling is not as important as in the Pacific and some studies acknowledge the dominant role of the thermodynamic coupling in driving the tropical and equatorial variability at seasonal to decadal timescales (Chang et al. 1997; Xie and Carton 2013; Saravanan and Chang 2013; Nnamchi et al. 2015). Saravanan and Chang (2013) show, in an atmospheric general circulation model (AGCM) coupled to a slab ocean model, that thermodynamic coupling enhances the variability of the surface winds, affecting mainly the meridional wind component. They attribute this phenomenon to the WES feedback mechanism. Nnamchi et al. (2015) show in coupled ocean-atmosphere model simulations that thermodynamical coupling can explain key features of the variability of Atlantic Niño (Keenlyside and Latif 2007), such as the seasonal cycle of variance, amplitude and structure. This is in stark contrast to its Pacific counterpart that is mainly controlled by dynamical ocean-atmosphere coupling. Contrastingly, Ding et al. (2010) suggest that the Atlantic Niño is an oscillatory normal mode of the observed coupled system governed by a delayed recharge oscillator mechanism (see section 1.3.1 and 1.3.2. for further explanation of these mechanisms) based on dynamical ocean-atmosphere interactions and that can explain the largest amount of the variability of the SST.

The computation of the heat budget is a common method to quantify the competing roles of the thermodynamics (controlled by solar forcing and latent heat flux) and of the ocean dynamics, in driving the variations of the upper ocean heat content. In the tropics, where the oceanic mixed layer is relatively shallow compared to higher latitudes and the atmosphere is more to responsive to SST anomalies (Saravanan and Chang 1999). The changes in the temperature of the mixed layer can be accurately approximated to changes in the SST (Alexander et al. 2000; Vialard et al. 2001; Li et al. 2002; Polo et al. 2015b,a; Jouanno et al. 2017). Several observational (Merle 1980; Foltz et al. 2003; Wade et al. 2011) and modelling studies (Peter et al. 2006; Jouanno et al. 2011; Neto et al. 2018) address the causes of the observed annual cycle in the equatorial Atlantic SST.

Philander and Pacanowski (1986) find that surface heat fluxes are mainly responsible for the observed warming in SST while vertical processes including vertical advection, mixing and entrainment are the main cooling terms that balance the warming produced by surface heat fluxes. Although many previous studies attempted to unveil the mechanisms behind the rapid development of the cold tongue in the eastern equatorial Atlantic during boreal summer and its variability at different timescales, the main mechanisms remain to be fully understood. Foltz et al. (2003) using satellite and in situ data, find that zonal heat advection, eddy advection, entrainment and net surface heat fluxes are important contributors to the seasonal SST variability in the western equatorial Atlantic. Contrastingly, in the east, the cooling from meridional heat advection and the warming from eddy advection balance each other so the absorbed shortwave radiation dominates. In the east they find the largest discrepancies between SST tendencies and the sum of all computed terms of their heat budget, which they attribute to an inaccurate estimation of the vertical entrainment and the unresolved vertical diffusion. Wade et al. (2011) in an observational study, find that the net surface heat flux is one of the main causes of the seasonal variability of SST with entrainment having a weak contribution. They also find the largest errors along the cold tongue region and hypothesize that the vertical turbulent mixing (not resolved in their analysis) is one of the main drivers of the cooling since it matches quite well the variability of their residual term.

Peter et al. (2006) in a high-resolution OGCM compute a more complete seasonal heat budget explicitly resolving vertical entrainment and diffusion. They show that the cooling in the equatorial band is mainly driven by vertical processes instead of by horizontal advection, and that the heating is controlled by surface heat fluxes and eddies. Jouanno et al. (2011) in a modelling study on the annual cycle of the SST in the Gulf of Guinea region find that there is no relation between a shallower thermocline in that region and the more intense cooling. They show that the cooling due to subsurface processes is stronger in the central equatorial Atlantic, where the thermocline is deeper than over the cold tongue region and that the annual cycle of surface air-sea heat fluxes is an important contributor to the differences in the SST between boreal summer and winter.

There is clearly no general agreement on the relative contribution of air-sea heat fluxes, horizontal surface advection fluxes and subsurface processes (driven by ocean dynamics) to the seasonal mixed layer heat budget in the equatorial Atlantic. In Paper II we carry out a computation of the seasonal mixed layer heat budget in the equatorial Atlantic in order to identify the relative contribution of the ocean dynamics and atmospheric-driven thermodynamics to the seasonal evolution of the equatorial SST. The heat budget calculation focuses on identifying the main contributors to the variability of SST in the Atlantic cold tongue region.

1.3 Multidecadal variability of El Niño-Southern Oscillation

El Niño-Southern Oscillation (ENSO) is a coupled ocean-atmosphere phenomenon in the tropical Pacific and the dominant mode of interannual variability in the tropics, driving major changes at seasonal to interannual timescales. Due to its vast impacts worldwide, ENSO is one of the most studied climate phenomenon but still many questions remain unclear. How predictable is ENSO? How does ENSO change at multidecadal timescales and why? In this thesis, I will focus on the changes of ENSO properties in multidecadal timescales and I will try to identify the mechanisms behind those changes.

1.3.1 Theory of ENSO

El Niño can be identified as an anomalous warming of the sea surface in the central and eastern equatorial Pacific basin beyond the normal warming in the region during southern hemisphere summer. For many years El Niño was considered an occasional local intensification of the oceanic seasonal cycle coinciding with the summer of the southern hemisphere and associated maximum SST, weaker trade winds and reduced upwelling (Wyrtki 1975). Bjerknes (1961) shows that El Niño is only the oceanic side of the so-called El Niño-Southern Oscillation (ENSO) coupled ocean-atmosphere mode and thus, interactions between ocean and atmosphere play a key role in this phenomenon.

The initiation of an ENSO event is a consequence of the relaxation of the trade winds in the equatorial Pacific, after an extended period of anomalously intense easterlies that build up a west-east sea surface positive slope in the Pacific basin (Wyrtki 1975).

The so-called Wyrtki theory for the initiation of an ENSO event can be divided in the following phases:

i) An extended period of intense easterly winds produce an east-west positive (negative) sea level (thermocline) slope.

ii) Once the easterly winds become weaker in the central-to-western Pacific, the surface water accumulated in the west is triggered in the form of an equatorially trapped Kelvin wave (KW) that travels eastwards and deepens the thermocline on its way to the eastern Pacific.

iii) The arrival of the KW to the eastern equatorial Pacific, along with the associated deepening of the thermocline, causes a warming of the SST and leads to the onset of ENSO.

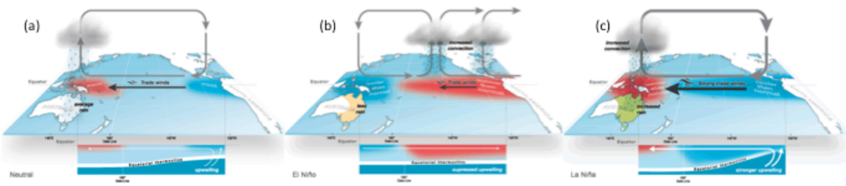

Fig. 6 (a) Neutral conditions in the tropical Pacific basin. The Pacific cell of the Walker circulation, the thermocline depth, the surface winds and the zonal SST gradient are shown. **(b)** and **(c)**, same as in (a) for El Niño and La Niña conditions, respectively. From http://www.bom.gov.au/climate/enso/history/ln-2010-12/three-phases-of-ENSO.shtml

The maintenance of an ENSO event requires the Bjerknes ocean-atmosphere positive feedback (Bjerknes 1969). This feedback involves several oceanic and atmospheric fields that interact with each other to increase the initial warm SST anomaly. For instance, an initial anomalous warming (cooling) in the SST in the equatorial eastern

Pacific would induce changes in the sea-level pressure, creating an east-west negative (positive) pressure gradient and a subsequent weakening (strengthening) of the trade winds. The weakened (intensified) trade winds lead to a deeper (shallower) thermocline in the east which intensifies the initial positive (negative) SST anomaly. El Niño (La Niña) is the warm (cold) phase of ENSO that is initiated after a warm (cold) SST anomaly. Figure 6 shows the state of the most relevant ocean and atmosphere fields during neutral, El Niño and La Niña phases.

The so-called Bjerknes-Wyrtki (BW) theory explained above accounts for the initiation and growing phases of both El Niño and La Niña, but not the transition mechanisms between the warm and cold state of ENSO. The Bjerknes feedback only amplifies the original warm/cold SST anomalies and thus, a negative feedback is required to terminate the growth of those anomalies. ENSO does not show a regular periodicity but presents a cyclic behaviour which indicates that the underlying dynamics could be represented with a harmonic oscillator model. Many conceptual oscillator models have been proposed to try to establish a complete theory of ENSO (Suarez and Schopf 1988; Battisti and Hirst 1989; Weisberg and Wang 1997; Wang et al. 1999). In this thesis I will focus on the recharge oscillator (RO) mechanism (Jin 1997a,b) based on the oscillation of the warm water volume contained in the upper equatorial Pacific Ocean. One of the most relevant negative feedbacks proposed in the literature that could stop the monotonic growing of the SST anomalies driven by the Bjerknes feedback is the discharge process due to the divergence of the Sverdrup transport; a process that is included in the recharge oscillator model and not in the other conceptual models. Equation (1) (known as Sverdrup relation) states that the meridional Sverdrup transport M_y is only dependent on latitudinal changes of the zonal wind stress τ_x.

$$M_y = \frac{-1}{\beta}\frac{\partial \tau_x}{\partial y} \qquad (1)$$

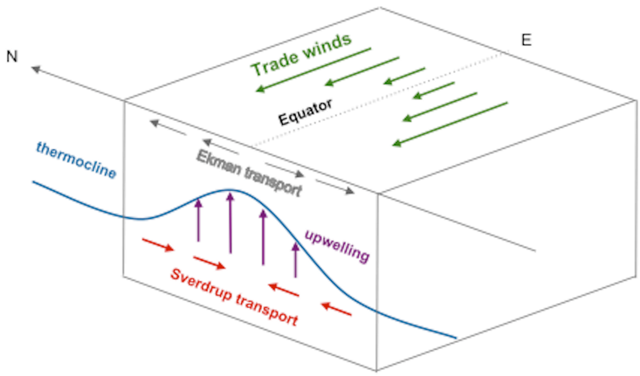

Fig. 7 Schematic of the ocean circulation at the equator. Ekman transport at the surface, Ekman pumping, Sverdrup transport in the ocean interior and changes in the thermocline are shown.

Around the equator, the Ekman transport is predominantly divergent as a consequence of the prevailing easterly winds, (note that Ekman transport is 90º to the right (left) of the surface wind in the northern (southern) hemisphere) originating upwelling of cold waters. The prevailing upwelling at the equator creates a relative SST minimum at the equator with warmer SST sitting a few degrees further poleward. In the ocean interior, an anomaly of surface easterly (westerly) winds is associated with an equatorward (poleward) Sverdrup transport (see equation 1) and hence convergence (divergence) at the bottom of the thermocline (see red arrows in Fig 7). In the recharge oscillator framework the anomalous convergence (divergence) of the Sverdrup transport is responsible of increasing (decreasing) the heat content of the oceanic upper layer bringing warm water towards (out of) the equator.

1.3.2 ENSO as a recharge oscillator model

Figure 8 shows the schematics of the four phases distinctive of the recharge oscillator mechanism and the relationship between SST and wind stress anomalies and Sverdrup transport (see Eq. 1 for Sverdrup relation). According to the RO model, ENSO can be divided in four different phases involving the recharge and discharge of the equatorial upper ocean heat content. Prior to an El Niño event, the heat content (or warm water volume) along the whole tropical Pacific basin is maximum (charged phase; Fig. 8iv). The characteristic westerly wind stress anomaly that initiates El Niño produces Sverdrup divergence at the equator (see equation 1) that releases the accumulated warm water towards higher latitudes (discharging phase; Fig. 8i). The divergence of the Sverdrup transport during this warm phase is associated with a deeper thermocline in the east of the basin, which generates a warm SST anomaly. The discharging of the equatorial heat content leads to a transition phase with an anomalously shallow thermocline along the entire Pacific basin (discharged phase; Fig. 8ii). The negative thermocline depth anomaly during this transition phase allows cold water to be upwelled to the surface layer via climatological upwelling, leading the system to the cold La Niña phase. During the cold phase, the system increases its heat content due to the convergence of Sverdrup transport of off-equatorial surface warm waters associated with an easterly wind stress anomaly (charging phase; Fig. 8iii). The easterly wind anomaly creates an east-west positive slope in the thermocline and hence a negative SST anomaly in the eastern equatorial Pacific.

The full cycle of the coupled ocean-atmosphere oscillation characteristic of ENSO is well described by the above explained equatorial ocean heat content charge-discharge process (Burgers et al. 2005).

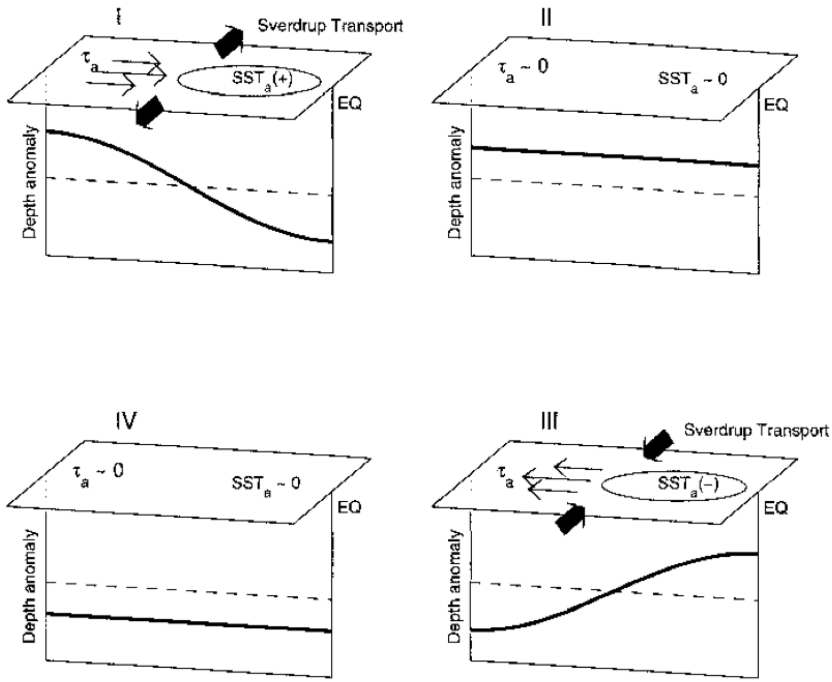

Fig. 8 Schematics of the ENSO phases according to the recharge oscillator mechanism: (i) warm El Niño phase, (ii) transition between warm and cold phase, (iii) cold La Niña phase and iv) transition between cold and warm phase. i, ii, iii and iv correspond, in the same order, to the discharging, discharged, charging and charged phases of the oscillator. (From Meinen and McPhaden 2000)

1.3.3 Modulation of ENSO at multidecadal timescales

ENSO phenomenon can be well characterized by the following set of properties: frequency, amplitude, spatial structure of the SST anomalies and length of the event. ENSO shows an irregular periodicity, between 2 and 7 years, and amplitudes varying from event to event. According to a number of previous studies, ENSO characteristics change in decadal and multidecadal timescales (Enfield and Cid S. 1991; Gu and Philander 1995; Kirtman and Schopf 1998; Fedorov and Philander 2001;

Wang and An 2001; Philander and Fedorov 2003; Yeh and Kirtman 2004).

