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# ON THE OCEAN-ATMOSPHERE COUPLED DYNAMICS OF ATLANTIC NIÑO: REVISITING THE BJERKNES POSITIVE FEEDBACK

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## ABSTRACT

*The Atlantic Niño is the leading mode of inter-annual sea surface temperature variability in the equatorial Atlantic, with strong impacts on West African rainfall, tropical cyclone activity, and broader climate teleconnections. While it shares similar dynamics with the Pacific El-Niño, particularly in terms of coupled ocean-atmosphere dynamics, the structure and amplitude of the Atlantic coupled ocean-atmosphere dynamics are not fully understood. This study revisits the classical Bjerknes positive feedback- the mechanism driving coupled ocean-atmosphere in the equatorial Atlantic by diagnosing its full coupled structure using multiple observational and reanalysis datasets. The analysis focuses on three key components: the response of zonal wind stress to eastern SST anomalies, the thermocline adjustment due to wind stress forcing, and the reinforcement of SST through changes in upper-ocean heat content. Results show that all three components of the Atlantic Bjerknes feedback are active. The feedback strength varies across components, with explained variances ranging from 21% (SST-wind stress) to 46% (SST-heat content). Additionally, atmospheric convection-modulated by the seasonal migration of the Intertropical Convergence Zone (ITCZ) emerges as an important mechanism influencing the development of SST anomalies through diabatic heating. These findings demonstrate that the complete Bjerknes feedback loop operates in the Atlantic. The study highlights the essential role of atmospheric deep convection and provides new insight into the coupled dynamics of Atlantic Niño events.*

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## 1. INTRODUCTION

The Atlantic Niño is the dominant mode of inter-annual sea surface temperature (SST) variability in the equatorial Atlantic and has substantial influence on regional and global climate patterns, including West African rainfall and tropical Atlantic cyclone activity (Folland *et al*., 1986;

Nobre and Shukla, 1996; Giannini *et al*., 2003; Vallès-Casanova *et al*., 2020). Its underlying dynamics bear similarities to the El Niño-Southern Oscillation (ENSO) in the Pacific, particularly through coupled ocean-atmosphere interactions governed by the Bjerknes positive feedback mechanism (Bjerknes, 1969; Cane and Zebiak, 1985; Cane, 1992; Timmermann *et al*., 2018).

This feedback loop involves three key processes: eastern equatorial SST anomalies force westerly wind anomalies in the western basin; these winds modify the thermocline depth and upper-ocean heat content in the east; and the resulting oceanic changes further amplify the initial SST anomalies. Although the individual components of this feedback have been studied in equatorial Atlantic (Zebiak, 1993; Keenlyside and Latif, 2007; Lübbecke and McPhaden, 2012; Dippe *et al*., 2019), a complete assessment of the full feedback loop, especially one that accounts for atmospheric diabatic heating remains limited.

While delayed negative ocean feedback also play a role in tropical variability, this study focuses specifically on the positive feedback processes. In addition to the classical Bjerknes mechanism, recent work has highlighted the importance of diabatic heating as an alternative driver of SST evolution in the eastern equatorial Atlantic (Nnamchi *et al*., 2021). This positive feedback loop is explained below: an initial SST anomaly modifies the zonal SST gradient, which alters the vertical profile of diabatic heating through changes in convection, water vapour, cloud structure, and precipitation (Houze, 1982; Hartmann *et al*., 1984; Chiang *et al*., 2001). This enhanced heating decreases the strength of the Walker circulation but triggers westerly wind stress anomalies over the western basin (Figure 1).

The triggered westerly wind stress anomalies tilts the zonal thermocline slope by deepening the thermocline in the east and shoaling it in the west which increases upper-ocean heat content and sea surface height (SSH) in the eastern basin (Keenlyside and Latif, 2007; Dippe et al., 2018). Given this strong relationship, SSH serves as a useful proxy for upper-ocean heat content (Rebert et al., 1985). Through thermocline feedback, the warm SST anomalies are further amplified, reinforcing the coupled system (Figure 1).

