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Key Points:

- The Atlantic Niño bias weakly depends on the climatological SST, wind, and thermocline errors
- Errors in the representation of the seasonal cold tongue development affect the simulation of the Atlantic Niño
- Biases in the Bjerknes feedback climatology and variability are related to each other

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How Does the Seasonal Cycle Control Equatorial Atlantic Interannual Variability?

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Abstract It has long been thought that reducing mean-state biases would lead to improvements in variability. However, so far, there is no confirmation of a relation between model mean biases and variability. While most coupled models exhibit substantial sea surface temperature (SST) biases in the Tropical Atlantic, they are still able to reproduce reasonable SST variability in the basin. We investigate the relationship between the first- and second-order moments of the SST distribution in the equatorial Atlantic using Coupled Model Intercomparison Project Phase 5 simulations. Results suggest that the ability of the coupled models to properly reproduce the interannual variability is linked to their ability to simulate a realistic seasonal cycle evolution, that is, a realistic cold tongue development and a realistic Bjerknes feedback during the beginning of summer, rather than to their ability to represent the summer SST climatology.

Plain Language Summary To study climate change and natural climate variability, the climate community uses global coupled models. However, these models are not perfect; model systematic errors or biases appear due to approximations in the equations and misrepresentation of different parametrized processes. Biases affect all timescales: the climatology, the seasonal cycle evolution, and interannual variability. In the Tropical Atlantic, almost all state-of-the-art coupled models show very large biases in sea surface temperature. At the same time, this region has a very strong seasonal cycle and a leading mode of variability at equatorial latitudes called the Atlantic Niño. In the present study, by analyzing 36 coupled models, we conclude that it is essential to properly simulate the seasonal cycle evolution to yield a realistic simulation of the Atlantic Niño.

1. Introduction

In the Tropical Atlantic (TA), the climatological sea surface temperature (SST) is strongly biased in most Coupled Model Intercomparison Project Phase 5 (CMIP5) coupled models (Figure 1, Wang et al., 2014). TA SST also displays a marked seasonal cycle, with the development of a strong cold tongue in the eastern part of the basin from May to July (Merle et al., 2013, Figure 2a). In spring, when SST starts to cool in the eastern TA due to the northward migration of the local Inter Tropical Convergence Zone, the easterlies along the equator increase. These easterlies shallow the thermocline in the east, which leads to enhanced SST cooling (Okumura et al., 2004). This ocean-atmosphere coupling is regulated by the Bjerknes feedback (Bjerknes, 1969) and is poorly represented in the CMIP5 models (Richter et al., 2014). Wind errors seem responsible for the wrong settlement of the cold tongue in summer (Richter et al., 2014; Voldoire et al., 2014), but erroneous heat fluxes might play a role in the existence of the warm SST bias throughout the year (Hourdin et al., 2015; Voldoire et al., 2014).

TA SST displays large interannual variability, which strongly affects surrounding population through fishery (Bacha et al., 2017) and modulation of the West African monsoon (Rodríguez-Fonseca et al., 2015). The TA interannual variability also influences the El Niño-Southern Oscillation (Rodríguez-Fonseca et al., 2009; Terray et al., 2015), the Indian Monsoon (Kucharski et al., 2008), and European climate (Cassou et al., 2005). The main SST mode of variability at interannual timescale is the equatorial zonal mode or Atlantic Niño, occurring with a periodicity of 2–5 years (Carton et al., 1996). The Atlantic Niño peaks during boreal summer,