There are periods in which ENSO is more energetic and also periods with more regular El Niños than La Niñas, and vice versa. There are different theories trying to explain the event-to-event differences and other characteristics of ENSO. In this thesis, I will distinguish between two different sources that can modulate ENSO properties at decadal to multidecadal timescales: internal variability (Section 1.3.3.1) and remote impacts (Section 1.3.3.2). This section is rather brief because the drivers of ENSO multidecadal modulation are briefly treated in this thesis. Timmermann et al. (2018) and Cai et al. (2019) can provide a complete picture on the state-of-the-art ENSO theory and drivers of ENSO changes at multidecadal timescales.

1.3.3.1 Changes in ENSO driven by internal variability

Previous studies show that ENSO properties in decadal to interdecadal timescales can be driven by Pacific internal variability (Kirtman and Schopf 1998; Fedorov and Philander 2001; Philander and Fedorov 2003; Yeh and Kirtman 2004). Philander and Fedorov (2003) describe ENSO as a nearly regular oscillation superimposed on natural decadal and multidecadal oscillations and on a global warming trend (see also: Lau and Weng 1999; Cai and Whetton 2001). Other studies consider ENSO a chaotic oscillation that can be seen as a nonlinear modulation by a changing background state or stochastic fluctuations (Timmermann et al. 1999; An and Jin 2000; Fedorov et al. 2003). Fedorov and Philander (2001) define El Niño and La Niña phases as anomalies from the mean state in the Pacific Ocean and suggest that changes in the background state are the main driver of the multidecadal changes in ENSO. Contrastingly, Yeh and Kirtman (2004) show that the changes in the tropical Pacific background state are not related to ENSO changes at decadal timescales. Wang and An (2001) find that the observed changes in ENSO properties from mid-1970s onwards can be attributed to decadal changes in surface winds and are independent of changes in the mean thermocline. The origin of those changes in the winds is unclear. Pierce et al. (2000) propose a mid-latitude SST influence while Liu et al. (2002) suggest tropical ocean-atmosphere interactions.

1.3.3.2 Changes in ENSO driven by remote forcing

ENSO characteristics in decadal to multidecadal timescales can also be explained by remote impacts from the Indian (Yu et al. 2002; Wu and Kirtman 2004; Yeh et al. 2007) and the Atlantic basins (Dommenget et al. 2006; Polo et al. 2008; Jansen et al. 2009; Rodríguez-Fonseca et al. 2009; Ding et al. 2012; Martín-Rey et al. 2012). A number of studies have shown a significant relationship between summer Atlantic Niños and the following winter Pacific Niñas (Keenlyside and Latif 2007; Polo et al. 2008; Rodríguez-Fonseca et al. 2009; Ding et al. 2012). Rodríguez-Fonseca et al. (2009) show that the Atlantic Niño occurring during boreal summer can trigger a Pacific La Niña with a 6-month lead via a strengthening of the Walker circulation with the ascending branch over the Atlantic and descending branch over the central Pacific. Ham et al. (2013) proposed that the impact of the tropical Atlantic on ENSO can be separated into two major regions, North Tropical Atlantic and Atlantic Niño regions, each contributing to different types of El Niño events.

Only a few studies have looked at the impacts of equatorial Atlantic SST on ENSO properties. Jansen et al. (2009) showed in a conceptual model for the Pacific ENSO that the inclusion of a feedback from Atlantic SST on the Pacific can improve the forecast skill of their model.

They also found that Atlantic SST has a small impact on periodicity of ENSO while Dommenget et al. (2006) found a significant shift towards longer periods and increased variance when they remove Atlantic SST feedback on ENSO. The above mentioned studies look at the impacts of the Atlantic SST on ENSO properties for the second half of the 20th century, and none of them look at tropical Atlantic impacts on ENSO at multidecadal timescales.

In paper III, I investigate the multidecadal changes on ENSO properties using a simplified conceptual recharge oscillator model (Burgers et al. 2005) that simulates Pacific El Niño SST and thermocline depth. We explore whether the recharge oscillator model represents well the statistics and dynamics of ENSO during the whole observational record. We also check the relation of ENSO properties to remote forcing.

2. Main objectives

This thesis is divided into two different topics each one with a clear scope. In the first part of the thesis (Paper I and Paper II) I present an in-depth study of the seasonal cycle in the equatorial Atlantic region. The main objective in this part is to gain a deeper understanding of the characteristics of the seasonal cycle and the physical mechanisms behind them, with a focus on the relative role of the coupling between the ocean and the atmosphere.

The relative roles of the land processes and ocean-atmosphere interactions in the determination of the seasonal cycle in the tropical Atlantic are still debated. Papers I and II address the following questions related with the dynamics of the seasonal cycle in the tropical Atlantic:

- What is the relative role of the equatorial Atlantic SST in driving the seasonal cycle of the atmosphere in the tropical Atlantic?

- Which are the main drivers of the SST in the equatorial Atlantic? How important is the coupling between the ocean and the atmosphere in setting the seasonal cycle of the SST?

In the second part of this thesis (Paper III), I explore the changes on ENSO characteristics at multidecadal timescales by means of a strongly simplified conceptual model. The main objective of this study is to identify changes in ENSO properties during the 20th century and to identify the drivers of those changes.

There is no agreement on which are the main drivers of the observed ENSO multidecadal variability. Coupled general circulation models seem to be too complex to identify the mechanisms behind those changes. In paper III, I address the following questions using a simplified conceptual model for simulating ENSO:

- Which are the main changes in ENSO properties at multidecadal timescales?

- Are those changes modulated by a changing background state or remotely triggered via teleconnections from other basins?

3. Summary of results

The results of the three papers composing this thesis show the important role of ocean-atmosphere interactions in the tropics in timescales ranging from seasonal to multidecadal. In Paper I and II I present an in-depth study of the dynamics of the seasonal cycle of the ocean and the atmosphere in the equatorial Atlantic. Paper III focuses on the multidecadal variability of ENSO properties and on the mechanisms behind the large changes in ENSO in the recent decades.

Paper I: **The role of sea surface temperature in the atmospheric seasonal cycle of the equatorial Atlantic**

Lander R. Crespo, Noel Keenlyside and Shunya Koseki (2018) *published online in Climate Dynamics*. doi:10.1007/s00382-018-4489-4

In Paper I we look at the impact of the SST in the seasonal cycle of the atmosphere through the comparison of two CAM4 simulations forced with a climatological observed SST and an annual mean SST at the equator and climatological SST elsewhere. With this modeling approach, I can quantify the relative contributions of the internal atmospheric variability and the ocean-atmosphere interactions to the atmospheric seasonal cycle. The dynamics of the seasonal cycle in the equatorial Atlantic show significant differences between the western and the eastern side of the basin. In the west, ocean-atmosphere interactions are a key driver of the atmospheric seasonal cycle while in the east they do not dominate but contribute to the amplification of the seasonal cycle.

Key findings:

- The seasonal cycle of the SST is a major driver of the surface winds and precipitation in the western equatorial Atlantic.
- The monsoon is the main driver of the seasonal cycle of meridional winds and precipitation in the eastern equatorial Atlantic, and the SST also plays and important role there.
- The zonal winds in the central and eastern equatorial Atlantic are insensitive to changes in the underlying SST.

Paper II: **What drives the seasonal cycle of the sea surface temperature in the equatorial Atlantic?**
Lander R. Crespo, Shunya Koseki, Noel Keenlyside and Yanchun He. *Manuscript in preparation.*

In paper II I investigate the relative role of ocean-atmosphere interactions in driving the seasonal cycle in the equatorial Atlantic Ocean from MICOM ocean model simulations. The model is forced with the output of the two previous CAM4 atmospheric model simulations from Paper I. The first simulation was forced with prescribed climatological SST globally and the second one with equatorial annual mean SST and climatological elsewhere. Therefore, the comparison of the output of the ocean model simulations is a first order estimation of the importance of the coupling between the ocean and the atmosphere in the seasonal cycle of the equatorial Atlantic Ocean. I compute a seasonal heat budget to quantify the relative contributions of radiative heat fluxes, turbulent heat fluxes and of ocean dynamics to the seasonal cycle of the SST. I show that the mechanisms behind the seasonal cycle of the SST in the equatorial Atlantic vary across the basin. In the east the strong summer cooling over the Gulf of Guinea is driven by an enhanced evaporation produced by the intensified surface winds during the monsoon season and the intense upwelling coinciding with a shallower thermocline. In the west, thermodynamic coupling is the major driver of the oceanic seasonal cycle and in the east ocean dynamics predominate with air-sea coupling contributing to amplify the seasonal cycle.

Key findings:

- The upwelling is the main contributor to the strong cooling over the Atlantic cold tongue during boreal summer and it is remotely driven from the west.
- The strong evaporation driven by the intensified monsoonal winds largely contributes to the development of the cold tongue.
- The coupling between the ocean and the atmosphere in the equatorial Atlantic is mainly thermodynamically driven and is strongest in the west.

Paper III: **Multidecadal variability of ENSO in a recharge oscillator framework** Lander R. Crespo, Belen Rodríguez-Fonseca, Irene Polo and Noel Keenlyside. *Manuscript in preparation.*

In paper III I show that the observed increase in the amplitude of ENSO since the 1970s can be reproduced in a conceptual model based on the recharge and discharge of the Pacific upper ocean heat content. The recharge and discharge of the heat content is the driving mechanism of Pacific ENSO since the mid 1970s. The WWV drives anomalies in SST with 3 seasons leadtime and the SST feedbacks onto the WWV with a leadtime of about 2 seasons. Before the 1970s only the recharge mechanism is active; the SST variations regulate equatorial heat content through ocean-atmosphere interaction, but the heat content variations themselves do not substantially influence SST. Other mechanisms such as the zonal advection feedback are likely to be stronger during these decades.

Key findings:

- The multidecadal changes in ENSO in the recent decades can be reproduced with a simple recharge oscillator conceptual model.
- The recharge and discharge of the equatorial heat content, based on the so-called thermocline feedback, is the main driver of ENSO dynamics since the mid 1970s.
- The multidecadal modulation of ENSO variability appears related to the Atlantic Multidecadal Variability and global warming.

4 Conclusions and future perspectives

This thesis studies the role of ocean-atmosphere interactions in the tropical regions for seasonal to multi-decadal variability for two different cases. In the first two papers I explore the relevance of the coupling between ocean and atmosphere in the equatorial Atlantic seasonal cycle. The seasonal cycle in the equatorial Atlantic has been object of many studies and papers on the topic were especially prolific in the 1980s and 1990s. In the last couple of decades the number of studies focusing in the seasonal cycle in this region has gradually decreased. I revisit the topic with the aim of clarifying a number of questions that remain unanswered. I do not manage to answer all those questions but this thesis provides a good overview of the state-of-the-art and it presents an in-depth study of the mechanics of the seasonal cycle. Previous studies mainly focused on the seasonal cycle over the Atlantic Cold Tongue (ACT) region. I extend my investigation to the whole equatorial Atlantic basin to identify and compare the driving mechanisms in each part of the basin. There are significant differences in the dynamics of the seasonal cycle between the western and the eastern side of the equatorial Atlantic. Ocean-atmosphere interactions in the west are a key for the seasonal cycle over the entire equatorial Atlantic. In the west the coupling determines the seasonal cycle, while in the east it considerably strengthens its amplitude. The coupling in the east seems to be of secondary importance, as the zonal winds are hardly affected by the underlying SST. The west African monsoon and the Atlantic cold tongue are the main contributors to the seasonal variability in the equatorial Atlantic in the atmosphere and the ocean, respectively. Both phenomena occur in the eastern equatorial Atlantic and that is why this region has attracted so much attention. However, I believe that it is crucial to gain a deeper understanding of the processes governing the variability in the entire basin in order to fully understand the annual cycle in the eastern equatorial Atlantic since large part of the variability in the eastern tropical Atlantic can be determined by changes in the variability in the west. In particular, surface zonal winds in the west can excite equatorial waves in the ocean that propagate eastward modifying the thermocline depth and eventually the SST in the east.

In paper I, I decompose the relative role of atmospheric internal variability, land-atmosphere interactions and ocean-atmosphere interactions in the seasonal cycle. I believe that such a detailed decomposition has never been accomplished before, but previous studies rather focused on one of the drivers of the seasonal cycle. I find that equatorial SST controls the seasonal evolution of the surface winds and rainfall over the equatorial Atlantic but has little influence on the continental precipitation over West Africa, that is mainly controlled by the seasonal changes in land surface temperature. Okumura and Xie (2004) acknowledge a bigger impact of the SST in the precipitation over West Africa. The results in this thesis somewhat contradict them and suggest that the surface zonal winds over the Gulf of Guinea and the evolution of the ITCZ over continental west Africa is independent from the equatorial SSTs. The weaker coupling between the ocean and the atmosphere in the eastern equatorial Atlantic implies that the atmospheric predictability in the region is lower than in other regions with stronger coupling. There are many countries in West Africa whose economy and lifestyle strongly relies on the climate and especially on the seasonal monsoon precipitation. The atmosphere is influenced by the SST in this region, especially the meridional winds, but is not tightly coupled to the SST as it is the case in the western equatorial Atlantic. Therefore there is a need to explore other ways of improving the predictability in the climate system in this region. The SST in the eastern equatorial Atlantic influences the onset of the WAM and a better prediction of the timing of the establishment of the equatorial Atlantic cold tongue could largely improve the prediction of the start date of the monsoon.