While prior studies have analyzed individual links in this feedback loop, a comprehensive examination that quantifies all major components-including the role of atmospheric deep convection is still lacking. This study addresses that gap by systematically evaluating the strength and spatial structure of the equatorial Atlantic Bjerknes feedback.

Specifically, we assess the zonal components of the feedback to better understand the dynamic coupling processes that lead to the development of Atlantic Niño SST anomalies during their peak. In parallel, we analyze precipitation variability, used as a proxy for diabatic heating and deep atmospheric convection acting in the meridional direction to evaluate its role in modulating SST anomalies. Together, these analyses provide new insight into the coupled feedback mechanisms driving Atlantic Niño events.

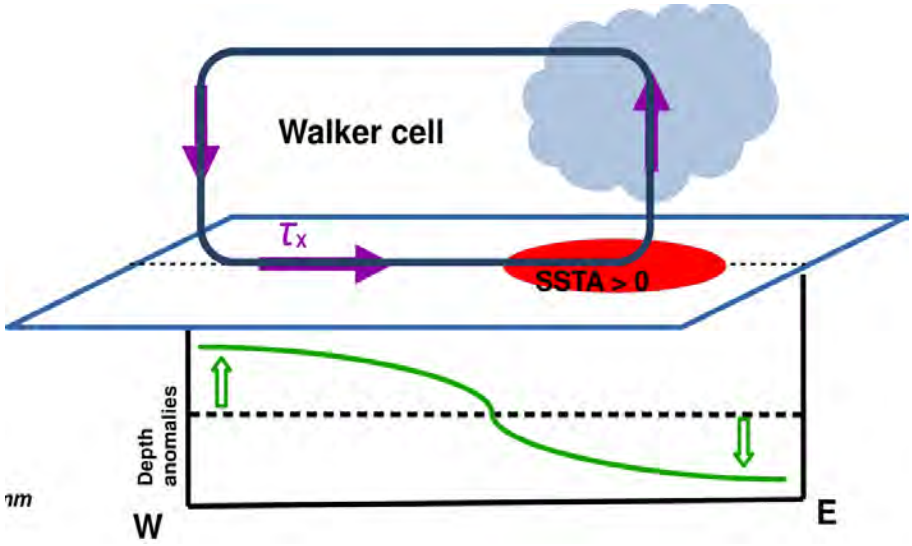



Figure 1: Graphical representation of atmospheric deep convection-ocean coupling and thermocline feedback (Nnamchi *et al.*, 2021).

## 2. Description of the study area

The Equatorial Atlantic is a dynamic and complex region of the Atlantic Ocean, spanning approximately 10°N to 10°S latitude and extending longitudinally across the ocean basin. This region is of critical importance in oceanography, climate science, and marine ecosystems due to its distinct oceanographic and atmospheric processes (Carton *et al.*, 2005).

The western boundary of the Equatorial Atlantic is defined by the coastlines of South and Central America, including Brazil, Colombia, and Venezuela, while the eastern boundary is delineated by the west coast of Africa, including Gabon, Congo, and Angola (Molinari and Johns, 1984). Ocean circulation in the region is influenced by major current systems, such as the North Equatorial Current (NEC) in the north and the South Equatorial Current (SEC) in the south (Stramma and Lutjeharms, 1997).

## 3. Data and Methods

### 3.1 Observational and reanalysis data sets

Monthly sea surface temperature (SST) data from the Hadley Centre Global Sea Ice and Sea Surface Temperature v1.1 dataset (HadISST; Rayner *et al*., 2003) and precipitation data from the Global Precipitation Climatology Project v2.3 (GPCP; Adler et al., 2003) were used in the analysis. Reanalysis datasets include sea surface height (SSH) and upper-ocean heat content from the Global Ocean Data Assimilation System v2.0.4 (GODAS; Behringer *et al*., 1998), zonal wind fields (u-wind) from the NCEP–NCAR reanalysis (Kalnay *et al*., 1996), and zonal wind stress from the ORAS5 ocean reanalysis (Zuo *et al*., 2019). Monthly anomalies were computed by removing both the climatological monthly means and long-term linear trends from each calendar month. Climatologies and trends were calculated using the period 1979 to 2021.

