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Resolving the Tropical Pacific/Atlantic Interaction Conundrum

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Key Points:

- The lead correlation of the equatorial Atlantic over the Pacific is not related to Atlantic-to-Pacific causality
- The tropical Pacific/Atlantic interaction is consistent with the nascent onset of Pacific events driving the equatorial Atlantic events
- The discrepancies between the observed and multi-model simulated tropical Pacific/Atlantic relationship can be reconciled in this new frame

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Understanding the interaction between the tropical Pacific and Atlantic Oceans has challenged the climate community for decades. Typically, boreal summer Atlantic Niño events are followed by vigorous Pacific events of opposite sign around two seasons later. However, incorporating the equatorial Atlantic information to variabilities internal to the Pacific lends no significant additional predictive skill for the subsequent El Niño-Southern Oscillation (ENSO). Here we resolve this conundrum in a physically consistent frame, in which the nascent onset of a Pacific event rapidly induces an opposite-signed summer equatorial Atlantic event and the lead correlation of Atlantic over Pacific is a statistical artifact of ENSO's autocorrelation. This Pacific-to-Atlantic impact is limited to a short window around late spring due to seasonally-amplified Atlantic atmosphere-ocean coupling. This new frame reconciles the discrepancies between the observed and multi-model simulated inter-basin relationship, providing a major advance in understanding seasonally-modulated inter-basin climate connections as well as their predictability.

Plain Language Summary

Previous studies interpreted the observed lead/lag relationship between Atlantic Niño/Niña and Pacific Niño/Niña sea surface temperature anomalies as evidence for a precursory role of the equatorial Atlantic on the development of El Niño–Southern Oscillation (ENSO) events. This study clearly demonstrates that this statistical relationship is not related to Atlantic-to-Pacific causality, but can rather be explained by seasonally modulated equatorial Atlantic's response to ENSO. We find that Pacific ENSO events drive equatorial Atlantic events rather than vice versa, and reconcile the apparent discrepancies between the observed and multi-model simulated tropical Pacific/Atlantic relationship.

1. Introduction

Tropical ocean basins provide a fertile ground for a wide range of coupled atmosphere-ocean phenomena across different timescales. The most energetic and best-known among them is the El Niño–Southern Oscillation (ENSO) in the equatorial Pacific (Figure 1a), which originates from large-scale atmosphere-ocean interactions, that is, the positive Bjerknes feedback involving sea surface temperature (SST), trade winds, and upper ocean heat content (Bjerknes, 1969; Philander, 1983). As a dynamically analogous coupled mode to El Niño in the Pacific, the Atlantic Niño dominates the interannual variability in the equatorial Atlantic (Figure 1a), albeit with considerably weaker SST amplitude and much shorter event duration (Carton & Huang, 1994; Zebiak, 1993). In addition, the equatorial Atlantic events have a distinct seasonality with a peak in boreal summer, in contrast to ENSO events that peak toward winter (Keenlyside & Latif, 2007). The Atlantic Niño phenomenon has prominent imprints on the regional climate (Grodsky et al., 2008; Yadav et al., 2018), and most remarkably, boreal summer equatorial Atlantic SST variations appear to lead ENSO variability by about two seasons (Keenlyside & Latif, 2007; Rodríguez-Fonseca et al., 2009).

Numerous studies have focused on possible inter-basin interactions between the equatorial Pacific and Atlantic SSTs. From a historical perspective, all three extreme El Niño events in the satellite era (1982, 1997, and 2015) peaked following an Atlantic Niña the summer before. Such Atlantic-to-Pacific linkage beyond these individual