In paper II I disentangle the particular contributions of ocean adjustment processes and ocean-atmosphere interactions to the oceanic seasonal cycle. I separate and quantify how much of the seasonal cycle in the ocean is driven by winds dependent and independent of the local coupling to the atmosphere. This approach allows to confirm the leading role of the thermodynamic coupling between the ocean and the atmosphere in driving the seasonal cycle of the ocean in the western equatorial Atlantic. The coupling is effective through the wind-evaporation-SST feedback and is vital to the determination of the seasonal cycle in the west. It can also impact the seasonal variability elsewhere along the equatorial band through equatorial wave propagation that modifies the thermocline depth in the central and eastern equatorial Atlantic. Those changes in the thermocline depth control the seasonal changes in the SST in the eastern equatorial Atlantic, especially during boreal summer when the shallow thermocline allows the entrainment of cold water that rapidly cools down the SST over the Atlantic Cold Tongue region. I believe that a set of experiments with a model composed by a slab ocean (only at the equatorial band) coupled to the atmosphere could show that the seasonal cycle in the equatorial Atlantic is mainly driven by thermodynamic coupling.

The relatively important role played by ocean-atmosphere interactions in the equatorial Atlantic underlines the necessity to use coupled general circulation models (CGCM) to simulate the climate system in this region. However, the state-of-the-art models and the coupled models show large biases and systematic errors in simulating the tropical Atlantic climate and thus it is difficult to use these models to study the seasonal cycle. I present an alternative approach to coupled ocean-atmosphere model simulations. I run standalone simulations with an atmospheric (paper I) and an ocean model (paper II) to try to isolate the drivers of the annual cycle in the atmosphere and the ocean separately. The understanding obtained and methodology can be useful for better diagnosing the sources of biases in the models and improving the simulation of climate. In coupled general circulation model simulations is harder to identify individual mechanisms and the origin of the biases. In this framework I am able to look at the relative role of the coupling between the ocean and the atmosphere in driving the annual cycle. Previous studies have mostly understood that the equatorial Atlantic bias results from too weak trade winds in boreal spring that lead to a too weak cold tongue in summer. My work suggests that the coupling over the western equatorial Atlantic could also be important in the development of the bias. In particular, I show in papers I and II that the strength of the coupling plays a determinant role in the seasonal cycle in the western equatorial Atlantic atmosphere and ocean. In the east, although the WAM and ocean dynamics are the major drivers of the seasonal cycle in the atmosphere and the ocean, respectively, ocean-atmosphere interactions largely contribute to amplify the seasonal cycle.

We need a better understanding of the ocean adjustment processes that establish the cold tongue. I show in paper II that the cold tongue over the eastern equatorial Atlantic is not strongly influenced by the local atmospere. Ocean atmosphere interactions in the west amplify the strong seasonal cycle in the SST in the east. Further research focusing on the drivers of the cold tongue with a special focus on the remote drivers from the west equatorial Atlantic could lead to a large improvement of the predictability of the cold tongue in the east.

On the other hand, the fact that we use only one model for simulating the atmosphere and one model for simulating the ocean can be considered one of the main caveats of this thesis. Given the large biases exhibited by the state-of-the-art models in the tropical Atlantic, it would be very beneficial to extend this study on the equatorial Atlantic seasonal cycle to coordinated model experiments to test the sensitivity of the results to model formulation and the impact of model biases.

None of the previous studies computed a closed heat budget in the equatorial Atlantic focusing on the role of the ocean-atmosphere interactions. The approach in paper II of this thesis allows to capture the role of local ocean-atmosphere interactions at the equator but I found many difficulties to close the heat budget with the output variables provided by the NorESM ocean component. The vertical terms of the heat budget are difficult to compute directly and they can have a major role in the determination of the seasonal changes in SST in the equatorial Atlantic. This is a caveat in the study and a future study should focus in a more complete computation of the heat budget keeping the focus on the role of the coupling between the ocean and the atmosphere.

In Paper III, I use a conceptual recharge oscillator model to investigate changes in ENSO properties during the 20th century. I investigate the large changes in ENSO characteristics with the most pronounced changes occurring from the mid 70s onwards. The conceptual model utilized in this study is able to reproduce those changes and it proves to be a very good tool for the analysis of ENSO characteristics in the recent decades. Contrastingly, the recharge oscillator does not provide a good fit to the observational data for the earlier periods from 1901 to 1965. The recharge oscillator explains well the dynamics of ENSO for the periods when the coupling between the SST and the thermocline is stronger and ENSO is mostly driven by the so-called thermocline feedback, which is the case in the latest decades, as discussed in previous studies. The zonal advective feedback might be the driving mechanism of ENSO during other periods and it is a feedback not represented in the model I use that is based only on the recharge-discharge of the equatorial upper ocean heat content.

The changes in the background state of the thermocline depth modulate the strength of the thermocline feedback and thus the relevance of the recharge oscillator model. The determination of the multidecadal changes in the mean thermocline depth present some limitations due to the scarce ocean subsurface data available prior to 1960s. Both our observational and model analysis are based in reanalysis and model output data. The reanalysis data we used hardly contains any observations prior to 1960s and the model output data. In the current satellite data era, there is a better coverage of ocean subsurface which will allow a better future understanding of the changes in the thermocline.

The multidecadal modulation of ENSO can also be controlled by remote forcing from other basins. I find that the coefficients of the recharge oscillator model to simulate ENSO evolve in phase with the Atlantic Multidecadal Variability (AMV). This result agrees with other studies that show how the equatorial Atlantic has a large impact in ENSO variability. Neverthelesss, the causes of this evolution need to be clarified and would require additional work

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The role of sea surface temperature in the atmospheric seasonal cycle of the equatorial Atlantic

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Abstract
We investigate the role of sea surface temperature (SST) and land surface temperature (LST) in driving the seasonal cycle of the atmosphere (surface winds and precipitation) in the tropical Atlantic. For this we compare three atmospheric general circulation model (AGCM) experiments for the historical period 1982–2013 forced by different SST: (1) observed daily-climatological SST, (2) globally annual-mean SST, and (3) annual-mean SST in the equatorial Atlantic and daily-climatological SST elsewhere. Seasonal variations in SST strongly influence the seasonal evolution of the West African Monsoon (WAM) and ITCZ over the equatorial Atlantic Ocean. Forcing the model with annual mean SST (globally and in the equatorial Atlantic) considerably reduces the seasonal variance in the atmosphere, except for the zonal winds in the eastern equatorial Atlantic. Equatorial Atlantic SST contributes to the seasonal cycle in precipitation and meridional winds over the entire equatorial Atlantic, but only strongly influences zonal winds in the western equatorial Atlantic and has little influence on the northward penetration of the WAM. The leading modes of coupled SST–LST-atmosphere co-variability are identified by multivariate analysis. The analysis shows that both LST and SST drive seasonal variations in precipitation over equatorial Atlantic, with the LST being a larger contributor to the continental rainfall in West Africa. The coupling between ocean and atmosphere is stronger in the western than in the eastern equatorial Atlantic. The pressure adjustment mechanism is the main driver of the surface meridional wind convergence in the eastern tropical Atlantic.

Keywords Equatorial Atlantic · ITCZ · WAM · Seasonal cycle · AGCM

1 Introduction

The Intertropical Convergence Zone (ITCZ) is a band of tropical deep-convection that can be identified as the maximum in time-mean precipitation, and by the convergence of surface winds from both hemispheres. In the climatological mean the ITCZ sits north of the equator in the Atlantic. The ITCZ movement in the Atlantic is not symmetric about the equator and does not follow the insolation maximum, but it exhibits an annual cycle in the eastern tropical Atlantic (see Fig. 1). The sea surface temperature (SST) in the eastern equatorial Atlantic and the surface wind convergence onto the ITCZ, also show an annual cycle, in contrast to the semiannual cycle present in the insolation at the top of the atmosphere (Mitchell and Wallace 1992; Wallace et al. 1989). The ITCZ location is influenced by SST patterns, with warmer SSTs favouring deep convection, and thus determining the surface wind patterns. However, it is still not fully understood how the SST, winds and ITCZ interact to form the tropical Atlantic climatology.

The determination of the annual mean position of the Atlantic ITCZ implicates various processes. Philander et al. (1996) proposed local ocean–atmosphere interactions and continental asymmetries as the main factors determining the annual mean position of the ITCZ north of the equator. The shallower thermocline induced by prevailing easterly winds in eastern Atlantic, favours ocean–atmosphere interaction since the surface winds can affect the SST in this region more strongly. The shape of the continents, in particular the bulge of western Africa to the north of the Gulf of Guinea is a determinant factor that can explain why the Northern Hemisphere favours warmer SST and why the ITCZ is located north of the equator in the Atlantic. Other studies (Kang et al. 2008, 2009; Frierson and Hwang 2012)

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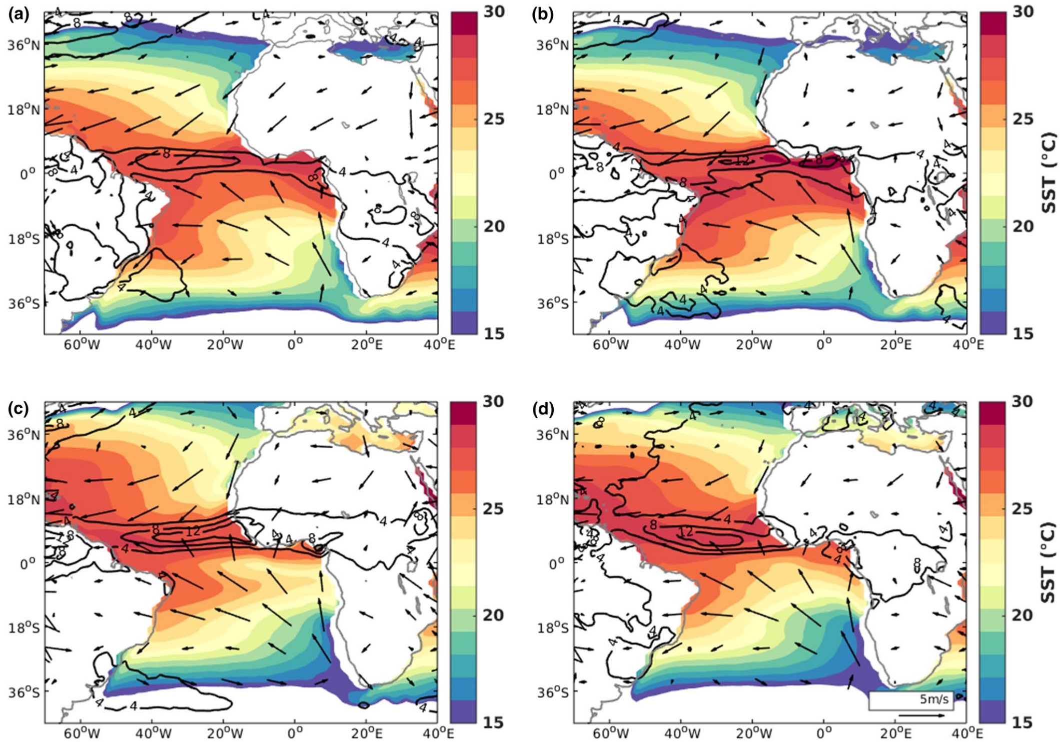

Fig. 1 Observed climatology of SST in °C, precipitation in mm and surface winds in m/s for the different seasons based on optimum interpolation sea surface temperature (OISST), tropical rainfall measuring mission (TRMM) and the Japanese 55-year Reanalysis (JRA-55) datasets, respectively. We show the SST in shading, the precipitation in contours and the winds in vectors

suggest that the position of the ITCZ is determined by extratropical interhemispheric differential heating. Consistently, Mechoso et al. (2016) found extratropical SSTs over the Southern Ocean to be an important trigger of the northern location of the ITCZ. The impact of remotely driven changes in the Hadley circulation is strongly counteracted by the local wind-driven circulation (Green and Marshall 2017). Contrastingly, Zhang and Delworth (2005) showed that the Atlantic Meridional Overturning Circulation (AMOC) controls the annual mean position of the ITCZ in the tropical Atlantic with a weakening of the oceanic overturning circulation resulting in a southward shift of the ITCZ. To maintain the energetic balance, the net atmospheric and oceanic heat transport has to be zero at the equator. Since the oceanic heat transport is northward at the equator due to the AMOC (Lumpkin and Speer 2007), the atmosphere transports heat southward across the equator in order to keep the energy balance. The atmosphere achieves this by situating the ITCZ north of the equator (Schneider et al. 2014; Marshall et al. 2014).

As for the annual mean, local and large-scale processes also control the seasonal evolution of the ITCZ and atmospheric circulation. The seasonal cycle in the equatorial Atlantic is particularly interesting because of the competing roles of ocean and land. The observed seasonal variations in SST, precipitation and surface winds reveal a tight relation between ocean and atmosphere in the tropical Atlantic (Fig. 1). During boreal winter (DJF) the precipitation sits close to the equator over the area where the SST is maximum and where the northern and southern hemisphere winds converge. The seasonal cycle of the SST is characterized by a rapid cooling from April to July, caused by stronger southeasterly winds close to the equator. These winds produce upwelling (downwelling) and elevate (deepen) the thermocline to the south (north) of the equator. This intensifies the contrast between warm waters north of the equator, and cold waters south and at the equator (Moore et al. 1978). The minimum in the SST along the Gulf of Guinea—known as the Atlantic Cold Tongue (ACT)—lasts the whole boreal summer (JJA). This creates a strong temperature gradient between ocean and land, and it is associated with a strengthening of the southerly winds. The seasonal ACT and the intensified winds coincide with the northward migration of the rainband away from the equator onto the West African continent, with intense precipitation reaching as far north as 15°N in boreal summer.

The seasonal evolution of the ITCZ is largely determined by differential hemispheric heating. The extratropical seasonal cooling and heating of the hemispheres shift the ITCZ towards the warmer hemisphere (Kang et al. 2009), thus moving northward (southward) in summer (winter) (here we refer to the Northern Hemisphere seasons). Li and Philander (1997) (LP97 hereafter) suggest that seasonal changes in the eastern tropical Atlantic SST are the passive response of the ocean to the seasonal changes in the winds, which in turn are mainly driven by the changes in land temperatures, and that local air–sea interactions play a minor role. Other studies suggest that the annual cycle of SST is a product of ocean–atmosphere interactions (Okumura and Xie 2004; Druyan and Fulakeza 2015; Meynadier et al. 2016; Diakhaté et al. 2018). Okumura and Xie (2004) (OX04 hereafter) showed that the ACT intensifies the southerly winds in the Gulf of Guinea, and these push the rainband farther north over the land. Supporting this, other modelling (Meynadier et al. 2016) and diagnostic (Diakhaté et al. 2018) studies found meridional SST and SLP gradients, and meridional winds over the Gulf of Guinea to be tightly related. In contrast, the regional modelling study of Druyan and Fulakeza (2015) suggested that the development of the ACT had little impact on the development of the West African summer Monsoon (WAM), but found an impact on its strength. While the impact of the continental WAM on ocean surface winds contributes to the cooling in the SST, the importance of the SST cooling for the development of the monsoonal winds, and subsequently, the precipitation is debated.