### 3.2 Methods

#### 3.2.1 The Index regions

The Atlantic Niño index used in this study is the Atl3 index, which is defined as the area-averaged sea surface temperature (SST) anomalies over the eastern equatorial Atlantic region (3°N–3°S, 0°–20°W) (Zebiak, 1993). The western equatorial Atlantic surface wind index (WEA) is defined as the area-averaged surface zonal wind anomalies over the region 3°S–3°N, 40°W–20°W, as shown in Fig. 2.

#### 3.2.2. Regression analysis

We analyze the relationship between two different variables using regression analysis. The strength of the atmosphere-to-ocean Bjerknes feedback will be quantified by the regression of zonal wind stress, precipitation, sea surface height (SSH), and heat content (HC) onto the Atlantic Niño index. This method involves applying a linear equation to the already proposed dataset to establish a relationship between the two variables: the dependent variable and the independent variable. Equation (1) defines the standard linear regression model used to quantify the relationship between two variables:

$$Y=a+bX \quad (1)$$

where Y is the dependent variable, X is the independent variable, b is the slope of the line, and a is the intercept constant. A positive and negative value of b indicates that the data tend to increase or decrease with time, respectively.

All anomalies are computed by removing the climatological monthly means and linearly detrending each variable over the analysis period. Prior to regression, indices are also standardized. Regressions are performed using monthly data from 1979 to 2021, which serves as the baseline climatological period.

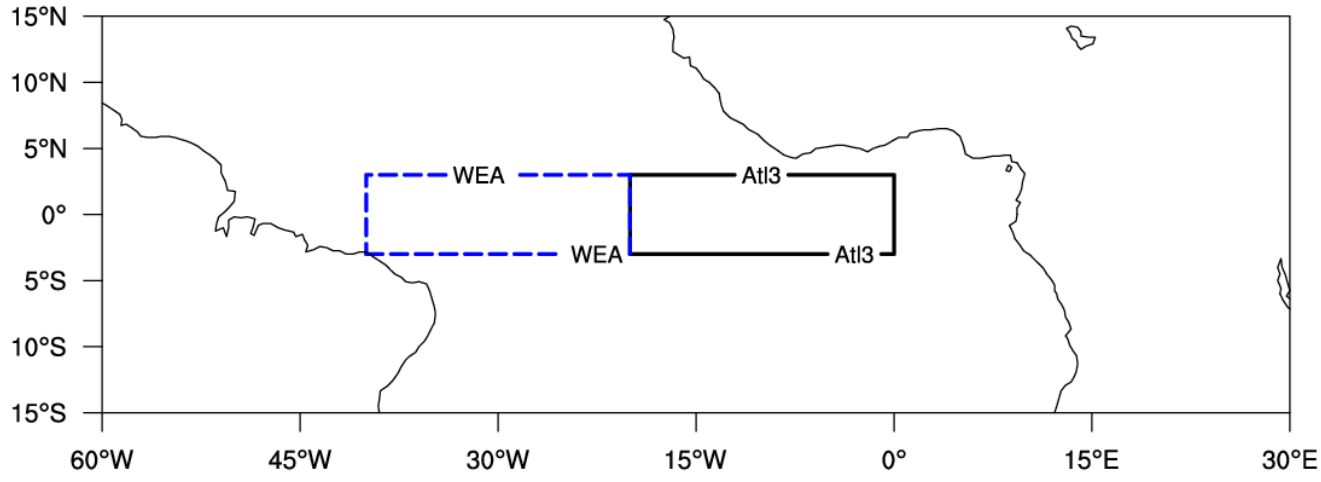



Figure 2: Map of the study area showing the location of Atl3 (3°S–3°N, 0°–20°W) and WEA (3°S–3°N, 40°–20°W) used to compute thezonal gradient, as the difference between the anomalies averaged over the two boxes.