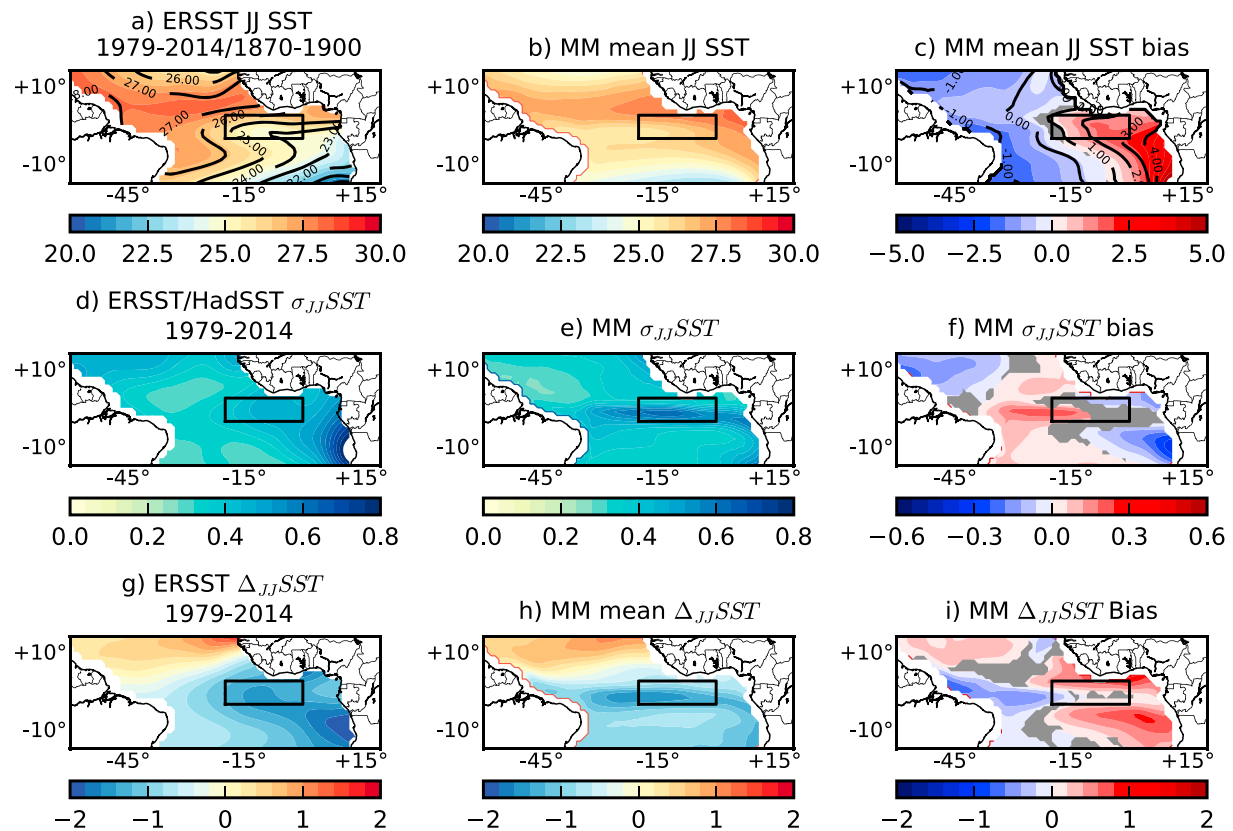


Figure 1. (a) Observed mean sea surface temperature (SST) in JJ. (b) Multimodel (MM) mean SST in JJ. (c) Difference between MM and observed mean JJ SST. (d) Observed standard deviation of SST in JJ ($\sigma_{JJ}SST$). (e) MM mean of $\sigma_{JJ}SST$. (f) Difference between MM and observed $\sigma_{JJ}SST$. (g) Observed $\Delta_{JJ}SST$. (h) MM mean $\Delta_{JJ}SST$. (i) Difference between MM and observed $\Delta_{JJ}SST$. For all panels, reference data set is ERSST 1979–2014, unit ° C; black box shows the Atl3 region. For panels (a) and (c) the contour shows ERSST 1870–1900. Panels (c), (f), and (i): the areas where MM bias is smaller than the difference between ERSST and HadSST are shaded

when the cold tongue develops. The Atlantic Niño, described as the anomalous state of the cold tongue, has mainly been attributed to the Bjerknes feedback (Keenlyside & Latif, 2007; Zebiak, 1993) whereby it is strongly tied to the seasonal cycle (Burls et al., 2011).

Despite the large biases of climatological SST in the region, models are able to reproduce reasonably the Atlantic Niño and the Bjerknes feedback (Deppenmeier et al., 2016). Ding et al. (2015) and Dippe et al. (2017) show that an improved mean state of the TA can lead to better representation of interannual variability in the Kiel climate model, suggesting that error in the climatological SST could be related with errors in the interannual variability.