There is agreement that ocean–atmosphere interactions are important for the seasonal cycle of the ITCZ, the surface winds, and the SST over the western equatorial Atlantic. In particular, both LP97 and OX04 found a strong dependence of the seasonal cycle of surface winds in this region on the underlying SST. Furthermore, observational and modelling studies indicate that year-to-year variations in the ACT strongly influence the rainfall and the winds in the western equatorial Atlantic (Zebiak 1993; Chang et al. 2000; Keenlyside and Latif 2007; Richter et al. 2014). Diagnostic analysis indicates that the surface wind convergence in this region is not closely related to the underlying SST and SLP gradients, and rather related to convective heating anomalies (Richter et al. 2014; Diakhaté et al. 2018).

The present study investigates the role of the atmosphere–land–ocean interactions in driving the seasonal cycle of the atmosphere in the tropical Atlantic basin, with a special focus on the impact of the SST in the eastern Atlantic, where the WAM dominates the annual variability in the atmosphere. We perform a series of sensitivity experiments with an atmospheric general circulation model (AGCM) to identify the impact of the SST on the seasonal variability of the atmosphere. We use different statistical techniques to carry out an objective quantification of the impact of SST and land surface temperature (LST) on the seasonal cycle of the low-level atmospheric circulation and deep convection. We find the main covariability ocean–atmosphere coupled mode related to the equatorial SSTs variability in the tropical Atlantic using Maximum Covariance Analysis (MCA). We also identify a dynamical mechanism that can explain the impact of the SST gradients on surface wind convergence, and subsequently deep convection, in the central and eastern equatorial Atlantic.

Section 2 describes the AGCM, the experimental design, and the datasets used. In Sect. 3 we summarise the two statistical techniques we use: (1) statistical verification and (2) a coupled field multivariate analysis. We present and discuss our main findings in Sect. 4 and summarize our conclusions in Sect. 5.

2 Data, model, and experimental design

2.1 Data and AGCM simulations

The following observational based products are used to characterise the observed seasonal cycle: Japanese 55-year Reanalysis (JRA-55, Kobayashi et al. 2015) dataset at a $1.25° \times 1.25°$ horizontal resolution with daily time resolution; Tropical Rainfall Measurement Mission 3B42 (TRMM, Huffman et al. 2007) daily data with horizontal $0.25° \times 0.25°$ resolution; and the National Oceanic and Atmospheric Administration (NOAA) Optimal Interpolated Sea Surface Temperature (OISST, Reynolds et al. 2007) dataset. We calculate the monthly climatological averages for the period 1982–2013 (except for TRMM that the period is 1998–2012) to characterise the seasonal cycle.

We conduct numerical simulations with the version 4.0 of the Community Atmospheric Model (CAM4) (Neale et al. 2013), which is a low-top global finite-volume gridded AGCM developed by the National Center for Atmospheric Research (NCAR). The model is integrated with the standard $0.9° \times 1.25°$ horizontal resolution and 26 vertical layers (from the surface up to 5 hPa). The deep convection parameterization in CAM4 is based upon the bulk mass-flux scheme of Zhang and McFarlane (1995).

The model is forced with realistically varying solar radiation, and with different prescribed SSTs, which are derived from the OISST. This model also requires the prescription of the sea ice coverage (SIC), which is set to be the observed fully varying field provided with the OISST in all experiments.

We carry out three numerical simulations for the period 1982–2013, in order to understand the impact of the seasonal cycle of the tropical Atlantic SST on the atmosphere. In the control run (**climSST**), daily mean climatological observed SSTs are prescribed globally, so that the interannual variability of SST is removed while the seasonal cycles of both land and ocean are retained. In the second run (**meanSST**), the model is forced with annual mean observed SSTs prescribed globally; hence, the insolation over the land is the only time-varying surface driver of the atmosphere relevant here. In the third run (**eqmeanSST**), annual mean observed SSTs are prescribed in the equatorial Atlantic (10S-5N, 70W-20E), and observed climatological SSTs are prescribed elsewhere; with this experiment we can investigate the role of the ocean variability in the equatorial Atlantic Ocean. We also performed a fourth historical simulation where the AGCM is forced by realistic SSTs including inter-annual variability, but the comparison of the resultant fields show that interannual variability of the SST does not greatly affect the seasonal cycle of the atmoshere (not shown), so we do not consider this experiment further.

The seasonal cycle of the simulated atmospheric fields is calculated as the monthly averaged daily climatology of the corresponding period of 32 years. Our analysis focuses on three fields representative of the low-level atmospheric quantities associated with WAM: zonal and meridional surface winds, and total precipitation (hereafter, **U**, **V** and **PRECT**, respectively) in the tropical Atlantic basin. We also separately analyse the western (WEA, 4°S–4°N, 40°–20°W) and eastern (EEA, 4°S–4°N, 16°W–4°E) equatorial Atlantic regions.

2.2 Model performance in representing the tropical Atlantic climate

The model represents reasonably well the seasonal cycle of both precipitation and surface winds (Fig. 2), although our model tends to underestimate the amplitude of the zonal winds in the subtropics, where a stronger easterly component is evident. The equatorial region shows a higher agreement than the subtropics in surface winds, but the differences of

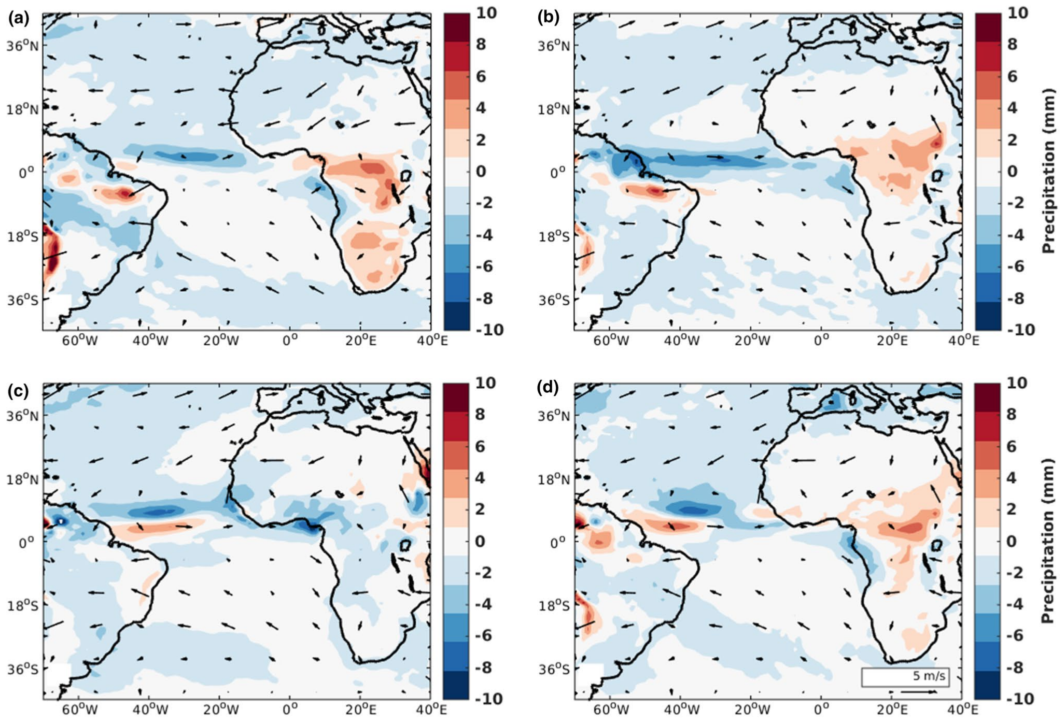

Fig. 2 Differences in rainfall in mm (shading) and surface winds in m/s (vectors) between climSST and TRMM dataset and between climSST and JRA dataset by seasons. Negative (positive) differences in rainfall are represented with blue (red) colors

surface winds between the model and the observations are still substantial (Fig. 2) along the equator. The model shows less precipitation than observations along most of the equatorial Atlantic probably associated with the errors in the representation of the surface winds (Fig. 2). There is a positive (negative) bias in zonal (meridional) winds over Angola coastal region in the southeastern Atlantic (e.g., Koseki et al. 2017). The monsoon region experiences stronger westerly and southerly winds in the annual average with respect to the observations; this might be related with the wet bias seen over west African continent.

The above enumerated biases are not only present in our model, but are common to most AGCMs (Richter 2015). Our study focuses on the equatorial Atlantic ocean and its surroundings, which we define as the region 70W–40E, and 15S–15N. In this region the errors of the model in simulating the surface winds are rather small, and in any season smaller than 20% of the actual observed value (Figs. 1, 2). The discrepancies in the precipitation compared to the observations (Figs. 1, 2), though, are larger, which is also a common issue present in many different GCMs (Mohino et al. 2011). The simulated and observed seasonal cycles of precipitation are strongly correlated (Fig. 3b) and the largest contribution to the mean squarre error (MSE) (Fig. 3c) with respect to the observations comes from the annual mean differences (Fig. 3a). Thus, the model captures really well the seasonality of the observations and hence is a suitable tool for investigating the seasonal cycle in the tropical Atlantic.

3 Statistical methodology

3.1 Verification of the joint distribution

We quantify the differences between datasets using a method analogous to the well-known forecast verification (Wilks 2011). Forecast verification is based, in general, on the study of the properties of the joint distribution function formed by the predictions and observations (Murphy and Winkler 1987). Here we perform three different verifications: (1) climSST run—observations, (2) meanSST run—climSST run and (3) eqmeanSST run—climSST run. In the first case, we evaluate the AGCM-ability to simulate the observations. In the second and third cases the joint distribution is formed from the model output values of each experiment. This provides an objective assessment of the agreement between simulations with alterned boundary conditions. The following statistical scores are used: standard deviation, the mean error (ME) or bias, the Pearson correlation coefficient, and the mean square error (MSE). Since we are interested in the seasonal cycle, all the indices are calculated for just 12 points in time corresponding to each month of the year. "Appendix" further describes the methodology. The results of these statistical analyses will be shown in Sect. 4.2. Note that the error in the model-to-model verification is interpreted as the difference between two sensitivity experiments.

3.2 Maximum covariance analysis

Maximum covariance analysis (MCA) or singular value decomposition (SVD) is a commonly used technique to identify a coherent temporal-spatial variability between two different fields. The method is based on the calculation of the principal vectors (pairs of empirical orthogonal functions, EOFs) that maximize the covariance between the two different fields and account for the largest fraction of the cross-covariance between the two jointly analyzed variables (Bjornsson and Venegas 1997) (see "Appendix" for a detailed explanation of the method).

We apply the MCA to three different cases to find the covariability patterns between ocean–atmosphere and between land–atmosphere. This way we identify the impact of land and ocean surface temperatures onto the atmosphere separately, and the mechanisms leading the spatial patterns of the coupled variability. In climSST-meanSST case, we apply the MCA to the difference between climSST and meanSST experiments using the SST as the predictor and the atmospheric variables U, V and PRECT as the predictands. This way we can identify the spatial patterns related with the influence of the ocean seasonal variability on the

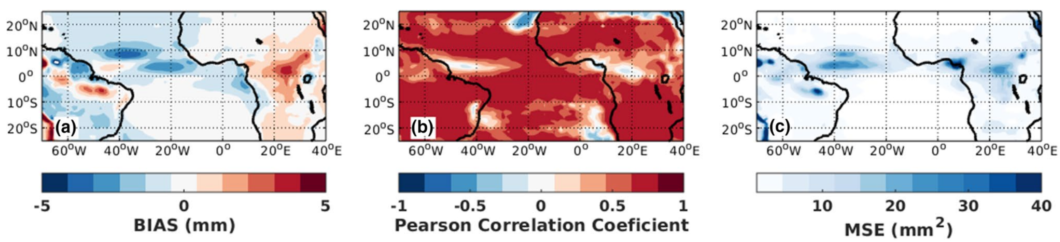

Fig. 3 Statistical indices accounting for the skill of our model. **a** Bias, **b** correlation and **c** MSE are shown for simulated precipitation from climSST run against TRMM dataset

atmosphere. In meanSST case, we perform the MCA of the meanSST experiment using the LST as the new predictor, and the same atmospheric variables as predictands. Thus, in this case, we can isolate the covariability between LST and the atmosphere when the annual cycle of SST is eliminated. The whole tropical Atlantic (30S–30N, 70W–20E) basin is considered for the first two cases. A third case, climSST-eqmeanSST, is presented where we analyze the coupled field patterns for the difference between climSST and eqmeanSST, using SST as the predictor against the atmospheric variables and focusing only in the equatorial Atlantic region (10S–5N, 70W–20E), since the difference of the SSTs is zero elsewhere. In this last case we only capture the covariability patterns between equatorial Atlantic SST and the tropical atmosphere. We will present the results of the statistical analysis with this methodology in Sect. 4.3.

The MCA is computed using the 12 month climatologies (and differences) computed from the runs. MCA requires a sufficient number of points to be efficient. Although we only have 12 points in time we find that the size of the grid is big enough and the annual cycle in the tropics dominant enough to build a cross-covariance matrix large enough for producing statistically reliable results.

4 Results

4.1 Simulation of the seasonal cycle

In this subsection, we show the difference in the seasonal cycle of the simulated atmospheric variables between climSST, meanSST and eqmeanSST runs to survey the impacts of global and equatorial Atlantic SST seasonal cycle on the atmosphere over the equatorial Atlantic.