#### 3.2.3. Tests for statistical significance

For all results of regression analyses conducted in this study, we tested for statistical significance using a two-tailed Student t-test with 95% confidence levels marked. Autocorrelation was accounted for in statistical significance tests for the regression maps by adjusting the number of degrees of freedom of the time series pairs as

follows (Bretherton *et al*., 1999):

$$N * N\frac{(1-r_1r_2)}{(1+r_1r_2)} \quad (2)$$

where $N$ is the time series length; $r_1$ and $r_2$ are the lag-1 autocorrelation coefficients of the time series, respectively; and $N^*$ is the adjusted number of degrees of freedom used for determining the statistical significance. The effective degrees of freedom (N*) were reduced from the nominal sample size of 516 months (43 years × 12 months) to approximately 92. This value was used to compute two-tailed Student's t-tests for all regression coefficients.

## 4. Results and Discussion

### 4.1 Coupling of convection, SST, and thermocline variability

Regression analysis of eastern equatorial Atlantic SST anomalies (Atl3 index) onto surface zonal wind anomalies reveals a clear ENSO-like response pattern (Figure 3a). Positive SST anomalies in the east are associated with westerly wind anomalies to their west and weaker easterlies to the east, mirroring the canonical structure of Pacific El Niño events. A 1°C increase in Atl3 SST corresponds to a peak westerly wind anomaly of approximately 0.6 to 1.0 m $s^{-1}$, centered over the western equatorial Atlantic. This coupling explains about 21% of the surface wind variability.

When the same regression is applied to zonal wind stress, a similar spatial pattern emerges, with a slightly higher explained variance of 23% (Figure 3b), likely due to the more direct dynamic relationship between wind stress and ocean surface forcing.

These findings confirm that the first component of the Bjerknes feedback whereby eastern SST anomalies influence surface winds to the west is active in the equatorial Atlantic. However, it accounts for only a modest portion of the total variability. This suggests that while SST-wind coupling contributes to Atlantic Niño dynamics, other processes such as thermocline adjustment, subsurface variability, and external atmospheric forcing likely play a significant role in shaping the evolution of events.

In summary, the first component of the Bjerknes positive feedback explains up to 23% of the variability in eastern equatorial SST anomalies and associated wind stress patterns in the western basin. While this indicates a statistically significant coupling, it also implies that a large portion of the variability over 75% remains unexplained by this feedback alone. This suggests that additional processes, such as subsurface ocean dynamics, remote atmospheric teleconnections, or stochastic atmospheric forcing, likely play a substantial role in modulating Atlantic Niño events and should be considered in future analyses.

The second component of the Bjerknes positive feedback involves the dynamic linkage between variability in surface winds, or more precisely, wind stress over the western equatorial Atlantic, and variations in thermocline depth in the eastern equatorial Atlantic. This feedback aspect describes how westerly wind stress anomalies in the west basin initiate oceanic adjustments in the east, amplifying the original SST perturbation. To demonstrate this connection, zonal surface wind