This study investigates how erroneous SST background, and/or erroneous SST seasonal cycle, affect the representation of interannual variability in the CMIP5 models. It aims at complementing two previous studies using the CMIP5 models in the TA: Richter et al. (2014), who investigated the relation between winds and SST biases and variability and Deppenmeier et al. (2016), whose analysis assessed the representation of the interannual variability in the Bjerknes feedback.

The paper is organized as follows: Section 2 presents the data and methods, section 3 presents the analysis of the CMIP5 data, and section 4 summarizes and discusses the results.

2. Data and Methods

2.1. CMIP5 Database

The model simulations used in this study are obtained from CMIP5 (Taylor et al., 2012). We use one member of the preindustrial control runs. For the thermocline depth, we use the 20° isotherm computed from 3-D monthly data. In the rest of the study, a color is associated to each model; the legend can be found in Figure 2.

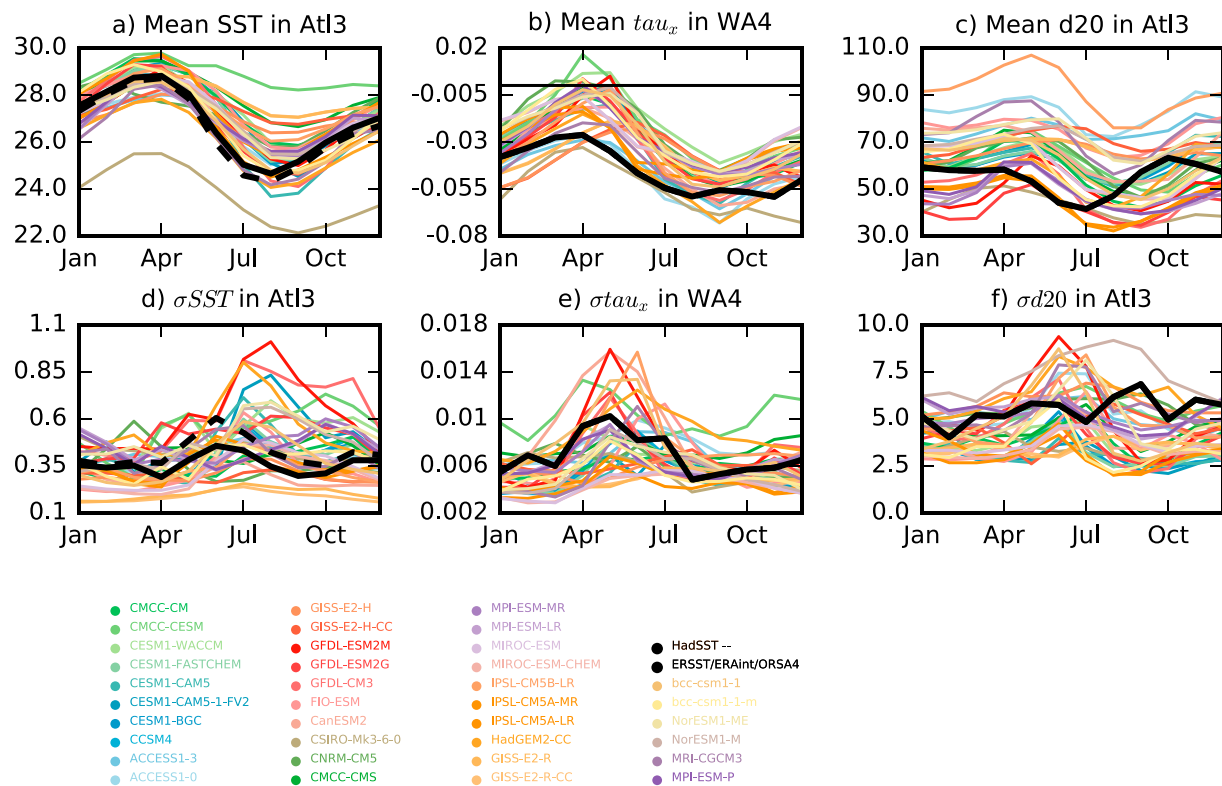


Figure 2. Seasonal cycle of (a) sea surface temperature (SST) averaged in Atl3. (b) τ_x averaged in WA4. (c) d20 in Atl3. (d–f) Same as (a)–(c) but for monthly standard deviation