In the western equatorial Atlantic (WEA) the observed zonal wind exhibits an annual cycle peaking in March to April, while in the eastern equatorial Atlantic (EEA) the annual cycle is dominated by a semiannual cycle peaking in February to March and September (Fig. 4). The meridional wind shows an annual cycle in both regions. Removing the annual cycle in the global SST (meanSST) reduces drastically the seasonal variability of surface winds in WEA, while in EEA the meridional component still exhibits a pronounced annual cycle because of the major role of the monsoon in that region. However, the abrupt jump of the meridional wind in spring associated with the onset of WAM is missed in the meanSST run. On the other hand, the zonal wind over EEA shows a very similar semiannual cycle for the climSST and meanSST runs, but it is weaker in meanSST. This indicates that neither the WAM nor the seasonality of SST play a role in the

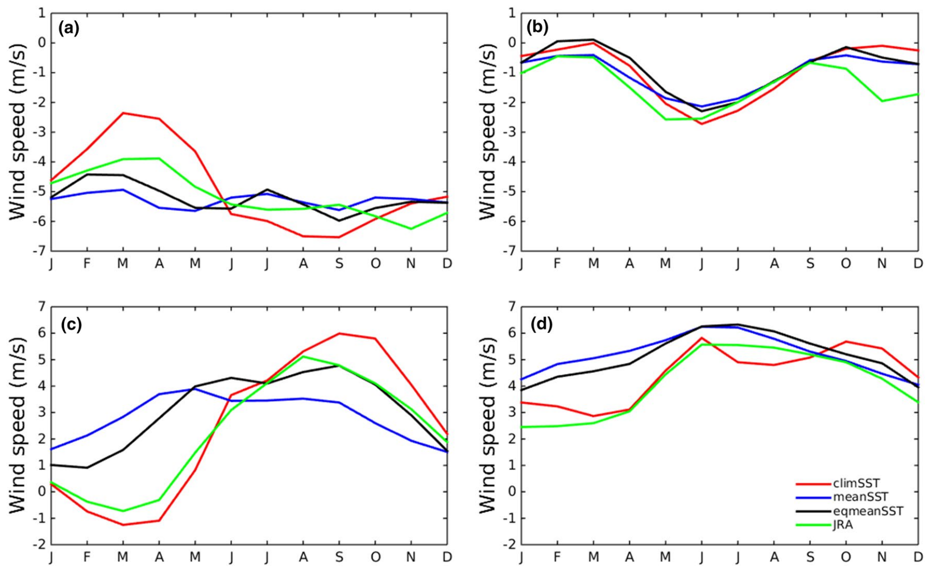

Fig. 4 Seasonal cycle of the surface winds in the WEA (4°S–4°N, 40°–20°W) (left panels) and EEA (4°S–4°N, 16°W–4°E) (right panels) regions for climSST (red), meanSST (blue) and eqmeanSST (black) runs and for JRA reanalysis (green). The panels (**a**) and (**b**) show the zonal winds, and (**c**) and (**d**) the meridional winds

seasonal cycle of EEA zonal winds. The semiannual cycle in zonal wind is poorly represented in all simulations, as they miss the strengthening of the zonal winds in October and November.

The impact of SST outside the equatorial Atlantic on the surface winds is estimated by comparing the meanSST and eqmeanSST runs (blue and black lines, Fig. 4). The EEA surface zonal winds have a similar seasonal evolution in EEA in both runs, with the largest difference during February to May. The annual cycle of meridional winds in the EEA is quite similar in both runs, while in the WEA the seasonal cycle is stronger in the eqmeanSST run. In summary, local SST have a large impact on the seasonal cycle of surface zonal and meridional winds in the WEA and on meridional winds in the EEA, while remote SST have only a secondary role.

Our model (climSST run) captures the seasonal cycle of the precipitation in the west and eastern tropical Atlantic, but it shows some discrepancies to the observations: in the east and the west the maximum during the boreal summer monsoonal season occurs later and is displaced south (Fig. 5c, d), which is a common issue in other AGCMs (Mohino et al. 2011). The phasing of the precipitation in the WEA region is weaker and not well captured in the run with the SSTs set to their annual mean globally (meanSST run) (Fig. 5e); over the EEA the ITCZ is constrained to a narrow band north of the equator, and it does not migrate northward during boreal summer as in observations (Fig. 5f). Moreover, the

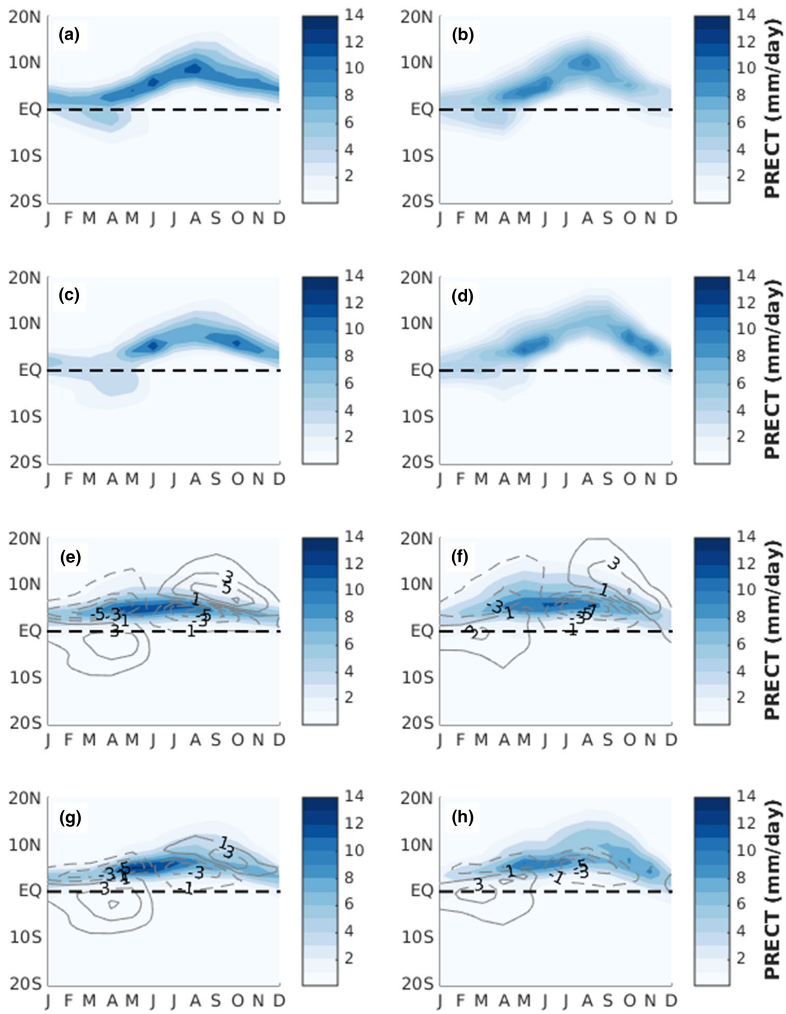

Fig. 5 Latitude-time precipitation Hovmoeller diagram for TRMM dataset (**a**, **b**), climSST (**c**, **d**), mean SST (**e**, **f**) and eqmeanSST (**g**, **h**) for the WEA (left panels) and EEA (right panels) regions. The monthly mean data has been longitudinally averaged along (35–15W) and (10W–10E) for WEA and EEA regions, respectively. Total precipitation is shown in blue shading. The differences between meanSST and climSST, and between eqmeanSST and climSST are highlighted in the panels **e**–**f** and **g**–**h**, respectively, with grey solid (dashed) line contours showing positive (negative) values

characteristic two maxima are not present in the meanSST run, but only one prolonged maximum in June-to-July instead, in agreement with the evolution of the meridional wind (Fig. 4d). The SST at seasonal timescales has a stronger impact on the precipitation patterns in the WEA comparing to that in EEA (Fig. 5e–h), where the latitudinal position of rain band still fluctuates even with annual mean global SST (meanSST) (Fig. 5e, f). The maximum in precipitation does not migrate but significant amount of precipitation (up to 6 mm/day) is present at 10°N (Fig. 5f). In the western equatorial Atlantic, the precipitation band is constrained to a much narrower band (4–8°N) for the same simulation without seasonality in global SSTs (Fig. 5e). Constraining only the equatorial Atlantic SST to its annual mean reduces the latitudinal extent of the seasonal migration of the ITCZ in both the eastern and western Atlantic (Fig. 5g, h).

The impact of equatorial Atlantic variations in SST is estimated by the differences between climSST and eqmeanSST experiments (Fig. 6). The precipitation difference is minimum in winter (DJF), coinciding with minimum SST difference (i.e., when the SST most resembles the annual mean). During the spring (MAM), the observed SST reaches its maximum so that SST in climSST is warmer than in eqmeanSST, and this favours more rainfall over the equatorial Atlantic (Fig. 6b). In summer (JJA), the ACT is fully developed enhancing the northward displacement of the ITCZ over the Atlantic in climSST run (Fig. 6c). In SON the ACT is still distinguishable and the precipitation differences are similar to those in summer (Fig. 6d). The effects of the ACT on precipitation are mainly local and over the ocean, but remarkable differences in rainfall are still observed over land in northeast of Brazil in MAM, and West Africa during the JJA season. The development of the Atlantic cold tongue during boreal summer suppresses rainfall along the Gulf of Guinea coast, leading to a more developed West African Monsoon in climSST. Similar enhancement of regional monsoon circulation due to the cold SST can be seen in East Asian Monsoon system (e.g., Koseki et al. 2013).

4.2 Statistical quantification of the impact of the SST on the atmosphere at seasonal timescales

In this subsection, we present a statistical comparison of simulated atmospheric variables between climSST and eqmeanSST runs to quantify to what extent atmospheric

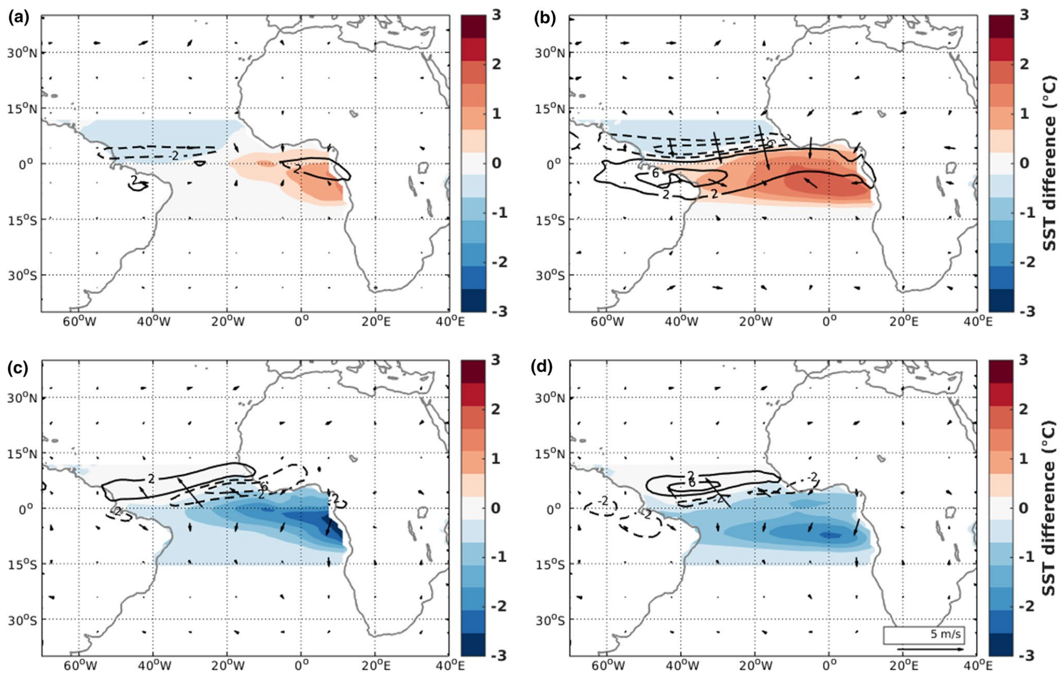

Fig. 6 Differences in rainfall (contours), surface winds (vectors) and SST (shading) between climSST and eqmeanSST runs by seasons. Negative (positive) differences in rainfall are represented with dashed (solid) lines. Negative and positive differences in SST are shown in blue and red, respectively. All the units are the same as in Fig. 1

seasonal variability is controlled by the seasonal cycle of the equatorial Atlantic SST. The MSE identifies the regions where there are larger differences between runs, i.e. where the equatorial SST is more relevant.

The decomposition of the MSE (see Eq 1 in the "Appendix") identifies the terms contributing most to increase the differences between the runs. The bias (Fig. 7d–f) is an indicator of the annual mean difference between the runs. Variances (Fig. 7g–l) contribute to the MSE when their magnitude is high and they differ between the two runs, and the covariance between them is low (Fig. 7m–o). In this analysis, the regions with high (low) covariance are those where the equatorial Atlantic SST has little (strong) influence on the atmosphere, and in this case the similar (differing) seasonal evolution in the two model runs does not (does) increase the MSE.

The bias and variance terms for precipitation are substantial and contribute to the MSE (Fig. 7d, g, j). The bias in precipitation is consistent with the strongly reduced seasonality in the latitudinal position of the ITCZ in the eqmeanSST (and meanSST) run (Fig. 5g, h), and this is also evident in the lower variance in the eqmeanSST run (Fig. 7j) with respect to the climSST run (Fig. 7g). There is a high positive covariance between climSST and eqmeanSST runs in the ITCZ region north of the equator in the western Atlantic, and in the far eastern equatorial Atlantic, and over continental regions (Fig. 7m). The covariance is low for precipitation over the western and central equatorial Atlantic and this leads to a high MSE in these regions.