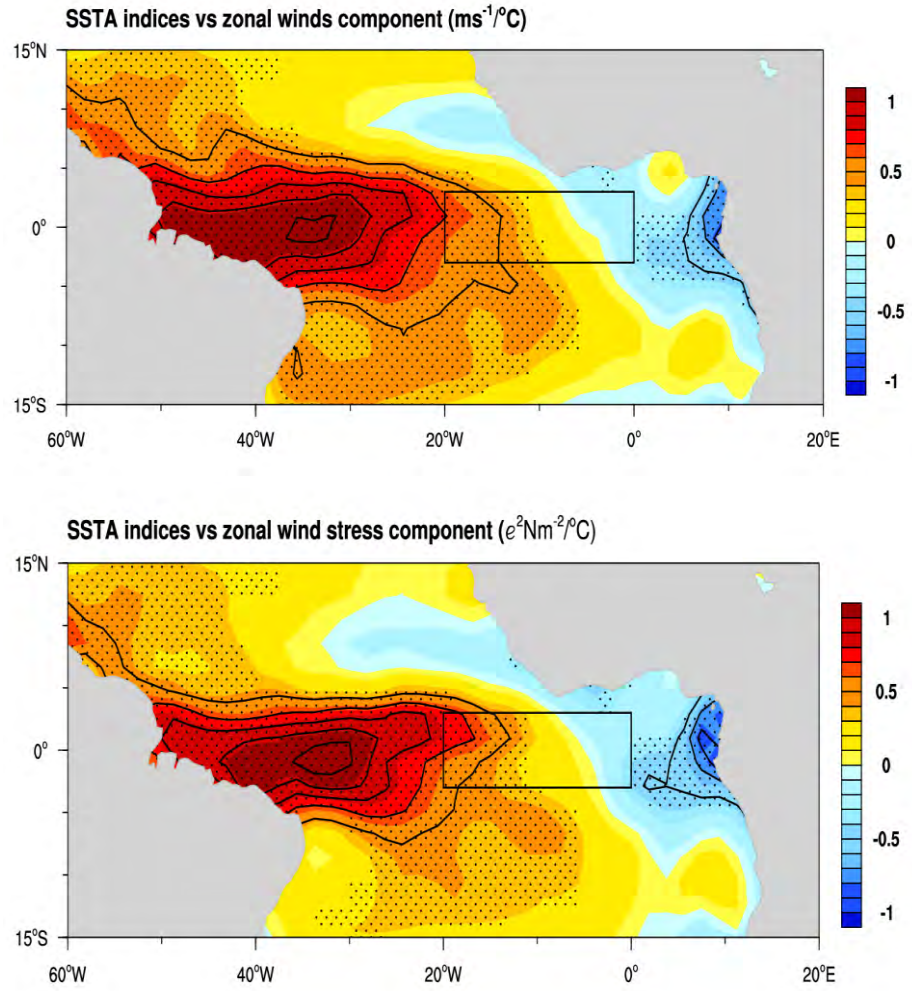



Figure 3: **a**. Atl3 SST anomalies regressed on the 10-m zonal wind speed. Black contours denote explained variances at 21% intervals. **b**. Atl3 SST anomalies regressed on the zonal wind stress. Black contours denote explained variances at 23% intervals. Stippling indicates regions where regression coefficients are statistically significant at the 95% confidence level, based on a two-tailed Student's t-test.

stress anomalies averaged (WEA) indexes are regressed onto sea surface height anomalies (SSHA), a commonly used proxy for thermocline depth displacement. An increase in SSHA in the eastern equatorial Atlantic corresponds to a deepening thermocline, which enhances upper-ocean heat content and supports further warming of SST anomalies. Conversely, a decrease in SSHA in the western basin is associated with a shoaling thermocline and reduced heat content. This regression analysis is also extended to upper-ocean heat content (HC) anomalies to clarify the oceanic response to atmospheric forcing further and assess the strength of this feedback.

The regression results show that westerly wind stress anomalies in the western Atlantic are associated with increased SSHA and enhanced