2.2. Reference Data Set

In order to quantify the SST biases we use two different data sets ERSST v3b (Smith et al., 2008) and HadSST1.1 (Rayner et al., 2006). For wind stress, we use the ERA-Interim reanalysis (Dee et al., 2011). For the thermocline depth, as for the CMIP5 models, we use the 20° isotherm as a proxy computed from ORAS4 3-D temperature reanalysis monthly data Balmaseda et al. (2013). We use the recent period from 1979 to 2014, common to all reference data sets. For the climatological SST, Figure 1 compares results for 1979–2014 and 1870–1900 period.

2.3. Methods

We characterize four aspects of the Atlantic Niño:

- $\sigma_{JJ}SST$: the standard deviation of SSTs in the Atl3 box (3°S 3°N 20°W 0°E; Zebiak, 1993) in June–July (JJ), when the observed variability is at its maximum (Figure 2d).
- $Cor(\tau_x, SST)$: the correlation between wind anomalies in May–June in WA4 and SST anomalies in Atl3 in JJ (Nnamchi et al., 2015). This index allows to quantify the wind-driven contribution, through the Bjerknes feedback, in SST variability.
- The position of the maximum of variability along the equator.

We use the difference between June and July SST as a proxy of the development of the cold tongue ($\Delta_{JJ}SST$ hereafter).

3. Results

Figures 1a–1c compares the multimodel (MM) mean with the observed climatological SST. The SST maximum is located too far to the south, and the east-west SST gradient along the equator is reversed. Therefore, a large warm bias exists along the equator and in the Angola-Benguela region. The bias is indeed exceeding the difference between the two observational data sets considered for the recent period. The bias is even larger when we compare the MM with the preindustrial period (Figures 1a and 1c). Figure 1d, which shows the observed standard deviation of JJ SST in the TA, illustrates the two main areas of interannual