The bias is relatively low for zonal and meridional surface winds and the variance terms mostly explain the MSE. Compared to climSST, the variance in zonal wind in eqmeanSST is less in the western equatorial Atlantic (Fig. 7h, k), and the variance in meridional wind is less in both the western and northwestern equatorial Atlantic (Fig. 7i, l). The covariance between eqmeanSST and climSST runs is also

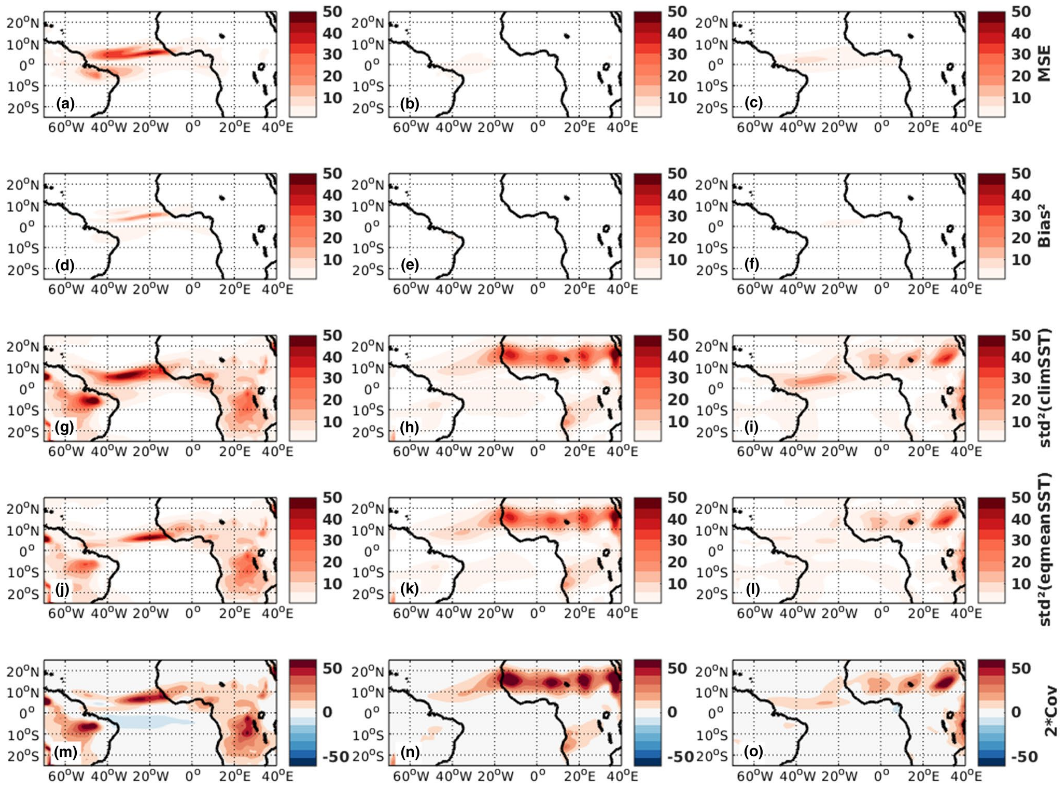

Fig. 7 Terms contributing to the mean square error between climSST and eqmeanSST runs of precipitation (left column), zonal (center column) and meridional (right column) winds. Total MSE (first row), bias (second row), standard deviation of the climSST (third row) and eqmeanSST (fourth row) runs, and covariance (fifth row) are shown. The units of the precipitation and the surface winds are mm^2 and m^2/s^2, respectively

low for surface wind in these regions (Fig. 7n, o). The MSE in the eastern equatorial Atlantic is mostly related to low covariance.

In our framework, the squared correlation maps for simulated precipitation and surface winds between climSST and meanSST (eqmeanSST) runs are a measure of the variance explained in these quantities in the absence of seasonal variability in global (equatorial Atlantic) SST (Fig. 8). A low (high) squared-correlation indicates that the impact of the seasonal variability of the SST is strong (weak). The seasonal cycle of the global SST can explain a high amount of the variance of the precipitation over the tropical Atlantic Ocean, with the exception of a narrow equatorial band in the western and easternmost sides of the basin (Fig. 8a). A high amount of the variance of terrestrial precipitation surrounding the tropical Atlantic basin can be explained without the annual cycle in global SST: 50–70% in the central/north Sahel and 80–100% in subtropical South America and Southern Africa. Thus, the monsoonal flow, which is generated by the land–ocean heat contrast and mainly controlled by the land surface temperature, seems to be the main driver of the precipitation in the Sahel region. However, our results suggest that there is also a smaller, but remarkable impact of SST on the rainfall over that region (Fig. 8a). Most of the seasonal cycle of the zonal wind in central equatorial Atlantic, Sahel and Amazon can be explained without the seasonal changes in the global SST (Fig. 8b). This is not the case in the western equatorial Atlantic, far eastern equatorial Atlantic, and northeast of Brazil (Hastenrath 2012), where the SST is known to play a key role in the determination of the seasonal cycle of the atmosphere. The SST seasonal cycle is crucial to induce the seasonal cycle in meridional wind along the equatorial Atlantic basin (Fig. 8c). The SST is also relevant for the determination of the winds along the *WAM generation oceanic region* as defined by Gallego et al. (2015).

The equatorial SST mostly affects the seasonal cycle of the atmosphere locally (Fig. 8d–f). Equatorial Atlantic SST variability explains most of the precipitation seasonal cycle over the equatorial Atlantic and has relevant impacts on precipitation for coastal areas of both South America and West Africa (Fig. 8d). In particular, around 40–60% of the precipitation cannot be explained in the absence of equatorial SST variability in the coastal Sahel. In central and north Sahel, the SST outside the equatorial Atlantic, explain up to 60% of the precipitation variance (from comparison between Fig. 8a, d). In the northeastern Brazil the precipitation is highly dependent on the equatorial Atlantic SST, with more than 80% explained variance from 10S to 10N along the coastal regions (Fig. 8d). The zonal wind is also highly influenced by the equatorial Atlantic SST in the WEA and in coastal EEA, but it seems independent of SST variability in the central equatorial Atlantic (Fig. 8e). Equatorial SST variability explains most of the variance of the meridional wind over the Gulf of Guinea (Fig. 8f). The comparison between the set of Fig. 8a–c, d–f indicates that SST outside the equatorial Atlantic have a remote impact in the equatorial band, especially in the surface winds at WEA region. In the particular case of the zonal winds, the comparison between Fig. 8b, e shows that the variability of the off-equatorial SSTs explain more variance in zonal winds in the WEA than equatorial SSTs. [Note that blue (red) indicates variance (not) explained by SSTs]. It also shows that SST variations outside the equatorial Atlantic are more important for the seasonal cycle of Sahel rainfall (Fig. 8a, d).

This analysis indicates that equatorial Atlantic SST variability is the main driver of the seasonal cycle in precipitation

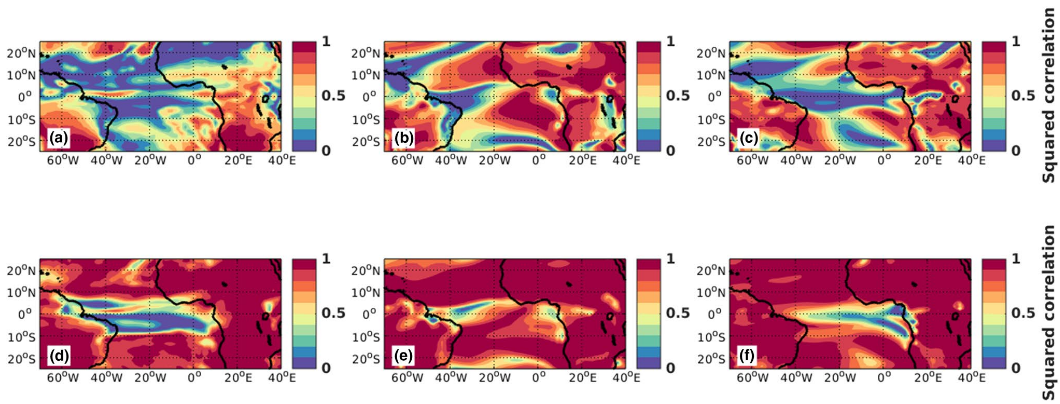

Fig. 8 Squared correlation between climSST and meanSST runs (top row) and between climSST and eqmeanSST runs (bottom row), for the precipitation (left), zonal (center) and meridional winds (right)

and surface winds in the western equatorial Atlantic, and it drives a substantial portion of seasonal cycle in precipitation and meridional winds over the eastern equatorial Atlantic.

4.3 Co-variability of the tropical Atlantic ocean-atmosphere-land coupled system at seasonal timescales

As shown in the previous subsection, low covariance is the main cause of the MSE between the control (climSST) and sensitivity (meanSST and eqmeanSST) runs in terms of the annual cycle of atmospheric quantities. A further analysis of the co-variability modes between ocean, land and atmosphere using MCA (see "Appendix") is performed to understand more deeply how the different components of the ocean-atmosphere-land system covary with each other, and to identify the role of the SST in the annual cycle. We only show the 1st covariability mode because in every case it explains by far the most of the squared covariance in all MCA cases we perform (97–99%); this confirms the dominance of the seasonal cycle in the tropics. We perform MCA for three different cases: climSST-meanSST, meanSST and climSST-eqmeanSST (Sect. 3.2). In climSST-meanSST case we investigate the coupled modes between atmosphere and SST over the tropical Atlantic domain while in climSST-eqmeanSST we investigate coupled variability only over the equatorial Atlantic domain. In the meanSST case, we analyze the coupled modes of the LST and atmosphere over the tropical Atlantic.

We consider the first MCA case on coupled variability between the ocean and atmosphere in the whole tropical Atlantic (climSST-meanSST). The homogeneous SST regression map shows a marked interhemispheric temperature gradient associated with the seasonal variations in insolation, with out-of-phase anomalies in the southern and northern hemispheres. However, the ocean dynamical processes contribute to several features in the SST maps not directly related to insolation: strong Senegal-Mauritanian and Angola-Benguela coastal upwellings, and the characteristic development of the cold tongue in the Gulf of Guinea during boreal summer (Fig. 9a). The precipitation and surface winds in the tropical band exhibit a prominent seasonal evolution (Fig. 9b) that is synchronized with the SST thermal forcing, with maximum anomalies in late boreal summer when the ITCZ is displaced to the north (Fig. 9c). The seasonal evolution of the ITCZ (in the

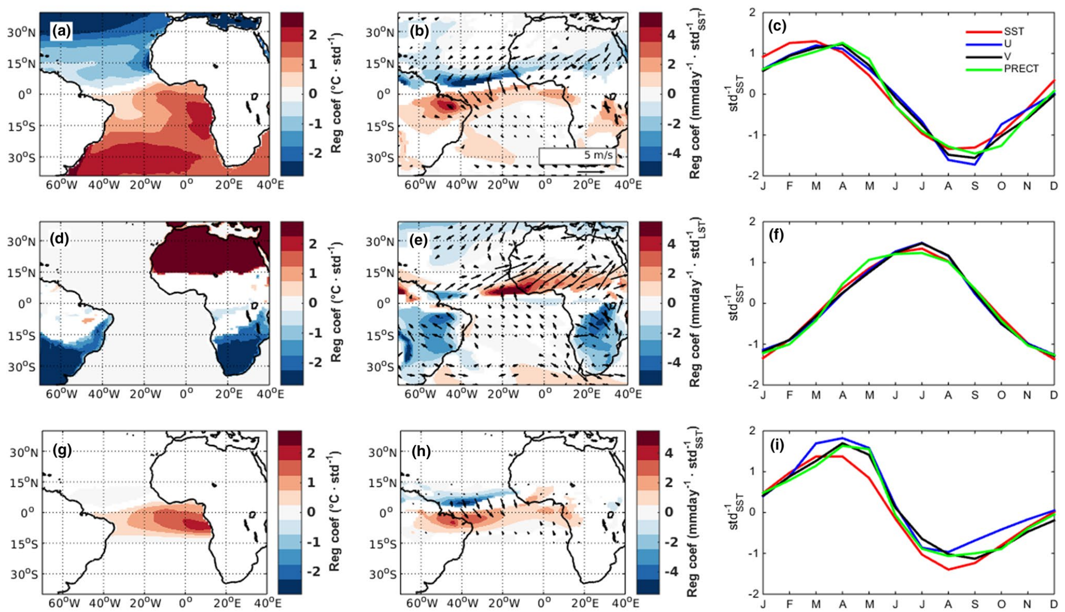

Fig. 9 (Top row) Spatial patterns of the first mode of the MCA between SST and atmospheric fields for climSST-meanSST case. SST homogeneous map (left panel), SST-(PRECT, U, V) heterogeneous map (center panel) and expansion coefficients (right panel) of the coupled fields. In the heterogeneous map, surface winds are represented with vectors and SST with shaded contours. All units are standarized to the predictor variable units. Only 95% significant anomalies are shown. The first mode accounts for more than 96% of the squared cross-covariance for every pair of variables. (Central row) Same as top row but for meanSST case with LST as the predictor variable instead of SST. (Bottom row) Same as top row but for climSST-eqmeanSST case

MCA coupled SST-atmosphere mode) is evident over the entire equatorial Atlantic Ocean. West African precipitation does not depend much on the SST, while northeastern Brazil does (Fig. 9b).

The dominant MCA mode of LST versus atmospheric variables in the meanSST case highlights the influence on the atmosphere of the seasonal variability of the LST, which is mainly controlled by that of the insolation. The homogeneous LST map (Fig. 9d) shows an interhemispheric temperature gradient analogous to that in the SST in the previous case. The maximum interhemispheric differences in LST coincide with the seasonal march of the sun (Fig. 9f). The comparison among the expansion coefficients of climSST-meanSST and meanSST cases reveals that the SSTs influence the timing of the precipitation. The coefficient of expansion for the SST MCA mode has the precipitation peak in August–September (Fig. 9c), coinciding with the fully developed cold tongue, while the LST MCA mode has the precipitation peak in July (Fig. 9f). Ocean thermodynamical and dynamical processes likely cause the maximum interhemispheric differences in SST to lag that in insolation by 1–2 months. The coupled heterogeneous regression map shows that LST is highly related to the Sahelian precipitation over the western Africa and with the associated southwesterly winds during boreal summer (see Fig. 9e). A clear monsoonal pattern is evident with strong large-scale winds blowing from the ocean towards the land from April to September transporting moisture and triggering the precipitation over land in Sahel. In the equatorial band we can easily distinguish two rainfall regimes; oceanic and continental precipitation, mainly controlled by ocean (SST; Fig. 9b) and land (LST; Fig. 9e) seasonal cycle variability, respectively (Gu and Adler 2004).

The ocean–atmosphere coupled mode when we only consider the equatorial SST variability (climSST-eqmeanSST case) closely resembles that of the case when we consider the global SSTs impact (climSST-meanSST case), but appears to be more localized at the equator (bottom row in Fig. 9). The equatorial SST is the main driver of the precipitation and low-level winds over the equatorial Atlantic Ocean (Fig. 9g, h). Over land, it exhibits a remarkable impact over the northeast of Brazil, where SST triggers intense precipitation during the boreal spring season (Fig. 9h, i); there is also a limited impact on coastal West African precipitation. The comparison of equatorial (bottom row in Fig. 9) and tropical (top row in Fig. 9) Atlantic SST MCA modes indicates that off-equatorial SST anomalies play a more important role in the northward migration of the ITCZ over the West African continent. Nevertheless, the equatorial cold tongue appears to play an important role in the sudden onset of WAM in boreal spring (Fig. 9i, and also Figs. 4, 5).

Our results show that the precipitation and low-level wind circulation over the Atlantic Ocean and equatorial Brazil rainfall are driven by the seasonal cycle of the equatorial Atlantic SST. LST and off-equatorial SST mostly determine the northward migration of the ITCZ in the WAM region, but equatorial SST contributes to the onset of the WAM.