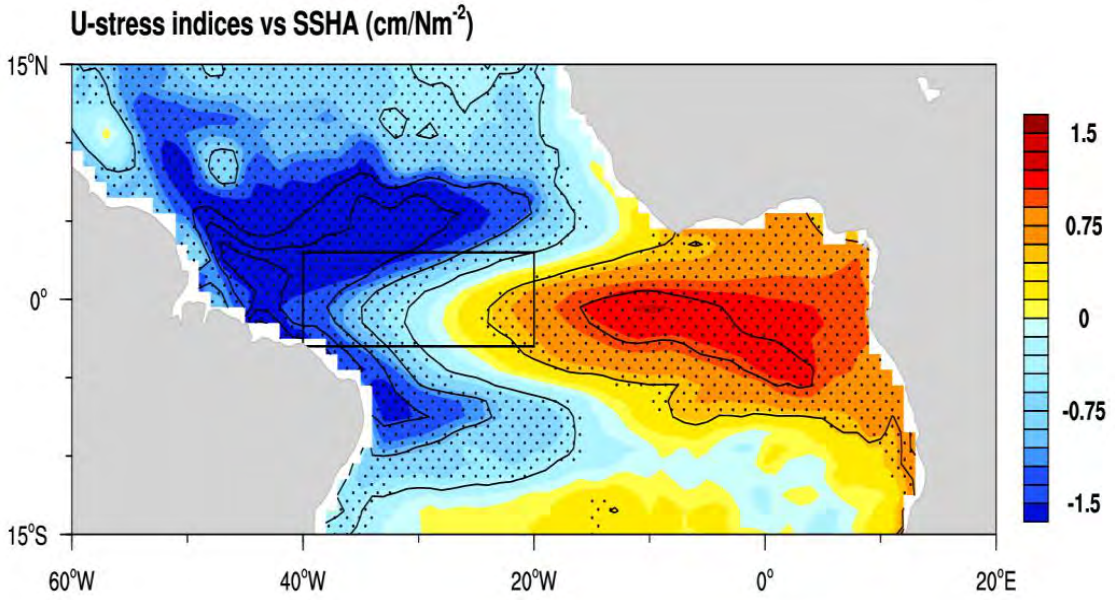



Figure 4: Zonal wind stress anomalies regressed onto the sea surface height anomalies. Black contour denotes explained variances at intervals of 38%. Stippling indicates regions where regression coefficients are statistically significant at the 95% confidence level, based on a two-tailed Student's t-test.

HC in the eastern equatorial Atlantic, accompanied by a concurrent reduction in SSHA and HC in the west Atlantic (Figure 4). This dipole-like structure reflects the eastward propagation of thermocline and warm water anomalies, consistent with the expected dynamics of equatorial Kelvin and Rossby waves triggered by wind perturbations. This spatial pattern strongly agrees with the analogous Bjerknes positive feedback observed in the Pacific Ocean.

However, it is essential to highlight that the strength of this coupling in the Atlantic is comparatively weaker. The regression coefficients are smaller, and the explained variance in SSHA by zonal wind stress anomalies is lower than typically observed in the Pacific. These results suggest that while the fundamental processes of the Bjerknes positive feedback are active in the Atlantic, their intensity is reduced.

The last element of the Bjerknes positive feedback loop involves the coupling between ocean dynamics and SST variability. In the case of ENSO, this coupling is well established, with the dominant contribution to SST variability in the eastern equatorial Pacific arising from the mean vertical advection of subsurface temperature anomalies (Neelin *et al*., 1998). Variations in thermocline depth primarily drive these subsurface anomalies. As a result, SST anomalies in the eastern Pacific exhibit a strong and coherent relationship with thermocline depth fluctuations, providing a critical mechanism for the amplification and persistence of ENSO events.

To investigate whether a similar dynamic coupling operates in the equatorial Atlantic, Atl3 SST anomalies are regressed onto sea surface height anomalies (SSHA) (Figure 5a). This approach effectively highlights regions where