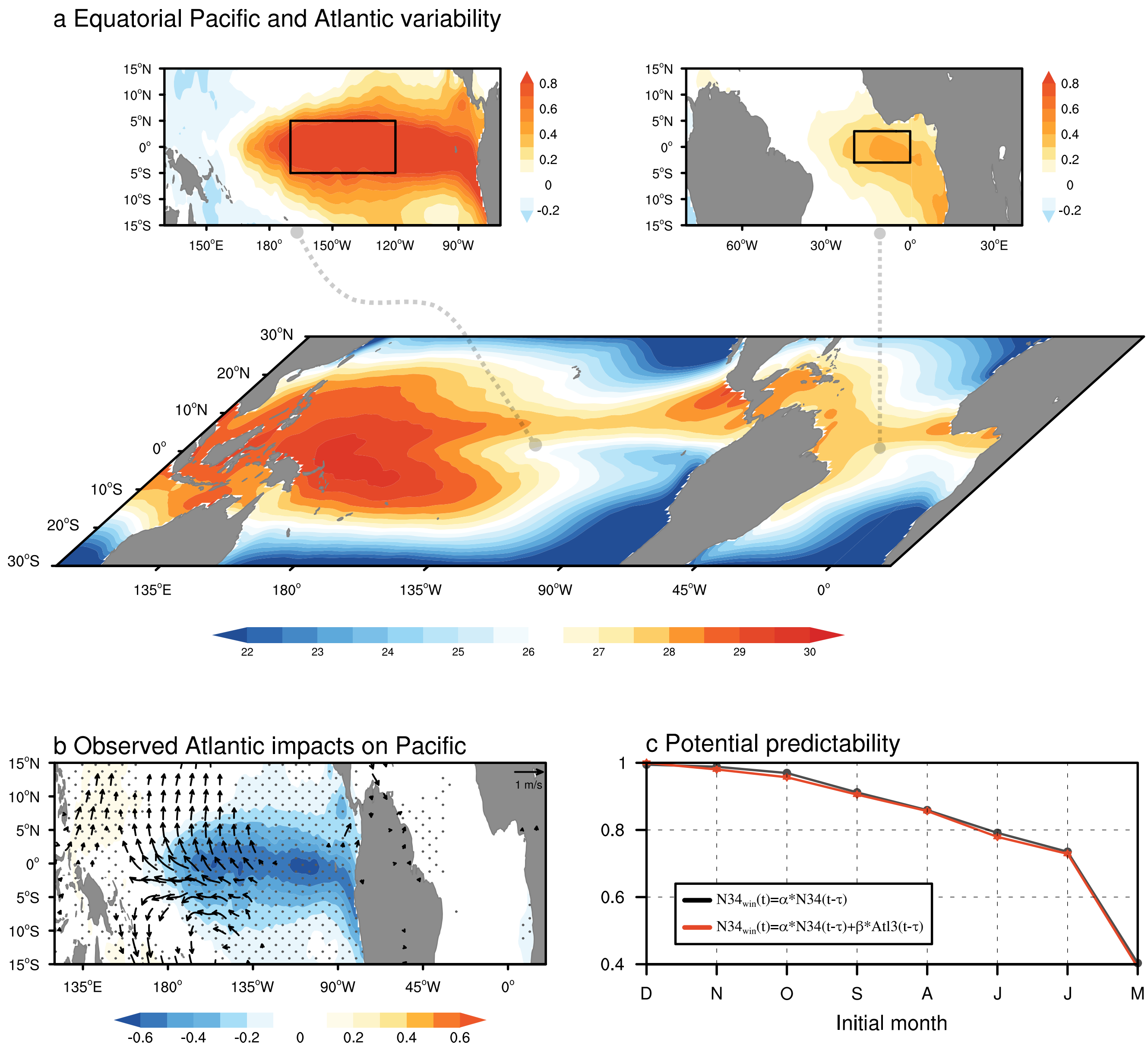

Figure 1. (a) The Pacific El Niño sea surface temperature (SST) pattern (top left panel), the Atlantic Niño SST pattern (top right panel), and tropical climatological SST pattern (bottom panel). The El Niño pattern is derived by regressing the SST anomalies on the monthly Niño3.4 index and the Atlantic Niño pattern by regressing them on the monthly Atl3 index. (b) Boreal winter SST (shading; °C) and surface wind anomalies (vectors, m/s) regressed on the previous summer Atl3 index. Dots indicate SST anomalies that are statistically significant at the 95% confidence level and wind anomalies are shown only for those exceeding the 95% confidence level. (c) Prediction skill of the winter Niño3.4 index ($N34_{win}$) by using the Niño3.4 index alone (N34, black line) and with additional consideration of Atl3 index based on multiple linear regression (red line) in different initial months. The prediction skill is evaluated as the anomalies correlation coefficient between the observed $N34_{win}$ and predicted values.