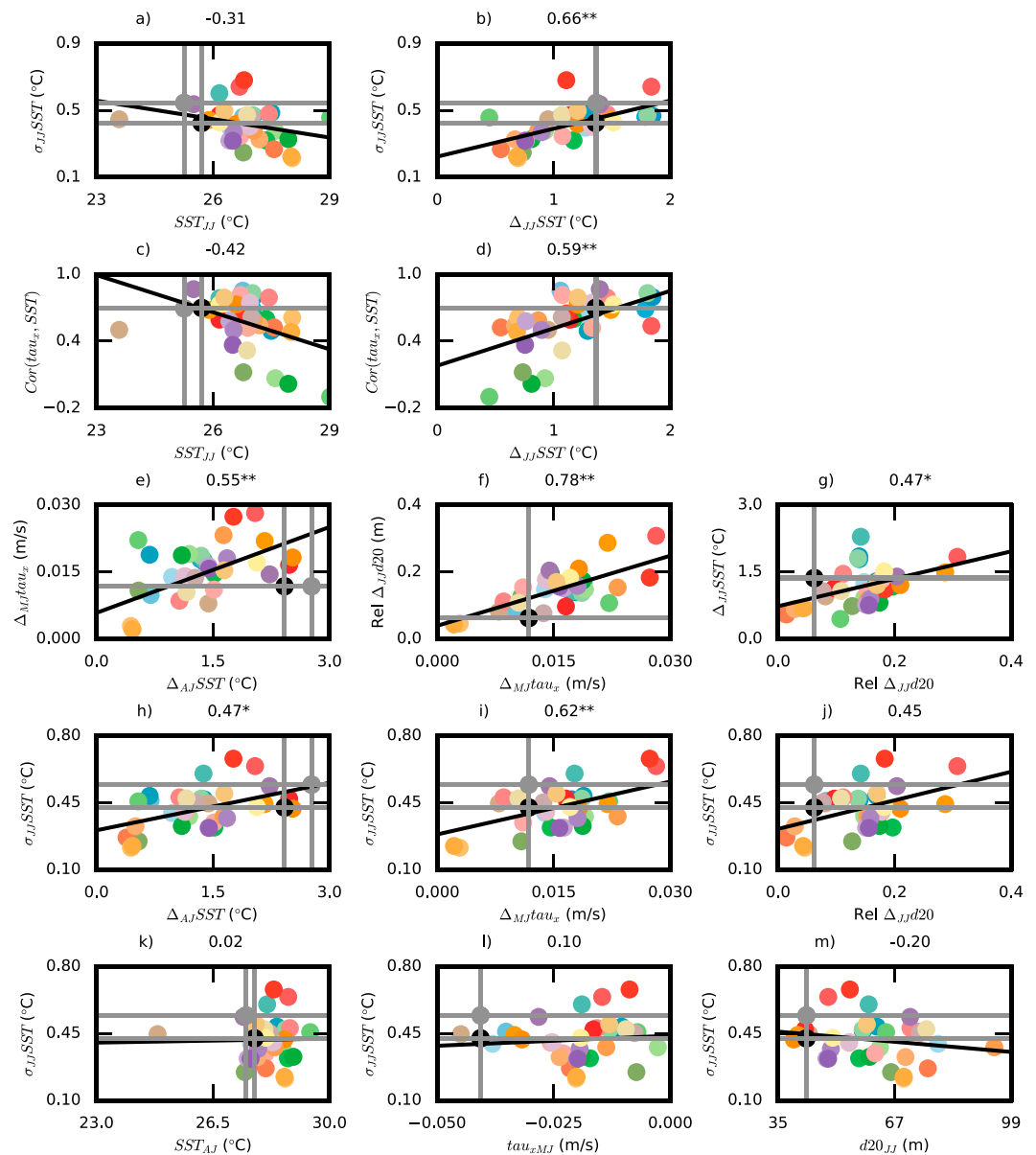


Figure 3. Each scatter plot relates two indicators of each CMIP5 models; for all figures black line shows the regression, number in the title the correlation marked with * (**) if it is significant at the 95% (99%) confidence interval; black, gray dots, and gray lines show the reference data sets. (a) Mean SST in JJ against the standard deviation of JJ SST ($\sigma_{JJ}SST$) in Atl3. (b) $\Delta_{JJ}SST$ against the $\sigma_{JJ}SST$ in Atl3. (c) Mean SST in JJ against $Cor(tau_x, SST)$. (d) $\Delta_{JJ}SST$ against $Cor(tau_x, SST)$. (e) Difference between April and June SST ($\Delta_{AJ}SST$) in Atl3 against the difference between April and May tau_x in WA4 ($\Delta_{AM}tau_x$). (f) $\Delta_{AM}tau_x$ against the difference between June and July d20 ($\Delta_{JJ}d20$) in Atl3. (g) $\Delta_{JJ}d20$ against the $\Delta_{AJ}SST$. (h) $\Delta_{AJ}SST$ against $\sigma_{JJ}SST$. (i) $\Delta_{AM}tau_x$ against $\sigma_{JJ}SST$. (j) $\Delta_{JJ}d20$ against $\sigma_{JJ}SST$. (k) Mean AJ SST against $\sigma_{JJ}SST$. (l) Mean AM tau_x against $\sigma_{JJ}SST$. (m) Mean JJ d20 against $\sigma_{JJ}SST$. SST = sea surface temperature; CMIP5 = Coupled Model Intercomparison Project Phase 5; JJ = June–July; AJ = April–June

variability in the TA: the equatorial Atlantic (Atl3) and in the Angola-Benguela region. In this study, we will focus on the Atl3 variability, associated with the Atlantic Niño, attributed to the Bjerknes feedback (Keenlyside & Latif, 2007). Despite a shift of the variability to the west, the error in MM interannual variability for Atl3 is smaller than the difference between the two observational products considered (Figure 1f). This suggests that models do not necessarily need to correctly represent the mean state to reproduce a relatively realistic interannual variability.