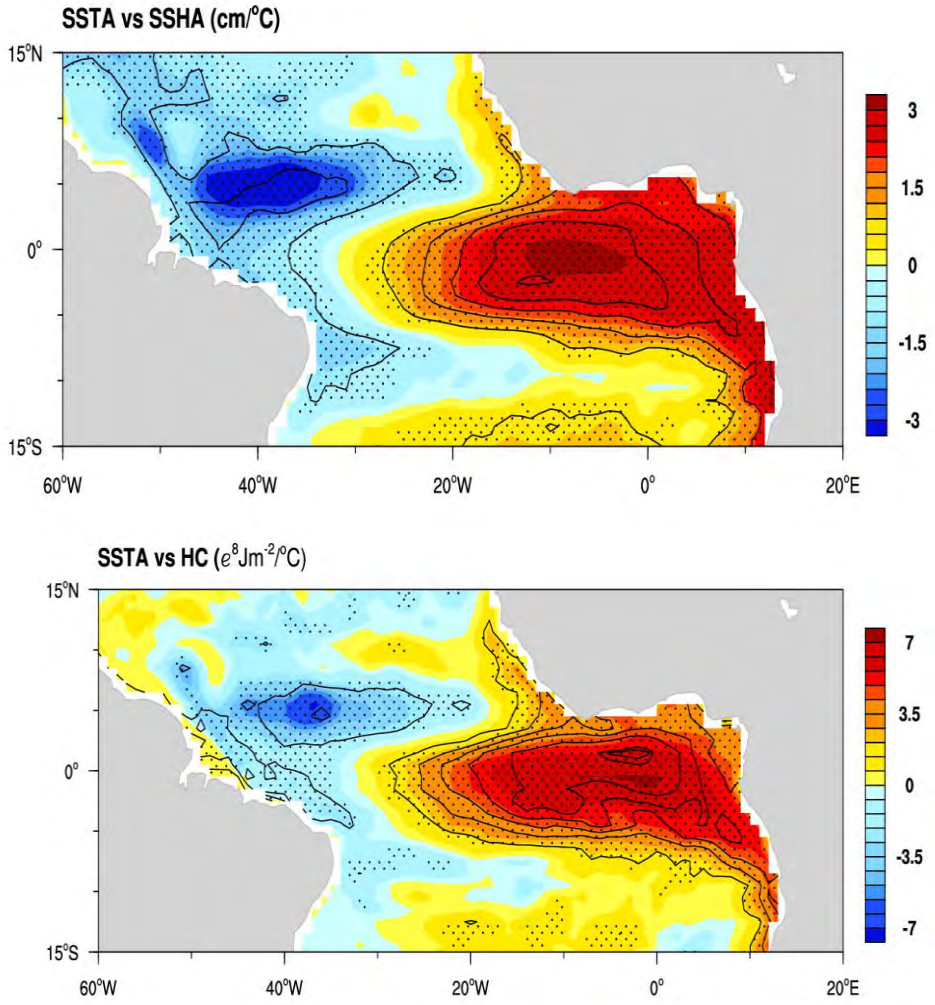



Figure 5. **(a)** Atl3 SST anomalies were regressed onto the sea surface height anomalies. Black contours indicate explained variances at the 37% interval. Stippling indicates regions where regression coefficients are statistically significant at the 95% confidence level, based on a two-tailed Student's t-test. **(b)** Atl3 SST anomalies regressed on heat content anomalies. Black contours indicate explained variances within the 46% interval. Stippling indicates regions where regression coefficients are statistically significant at the 95% confidence level, based on a two-tailed Student's t-test.

ocean dynamics, via thermocline displacements, are most tightly linked to surface temperature variability.

The resulting regression pattern in the Atlantic strongly resembles its Pacific counterpart in terms of spatial structure. Notably, the strongest coupling appears in the eastern to central equatorial Atlantic, particularly along the western boundary of Africa, where regression coefficients are slightly stronger. It suggests that thermocline depth variability plays a vital role in modulating SST anomalies in this region.

More significantly, the explained variance of SSHA by SST anomalies in the equatorial Atlantic reaches 37%, indicating a substantial degree of dynamical coupling between the upper ocean and

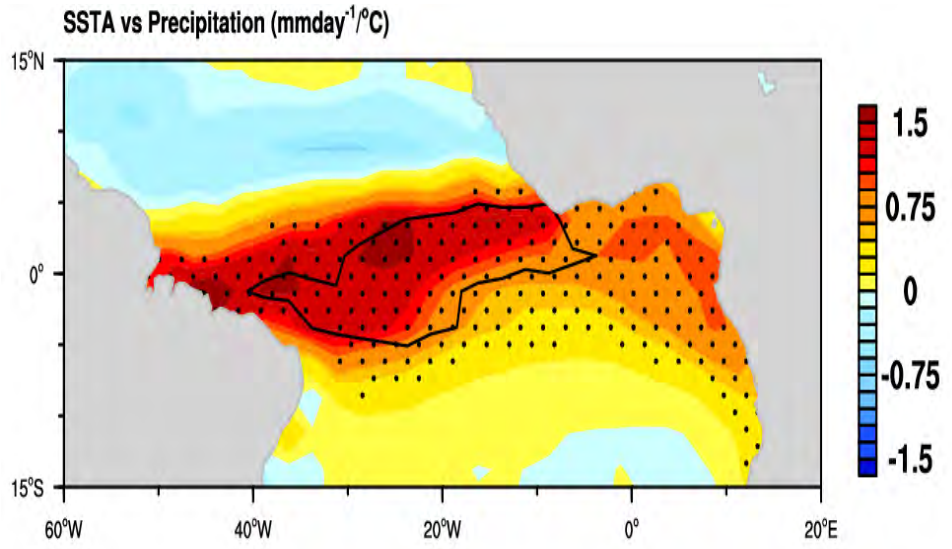



Figure 6: Atl3 SST anomalies regressed onto the precipitation anomalies. Black contour denote explained variances at 36% intervals. Stippling indicates regions where regression coefficients are statistically significant at the 95% confidence level, based on a two-tailed Student's t-test.