4.4 Dynamics driving the low-level wind convergence in the equatorial Atlantic at seasonal timescales

In this section we explain the dynamical connection between SST and surface winds in the equatorial Atlantic. Takatama et al. (2012) performed a diagnosis of the wind convergence budget by decomposing it into three major contributions: the so-called pressure adjustment mechanism (Lindzen and Nigam 1987), the downward momentum mixing mechanism (Wallace et al. 1989; Chelton et al. 2001; Zermeño-Diaz and Zhang 2013) and a term related with horizontal advection. We follow their approach using our AGCM output to evaluate the relevance of the pressure adjustment mechanism in driving the wind surface convergence over the equatorial Atlantic. In this mechanism, the surface wind convergence is linearly proportional to the Laplacian of the SLP, and a weaker opposite relation is expected between SLP and SST Laplacians (see "Appendix").

Figure 10 shows the spatial distribution of the wind convergence, SLP Laplacian and sign-reversed SST Laplacian, computed from the differences between climSST and eqmeanSST for each horizontal component in July (when the wind convergence is stronger). Note that this analysis excludes seasonal variations in winds not related to equatorial Atlantic SST. The meridional components of the sign-reversed SST Laplacian and SLP Laplacian are much larger than the zonal ones and they can explain most of the variance of the total wind convergence. They match quite well over the regions where the meridional SLP Laplacians and convergence are strong, in particular, in the oceanic ITCZ region. A weaker but remarkable relationship is also present between meridional component of the SLP Laplacian and sign-reversed SST Laplacian in that region.

Focusing on the equatorial band, we see a stronger relation over the EEA than over the WEA in July (Fig. 10). The relationship between SLP Laplacian and wind convergence remains strong (correlation ~ 0.64) in EEA region when considering all calendar months (Fig. 11a), and it is weak in the WEA (not shown). The weaker positive correlation between SLP and sign-reversed SST Laplacians remains in the EEA when considering all calendar months (Fig. 11b). Thus, the pressure adjustment mechanism appears to hold in the east of the basin.

The spatial variations in the relation among the different terms in the pressure adjustment mechanism are investigated across the equatorial Atlantic, by using 1.25° longitude and 8° latitude (4S–4N) zonally sliding window correlations and

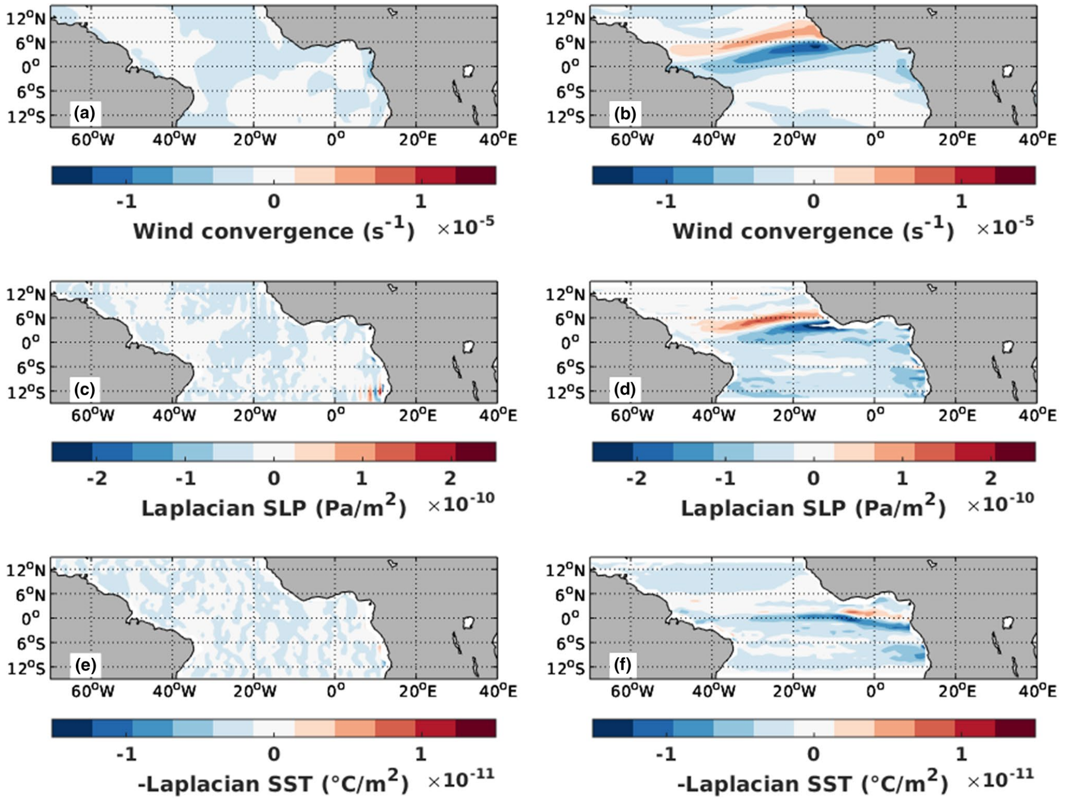

Fig. 10 Surface wind convergence (top row), SLP Laplacian (central row) and sign-reversed SST Laplacian (bottom row) over equatorial Atlantic basin for the difference between climSST and eqmeanSST runs in July. Zonal and meridional components are shown in left and right columns, respectively. Red and blue regions correspond to positive and negative values of the Laplacian and to convergence and divergence zones, respectively

considering all calendar months (Fig. 12). The validity of the mechanism extends from the eastern equatorial Atlantic to the center of the basin (around 20W) with correlations between SLP Laplacian and wind convergence exceeding 0.7, and correlations between SLP and SST Laplacian around 0.3 (Fig. 12a, d). In the far western Atlantic the correlations are in both cases weak and even negative. The relation is mainly determined by the meridional component of wind convergence, SLP Laplacian, and sign-reversed SST Laplacian (Fig. 12c, f). This result is consistent with seasonal variations in zonal winds in the central equatorial Atlantic not being driven by seasonal variations in SST in our experiments.

The greater importance of the Lindzen and Nigam (LN hereafter) model framework in the east is also consistent with the prevailing easterly winds that induce a shallow thermocline in the east, favouring dynamically driven SST variations and air–sea interactions. Here the coupling between ocean and atmosphere is determinant for the evolution of the low-level tropospheric wind field and convergence. On the other hand, in the western Atlantic with a deeper thermocline, the air–sea interactions play a secondary role in the wind convergence, which cannot be explained by the pressure adjustment mechanism.

The zonal components of SLP Laplacian and wind convergence do not follow the LN model in the equatorial Atlantic. Even if the SST is strongly correlated with the SLP, the relationship between SLP Laplacian and wind convergence (Fig. 12b) is less than expected following the LN model (see Eqs. 12 and 13 in the Appendix). This implies that the zonal wind convergence in equatorial Atlantic is driven by other mechanims. Richter et al. (2014) found no clear relationship between surface zonal winds and sea level pressure and showed that the

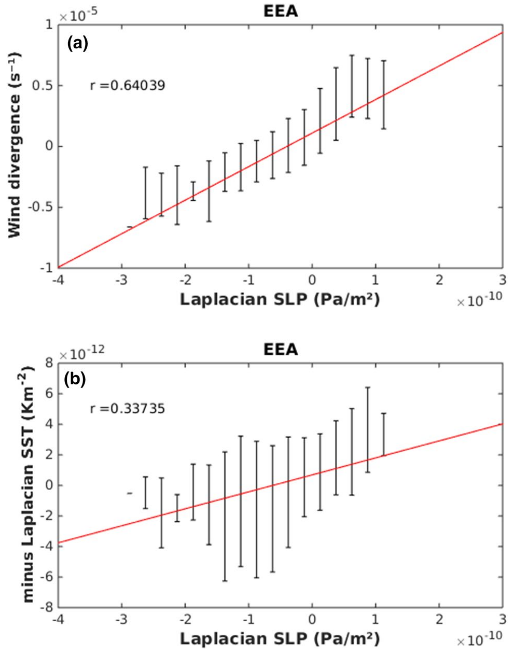

Fig. 11 **a** Relationship between the SLP Laplacian and wind convergence and **b** SLP Laplacian and sign-reversed SST Laplacian for the difference between climSST and eqmeanSST runs for EEA and every calendar month

downward momentum mixing mechanism is the main driver of the zonal winds during the MAM season in the WEA. Our results are consistent with this mechanism being a main contributor to the zonal wind convergence budget along the whole year since the correlation between SLP Laplacian and wind convergence is weak when considering all months (Fig. 12b).

In summary, in the central and eastern equatorial Atlantic we identify the LN mechanism as the main dynamical driver of the surface meridional winds; this is in agreement with the remarkable influence of equatorial SST variability on the meridional winds in this region. In the case of the zonal winds, which are insensitive to seasonal changes in SST, the LN model does not provide an explanation for the seasonal variations in zonal winds in the region. In the western Atlantic, we find no indications of LN model playing a dominant role in driving any of the wind components. The strong sensitivity of the surface winds to changes in the SST field indicates that another mechanism involving SST fronts is driving the wind convergence in the western equatorial Atlantic.

5 Summary and discussion

We have investigated the impact of the ocean on the atmosphere at seasonal timescales in the equatorial Atlantic region. We have performed a set of AGCM experiments especially designed to elucidate the role of the SST in atmosphere-ocean-land interactions in the seasonal cycle of the equatorial Atlantic. Our model results suggest a dominant influence of the seasonal variability of equatorial Atlantic SST on the precipitation over the equatorial Atlantic Ocean and over land in equatorial South America and in the Gulf of Guinea. Equatorial Atlantic SST do not have a strong influence on the WAM, as the seasonal cycle of precipitation over West Africa is reasonably represented in our simulations with annual mean equatorial SST. Although LST and off-equatorial SST play a more important role for the WAM, equatorial SST variations are critical for the abrupt shift in the meridional winds over the eastern equatorial Atlantic that are characteristic of the onset of the WAM. The meridional winds in the eastern equatorial Atlantic are strongly coupled with seasonal variations in SST, in stark contrast with the seasonal variations of zonal winds over the central equatorial Atlantic that show little dependence on the seasonal cycle of SST. On the other hand, the meridional and zonal winds over the western equatorial Atlantic are both strongly related to seasonal variations in equatorial Atlantic SST.

Equatorial Atlantic SST also explains a significant fraction of the seasonal variability of the rainfall over northeast Brazil (up to 80%) and coastal regions in the Gulf of Guinea (up to 50%), and global SST variations can explain large fractions of rainfall variability over continental tropical South America and Africa. The MCA coupled modes show that the precipitation and low-level wind circulation over the Atlantic Ocean and equatorial Brazil rainfall are driven by the seasonal cycle of the equatorial Atlantic SST. The seasonal evolution of LST and SST away from the equator mostly determine the northward migration of the ITCZ in the WAM region, but equatorial SST contributes to the sudden onset of the WAM in boreal spring. The main coupled MCA variability modes show the coexistence of two rainfall regimes (Gu and Adler 2004) in the tropical Atlantic, oceanic and continental rainfall, that are controlled by the seasonality of SST and LST, respectively.

In the eastern and central equatorial Atlantic, the atmospheric internal variability and land–ocean–atmosphere interactions are the major drivers of the low-level flow. The LN mechanism can explain the contribution of the ocean–atmosphere interactions to the low-level meridional winds. Strong meridional SST gradients modify the surface pressure field forcing strong meridional SLP gradients, which in turn drive the surface wind convergence.

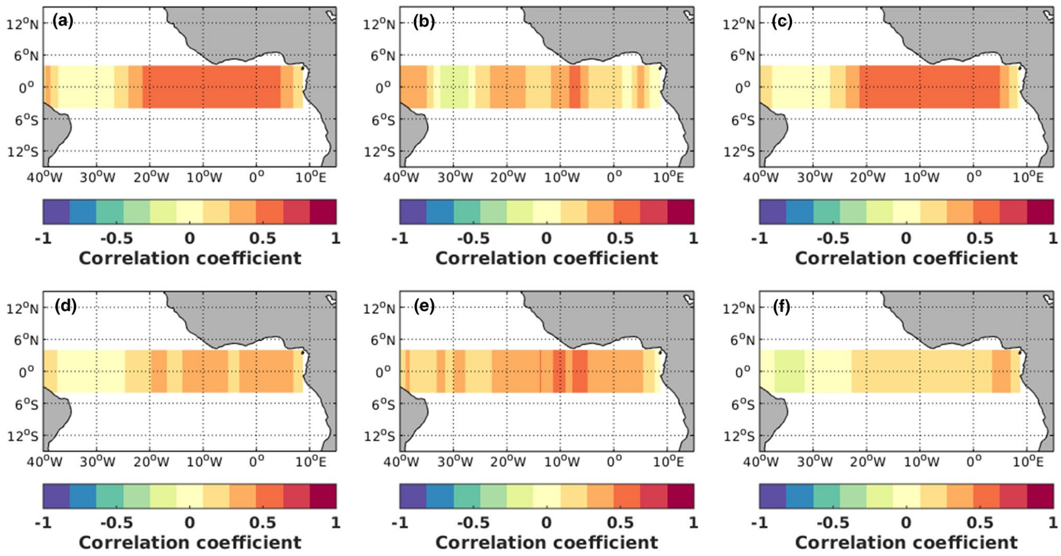

Fig. 12 Correlation maps of the SLP Laplacian and wind convergence (top row) and SLP Laplacian and sign-reversed SST Laplacian (bottom row) for sliding lat-lon boxes covering the equatorial Atlantic (4°S–4°N) basin. The left column shows the total contribution, and the central and right column show the zonal and meridional components, respectively. The sliding boxes are taken every 1.25° in longitude for the fixed latitude band (4ºS–4ºN). The correlations are calculated taking into account every calendar month

As suggested by previous studies, the zonal and meridional winds along the equator might be driven by different mechanisms. The meridional winds in the eastern equatorial Atlantic are well explained by the LN model (Richter et al. 2014, Diakhaté et al. 2018). In the western equatorial Atlantic, the LN model appears to only explain meridional wind variations at the northern and southern flanks of the ITCZ (Diakhaté et al. 2018). The zonal wind variations cannot be explained by the LN model but are likely related to entrainment and vertical mixing of zonal winds, meridional advection of zonal winds, and the large-scale response to elevated diabatic heating (Gill 1980, Zermeño-Diaz and Zhang 2013, OX04, Richter et al. 2014, Diakhaté et al. 2018). A complete computation of the zonal momentum budget would give a deeper insight into the mechanisms controlling the zonal momentum budget, but is beyond the scope of this study.