As introduced above, TA SST displays a very strong seasonal cycle, which is characterized by the development of a strong cold tongue between spring and summer. Figures 1g and 1h show that the seasonal cooling

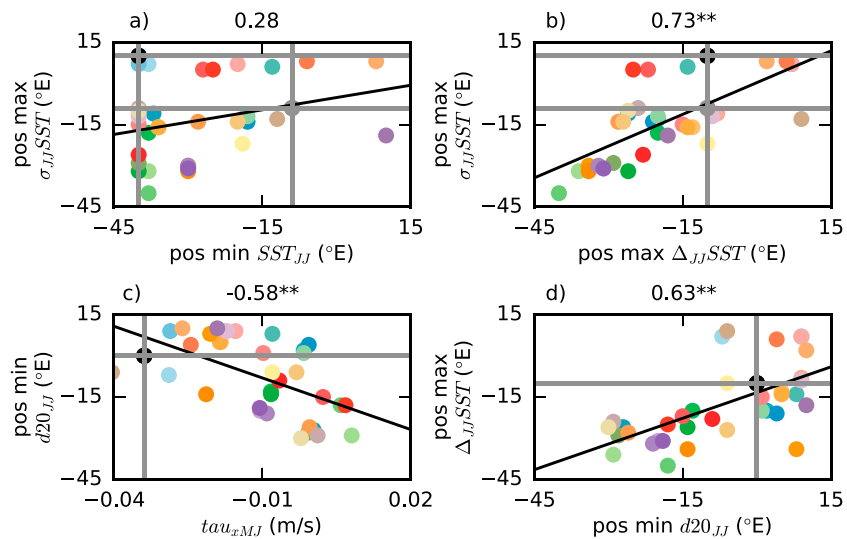


Figure 4. Same as Figure 3 for (a) position of minimum JJ SST along the equator (meridional SST averaged between 3°N and 3°S) against the position of maximum standard deviation of JJ SST (posmax $\sigma_{JJ}SST$). (b) Position of the strongest SST cooling along the equator between June and July ($\Delta_{JJ}SST$) against the position of maximum $\sigma_{JJ}SST$. (c) Averaged wind stress in May June in WA4 against the position of minimal d20 along the equator. (d) Position of minimal d20 along the equator against position of the strongest $\Delta_{JJ}SST$. SST = sea surface temperature; JJ = June–July

($\Delta_{JJ}SST$, defined in section 2) develops in two regions: Atl3 and Angola-Benguela. Models fail in representing the latter but reasonably reproduce the cold tongue development in Atl3.

We examine the monthly evolution of climatology and interannual variability of the three variables involved in the Bjerknes feedback (Deppenmeier et al., 2016): SST over Atl3 in spring and summer, zonal wind stress over the Western equatorial Atlantic (WA4: 40°W–2°W–4°S–4°N), and d20 over Atl3 in summer for all the CMIP5 models and observations (Figure 2). For SST, the bias develops mainly between April and July, when the cold tongue in observations develops. The wind stress biases precede the SST bias; they are already strong in April–May. Winds (and d20) in the models accelerate (shallow) a few month later than in observations, consistently with Richter and Xie (2008) (Figures 2b and 2c). In terms of interannual variability, the model biases are more widespread than for climatology, except for d20 (Figures 2d–2f).

To estimate if there is a linkage between climatology and interannual variability errors, Figure 3a shows the regression between the strength of interannual variability in Atl3 and JJ SST climatology among the CMIP5 models. There is a weak relationship between the amplitude of the bias and the amplitude of the interannual variability ($\sigma_{JJ}SST$), which is not significant at 95% confidence level. However, if instead of considering the mean bias, we consider $\Delta_{JJ}SST$, as a proxy of the strength of the seasonal cold tongue development, a strong and significant (at 99% confidence level) relationship appears (Figure 3b). It is interesting to note that the MM correlation of $\Delta_{JJ}SST$ and SST_{JJ} is only -0.35 (not significant at the 90% confidence level). To properly simulate the Atlantic Niño, a correct cold tongue development in the TA between spring and summer is necessary. Figures 3c and 3d show that the wind-driven contribution of Atl3 variability, $Cor(\tau_{x_z}, SST)$, is also strongly related with $\Delta_{JJ}SST$, which shows that the representation of the Bjerknes feedback in climatology is related to interannual variability in the Bjerknes feedback. A summary of how reliably each component in the Bjerknes feedback is simulated by the models follows (Figures 3e–3g)