surface temperature variability (Figure 5a). This result is further supported by a parallel analysis using ocean heat content (HC) anomalies instead of SSHA. Regression of Atl3 SST anomalies onto HC anomalies yields a similar spatial pattern and an even higher explained variance of 46% (Figure 5b). These findings confirm that, despite the Atlantic's smaller basin size than the Pacific, the coupling between thermocline variability and SST is robust, particularly in the eastern basin, and forms an integral part of the Atlantic Bjerknes positive feedback system.

To further investigate the role of atmospheric convection in setting the background condition for the development of Atlantic Niño events, a regression analysis was performed using Atl3 SST anomalies and precipitation anomalies across the equatorial Atlantic. In this context, precipitation is a proxy for atmospheric convection, providing insight into how SST anomalies interact with large-scale atmospheric circulation systems.

The results reveal a distinct temporal relationship between oceanic and atmospheric variability.

In the equatorial Atlantic, atmospheric convection is predominantly influenced by the Intertropical Convergence Zone (ITCZ), a key regulator of tropical precipitation and atmospheric circulation. Variability in the latitudinal position or intensity of the ITCZ can significantly alter the spatial structure and strength of the precipitation response to SST anomalies. Such shifts can, in turn, modulate the strength of the atmosphere-ocean coupling and the effectiveness of the Bjerknes positive feedback mechanism in sustaining or amplifying Atlantic Niño conditions.

The regression result indicates enhanced precipitation anomalies are primarily concentrated along the western to central equatorial Atlantic (Figure 6). This spatial pattern of convection suggests a strong atmospheric response to SST anomalies, especially during the

onset and development phases of the Atlantic Niño. The associated explained variance is approximately 36%, indicating a moderately strong relationship between SST and precipitation variability in this region.

These findings support the view that variability in atmospheric convection, particularly in the meridional direction governed by the northward migration of the ITCZ, contributes significantly to the development and amplification of warm SST anomalies in the eastern equatorial Atlantic.

## 4. Conclusions

This study investigates the coupled ocean–atmosphere dynamics governing Atlantic Niño events, with a particular focus on evaluating the strength and completeness of the Bjerknes positive feedback mechanism in the equatorial Atlantic. The analysis quantifies the interactions between surface SST anomalies, zonal wind stress, thermocline variability, and precipitation. The findings highlight that, although structurally similar to Pacific ENSO dynamics, the Atlantic Niño is governed by a weaker feedback system. However, as this study relies on linear regression techniques, the results primarily capture direct statistical associations and may not fully represent nonlinear, time-lagged, or dynamic feedbacks. These findings support the growing view that Atlantic Niño variability is shaped not only by local ocean–atmosphere feedbacks but also by remote influences from Pacific ENSO, the tropical Atlantic Meridional Mode, and stochastic atmospheric forcing.

While this study provides valuable insights into the coupled dynamics of Atlantic Niño events, several limitations should be acknowledged. First, the use of linear regression techniques restricts the analysis to capturing only linear, contemporaneous relationships. The Atlantic Niño events are inherently nonlinear, involving threshold behaviors, time-lagged interactions, and feedback asymmetries that may not be fully represented through this method. Second, although reanalysis and observational datasets offer broad coverage and long-term consistency, they may contain seasonal biases or aliasing errors particularly in regions with sparse in situ observations such as the equatorial Atlantic. These limitations could influence the strength and spatial structure of the diagnosed feedbacks. Future work using nonlinear statistical methods, coupled model simulations, and seasonally stratified analyses may offer a more complete understanding of the system.

Future studies should integrate coupled climate models to examine how Atlantic Bjerknes feedbacks may respond to greenhouse warming.

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