In terms of the two contrasting views on the role of SST in the eastern tropical Atlantic seasonal cycle, our results are in greater agreement with OX04 as they indicate that ACT impacts the seasonal cycle of meridional winds in the eastern equatorial Atlantic, rather than LP97 who identify little impact of equatorial Atlantic SST. However, while OX04 show that the development of the ACT has a remarkable impact on the rainfall over West Africa, we find only a muted impact more in line with Druyan and Fulakeza (2015). A likely reason for the difference could be the different experimental design. OX04 compare simulations where the seasonal cycle of equatorial Atlantic SST is set to a constant value from April onwards (i.e., when SST in the east is warmest) to simulations with a normal development of the ACT. While in our experiments we compare annual mean equatorial SST with the normal SST seasonal cycle. Thus, their equatorial SST anomalies during JJAS are approximately twice as large as ours. The larger land–ocean temperature contrast in their experiments likely enhances the precipitation response over West African continent. Therefore, the existence of previous warm SST in April appears a dominant factor for a further penetration of the ITCZ into the continent. A second reason for discrepancies could be the sensitivity to the model formulation. In particular, Druyan and Fulakeza (2015) apply a very similar SST forcing to OX04, but in a regional model configuration with limited ensemble size, and find the development of the ACT has little impact on the timing and northward migration of the monsoon. Differences between our results and those of LP97 in terms of the meridional winds also suggest a degree of model sensitivity, which might reflect differences in the modelling capabilities between several model generations. In agreement with both LP97 and OX04 model experiments, we find that the seasonal cycle of zonal winds over the eastern equatorial Atlantic is not strongly influenced by equatorial SST. However, OX04 argue based on budget analysis that the ACT does also influence the seasonal cycle of zonal winds over the equatorial Atlantic.

In terms of western equatorial Atlantic, our results agree with both LP97 and OX04 in showing that equatorial SST strongly influences the atmospheric seasonal cycle. Our finding that equatorial SST patterns strongly determine the seasonality of the winds in the western equatorial Atlantic is consistent with the Bjerknes positive feedback. In this mechanism, interannual variability in eastern Atlantic SST explains a large amount of the zonal wind variability over the western equatorial Atlantic, but explains little variability over eastern equatorial Atlantic (Keenlyside and Latif 2007). Thus, our results are consistent with the Bjerknes feedback playing a role in the equatorial Atlantic also at seasonal timescales. Note, as discussed above, that the impact of SST on zonal winds over the western equatorial Atlantic cannot be explained by the LN mechanisms; further research is needed to understand the SST impact on zonal winds in this region.

The Bjerknes feedback is one of the main mechanisms at play for the determination of the zonal gradients of SST and their relationship with zonal wind field but cannot explain the meridional SST pattern. Our finding that equatorial SST seasonal variations largely determine the pattern of the meridional winds throughout the entire equatorial Atlantic basin indicates that there must be another mechanism at play. Previous studies (Saravanan and Chang 2004; Chiang and Vimont 2004) have shown that the so-called meridional SST mode is largely determined by the wind-evaporation-SST (WES) feedback (Xie 1999; Saravanan and Chang 1999). Amaya et al. (2017) found that the WES feedback is the main contributor in driving the interhemispheric SST gradients at interannual to decadal timescales in the tropical Atlantic. In our modelling framework we found that WES-like feedback might play a role in the western equatorial Atlantic. In particular during all seasons of the year the latent heat flux anomaly in the WEA tends to drive the SST changes rather than damp them (not shown). In this region, the wind speed anomalies appear to be an important driver of the latent heat flux anomalies consistent with the WES mechanism. In EEA the pattern of latent heat flux anomalies damps the SST anomaly (that is, the ocean drives the heat flux anomaly). Further investigation on how the ocean responds to the wind field is needed to evaluate the relevance of the WES-like feedback in the equatorial Atlantic at seasonal timescales.

We showed evidences of the impact of the SST variability on surface meridional winds in the eastern equatorial Atlantic and proposed a dynamical mechanism explaining most of its variability, but surprisingly the seasonal cycle in SST does not seem to impact zonal winds in the central equatorial Atlantic. We hypothesize that the annual variability of the zonal surface winds in the central equatorial Atlantic is related to the extratropical interhemispheric differential heating that controls the large-scale Hadley Circulation. This is supported by the boreal winter to summer difference of the surface winds at the equator, the sea-level pressure in the whole south and equatorial Atlantic sector (50°S–20°N), and the pressure-meridional cross section of the winds in our experiments (Fig. 13). The comparison between climSST and eqmeanSST simulations shows little difference in the three-dimensional circulation, in particular, the southerly wind difference between JJA and DJF at the lower troposphere, indicates that the Hadley Circulation is identical in both experiments (Fig. 13b, d). Thus, the contributions from the Hadley Circulation to the equatorial trade winds are almost unchanged between the two experiments.

The mismatch between the semiannual cycle of the insolation and the strong annual cycle in SST in the eastern equatorial Atlantic remains an open question that cannot be addressed by atmospheric model experiments. In particular, it is well known the western part of the equatorial Atlantic is dominated by a local response to the annual wind forcing, while the central and eastern Atlantic have a relatively strong semiannual cycle due to ocean adjustment processes (Philander and Pacanowski 1986); these are resonantly excited by a weak semiannual cycle in surface winds at the equator (Ding et al. 2009). Our results indicate that the strength of the coupling between ocean and atmosphere might play a decisive role in the determination of the seasonal cycle in the equatorial Atlantic, with an annual (semiannual) cycle in the west (east) where the ocean–atmosphere interactions are stronger (weaker). However, other reasons might explain why a semi-annual cycle in ocean dyanmics does not lead to semi-annual cycle in SST in the eastern equatorial Atlantic.

In summary, our study shows that the seasonality of equatorial SST is important for the seasonal cycle of precipitation and meridional winds across the equatorial Atlantic, and of zonal winds in the western equatorial Atlantic, and that seasonal variations in zonal winds over the eastern equatorial Atlantic are likely determined by large-scale interhemispheric differential heating. Given the importance of zonal winds in driving the seasonal cycle of equatorial Atlantic SST, further investigation on the potential feedback of zonal winds on SST is needed to completely understand the role of the coupling between the ocean and the atmosphere at seasonal timescales in the equatorial Atlantic. Coordinated model experiments including momentum budget analysis would be very beneficial to understand the sensitivity of the results to model formulation and the impact of model biases. This is a priority given the large tropical Atlantic climatological biases that exist in the state-of-the-art models.

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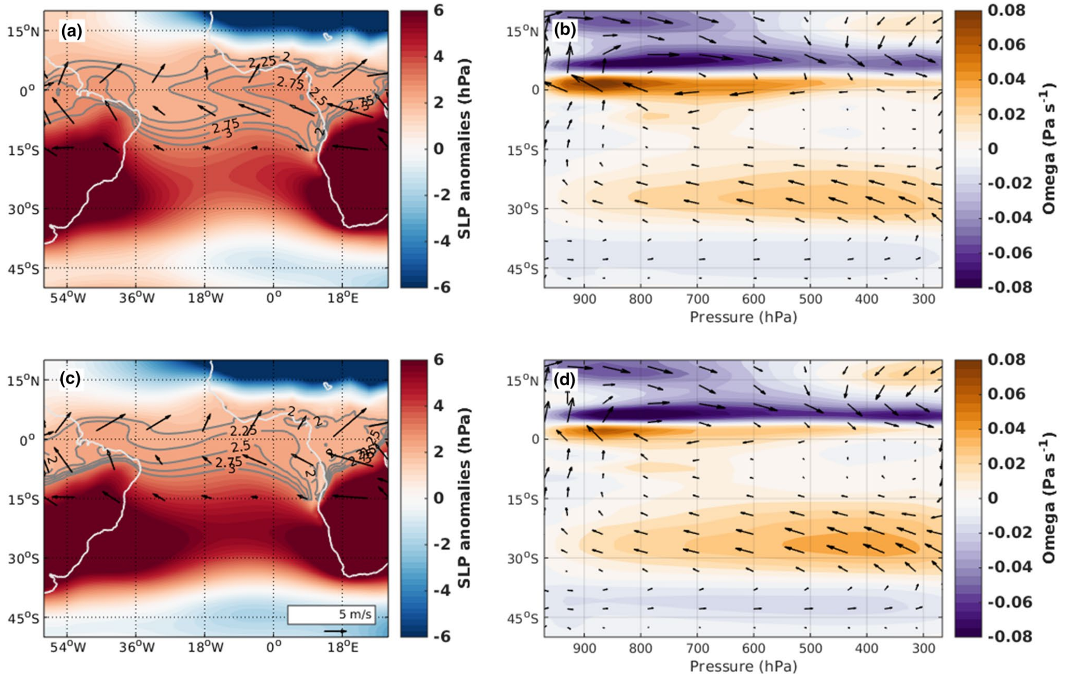

Fig. 13 Sea-level pressure anomalies of the winter to summer difference (JJA-DJF) for **a** climSST and **c** eqmeanSST simulations. The pressure contours at the equator are highlighted in grey contours. Surface winds are shown as vectors and shading shows positive (negative) sea-level pressure anomalies from the annual cycle in red (blue). The right panels show the pressure-meridional cross-section of the large-scale circulation for **b** climSST and **d** eqmeanSST simulations. Shading shows positive (negative) vertical velocity in orange (purple). Meridional-vertical winds are shown as vectors. The right panels have been inverted showing latitude in the y-axis and pressure in the x-axis so they match the latitude in the left panels, in order to facilitate the identification of the 3-dimensional large-scale circulation in the tropical Atlantic

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Appendix

Model-to-model verification

We analyze how eqmeanSST run values differ from climSST run, which will give us a hint of the impact on the atmosphere of the tropical and equatorial oceanic SST variability, respectively.

According to the Eq. (1) we can decompose the MSE into a sum of terms involving all the calculated statistical scores, and quantify the contribution of each term to the total error. This decomposition is really useful to understand the source of the difference between the two runs.

$$MSE = (\bar{y} - \bar{o})^2 + \sigma_y^2 + \sigma_o^2 - 2\sigma_y\sigma_o r_{yo} \quad (1)$$

In our framework, first term in the rhs is the bias between the output of the two simulations. Second term and third term in the rhs are the variances of climSST and eqmeanSST run, respectively. The last term in the rhs accounts for the covariance between climSST and eqmeanSST.

Explained variance

The square of the correlation coefficient in Eq. (2) is an estimate of the amount of the atmospheric variance that can be explained by the SST.

$$r^2 = \frac{Cov^2}{s_y^2 s_o^2} = \frac{EV}{TV} \tag{2}$$

r is the coefficient of correlation between atmospheric fields from climSST and meanSST/eqmeanSST runs. The squared correlation will represent a measure of the extent to which SST variability in different regions can determine the variability of the tropical Atlantic atmosphere. The squared correlation between climSST and meanSST (eqmeanSST) runs gives the atmospheric variance not explained by global (equatorial) SSTs seasonal cycle. In our framework, regions with a higher (lower) squared correlation coefficient are less (more) affected by the seasonal variability in the SST. In summary, the variance explained by SST variability is $(1-\mathrm{r}^2)$ instead of r^2.

Maximum covariance analysis (MCA)

The MCA statistical technique consists of applying the SVD algebraic method to the cross-covariance matrix (R_{SP}) of two fields, S (predictor) and P (predictand) (Suárez-Moreno and Rodríguez-Fonseca 2015). The data matrices S and P need to have the same size in time but the number of elements in space might be different.

$$R_{SP} = S' \cdot P'^T \text{ where } \quad S' = S - \langle S \rangle \quad \text{ and } P' = P - \langle P \rangle \tag{3}$$

with S' and P' anomalies respect to the annual mean denoted by $\langle\rangle$.

SVD is an algebraic technique to diagonalize non-squared matrices and compute all the components of the eigenvalue problem. Applying it to the cross-covariance matrix we find the matrices U, Q and V that satisfy the relation shown in Eq. (4).

$$R_{SP} = U \cdot Q \cdot V^T \tag{4}$$

The columns (rows) of the matrices U (V^T) are orthogonal and contain the singular vectors of S (P) data matrix. The diagonal matrix Q consists of the singular values $\gamma_k \geq 0$ placed in decreasing order of magnitude. The number of non-zero elements determines the maximum number of each SVD modes we can obtain (Venegas 2001). The evolution in time of the spatial patterns, named as the expansion coefficients, are obtained by projecting each field onto its respective singular vectors as shown in Eq. (5).

$$C_S = U^T \cdot S' \quad C_P = V^T P' \tag{5}$$

Each SVD mode of covariability between S and P is determined by a pair of spatial patterns (one for each field), a pair of expansion coefficients describing the evolution in time of each spatial pattern, and a singular value indicating how much of the squared cross-covariance between the two fields is accounted for by each mode (Storch 1999). Each singular value is proportional to the squared covariance fraction accounted by each mode as shown in Eq. (6).

$$scf_k = \frac{\lambda_k^2}{\sum_i^r \lambda_i^2} \text{ with } \quad \lambda_k = \lambda_1, \lambda_2, \dots \lambda_n \tag{6}$$

where k represents the k-th dominant mode and r the chosen truncation limit.

The k-th *homogeneous (heterogeneous) correlation map* (Eqs. 7, 8, respectively) can be constructed as the map of correlation coefficients between the principal component of the corresponding mode k of a field and the values of the same (other) field at each grid point.

$$r[A^k(t), S(t)]; \quad r[B^k(t), P(t)] \tag{7}$$

$$r[A^k(t), P(t)]; \quad r[B^k(t), S(t)] \tag{8}$$

where A and B (see Eqs. 9 and 10) are the principal components of the S and P fields, respectively.

$$A = U^T S \tag{9}$$

$$B = V^T P \tag{10}$$

Lindzen and Nigam mechanism

The Lindzen and Nigam model proposes that low-level winds in the marine atmospheric boundary layer (MABL) are forced by surface temperature gradients. The SST field determines the surface air-temperature resulting in low (high) pressure anomalies, which produce wind convergence (divergence) over warm (cold) SSTs. In this mechanism, the near-surface wind convergence is suggested to be proportional to the Laplacian of the SLP. In particular, Minobe et al. (2008) showed using a MABL model that the momentum equations (Eq. 11) can be reformulated to find that the wind speed convergence is proportional to the Laplacian of the sea level pressure (Eq. 12). In their model the SLP is forced by SSTs following the Eq. (13), so a relationship between SST Laplacian and SLP Laplacian is to be expected.

$$\varepsilon u - fv = \frac{-p_x}{\rho_0}, \quad \varepsilon v + fu = \frac{-p_y}{\rho_0} \tag{11}$$

$$-\left(u_x + v_y\right)\rho_0 = \frac{\varepsilon(p_{xx} + p_{yy})}{\varepsilon^2 + f^2} \tag{12}$$

$$\varepsilon p + H\left(u_x + v_y\right) = -\gamma T \tag{13}$$

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