- Step 1 (Figure 3e): Models simulating a stronger cooling between April and June ($\Delta_{AJ}SST$) are those simulating a stronger wind acceleration between May and June over WA4 ($\Delta_{MJ}\tau_{x_z}$).
- Step 2 (Figure 3f): The models simulating stronger $\Delta_{MJ}\tau_{x_z}$ are those simulating larger thermocline shallowing between June and July ($\Delta_{JJ}d20$). Here we consider the relative shallowing to the thermocline depth averaged over the same season. Individual models have different errors in thermocline depth (Figure 2), such that thermocline in models with very thin thermocline can hardly shoal as much as in models with deep thermocline.
- Step 3 (Figure 3g): Simulation of the relative thermocline shallowing is related to $\Delta_{JJ}SST$.

Figures 3h–3j show how the different components of the cold tongue formation are related to variability. It appears that there is a strong relationship between the strength of $\Delta_{MJ}tau_x$ and the Atlantic Niño. This highlights the importance of properly simulating the wind stress seasonal cycle to reliably simulate the Atlantic Niño, consistently with Richter et al. (2014, 2017).

Conversely, Figures 3k–3m show the same regressions as in Figures 3f–3h but using averaged values instead of difference between two months: Correlations are closed to 0, implying that the interannual variability is not directly linked to bias in climatology, but in the evolution of the seasonal cycle instead.

The variability in the models is not necessarily correctly situated in the Atl3 region. Figure 4 demonstrates how the positional error of the cold tongue and SST variability are related to each other. The position of maximum variability (pos max $\sigma_{JJ}SST$) is strongly correlated (0.75, significant at 99% confidence interval) with the position of the cold tongue development (Figure 4b), that is, the position of the maximum $\Delta_{JJ}SST$ along the equator (pos max $\Delta_{JJ}SST$). The position of the cold tongue maximum along the equator is in turn linked to the position of the d20 minimum (Figure 4d), itself is strongly related to the strength of wind stress in the WA4 region between May and June (Figure 4c).

4. Conclusion and Discussion

We have analyzed the relationship between climatology and interannual variability in the equatorial Atlantic using CMIP5 simulations. The representation of the Atlantic Niño is strongly linked to the cold tongue development and only weakly linked to the summer SST mean. In other words, the ability of a model to properly simulate the interannual variability in the TA is related to its ability to properly simulate Bjerknes feedback in climatology and the associated cold tongue development.

From this study, it appears that to improve the simulation of the Atlantic Niño, modelers should focus primarily on capturing the evolution of the seasonal cycle and the processes associated with it, rather than on representing climatological SST. We advocate for deeper attention, in the tuning exercise of coupled models, to the development of the seasonal cycle.

Investigating intermodel relationships does not allow us to fully understand the mechanisms connecting error in the seasonal cycle, summer SST climatology, and the variability. Using targeted sensitivity experiments with idealized wind field, ocean nudging, or anomaly coupling could be performed to further understand how wind phasing, thermocline depth, or mean SST at certain times of the year affect or not the variability. Beside, Deppenmeier et al. (2016) found that the relation between subsurface and SST anomalies was poorly reproduced by CMIP5 models, which is consistent with Figures 3g and 3j, so emphasis should also be put on better understanding the lack of connection between surface and subsurface anomalies.

Recently, Yang et al. (2017) and Nnamchi et al. (2015) have shown that some models are able to reproduce a realistic amplitude of variability driven by erroneous mechanisms. This might explain the outliers of the relationship in Figures 3 and 4, but it could also strongly affect the models' forecast skill in the region. More research is needed to quantify and understand sources of TA predictability in the seasonal forecasting context.

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