years is evident in the significant negative correlation between summer equatorial Atlantic and following winter Pacific conditions over the past few decades (Jansen et al., 2009; Keenlyside & Latif, 2007; Rodríguez-Fonseca et al., 2009), which is also supported by partially coupled pacemaker experiments (Chikamoto et al., 2020; Ding et al., 2012; Keenlyside et al., 2013; Polo et al., 2015). However, there has been little consensus regarding the extent of ENSO's impact on the equatorial Atlantic (Chang et al., 2006; Keenlyside & Latif, 2007; Latif & Grötzner, 2000). In general, there is no significant statistical relationship between SST anomalies in the equatorial Atlantic lagging those in the Pacific (Chang et al., 2006; Ding et al., 2012), and the inconsistency of ENSO's impacts on the equatorial Atlantic has been interpreted as resulting from the destructive interference

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of the Bjerknes-type oceanic dynamical response with the tropospheric temperature warming process (Chang et al., 2006) or the delayed negative feedback from the tropical North Atlantic (Lübbecke & McPhaden, 2012).

One might expect year-to-year variability in the equatorial Pacific and Atlantic to be dynamically related, considering that these regions are closely interconnected via the Walker Circulation (Cai et al., 2019; Chang et al., 2006; Wang, 2004). However, given that processes internal to the Pacific dominate ENSO dynamics (Jin, 1997), one might hesitate to conclude that an Atlantic Niño triggers a La Niña event (or an Atlantic Niña triggers an El Niño event), although previous statistical analyses and pacemaker experiments seem to suggest so. Here we provide a new dynamically consistent picture for the inter-basin equatorial Pacific and Atlantic relationship, in which ENSO plays an essential role in driving the interannual tropical Pacific-Atlantic relationship and not the other way around. This hypothesis, which is rigorously tested using observations, theoretical models, and different climate model simulations, resolves the apparent paradoxical interaction between Pacific Niño/Niña and Atlantic Niño/Niña from a new perspective.

2. Materials and Methods

2.1. Observational Data Sets

The SST data set at 1° × 1° horizontal resolution is derived from the global sea ice and SST analysis from the Met Office Hadley Centre (HadISST version 1.1) (Rayner, 2003). The precipitation data set is the global precipitation product from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (Xie & Arkin, 1997), which has a horizontal resolution of 2.5° × 2.5°. The near-surface horizontal winds are derived from the National Centers for the Environmental Prediction–National Center for the Atmospheric Research reanalysis (Kalnay et al., 1996) with a horizontal resolution of 2.5° × 2.5°. The subsurface ocean temperature is derived from the Global Ocean Data Assimilation System (GODAS) (Behringer & Xue, 2004) at a horizontal resolution of 1° × 1/3°.

2.2. Statistical Analysis

All data sets used in this study cover the period 1979–2020, except for the GODAS data (1980–2020). Anomalies for all variables were derived relative to the monthly mean climatology. The linear trend was removed, and a 10-year high-pass fast Fourier transform filter was applied to all data sets. All statistical significance tests were performed using the two-tailed Student's t test with $n - 2$ degrees of freedom, where n is the sample size. The Niño3.4 index and Atl3 index, calculated as SST anomalies averaged over 5°S–5°N, 120°–170°W and 3°S–3°N, 0°–20°W, were used to characterize the ENSO and Atlantic Niño/Niña variability, respectively. ENSO events are defined based on a threshold of ±0.5°C of the Niño3.4 index in boreal winter (November–January). The Atlantic Niño/Niña events were defined based on the ±0.5 standard deviation of the Atl3 index in boreal summer (June–August). Selected events are listed in Table S1 in Supporting Information S1.

2.3. Phase 6 of the Coupled Model Inter-Comparison Project (CMIP6) Data

We analyzed monthly SST and sea surface height (SSH), used as a proxy for upper-ocean heat content for simplicity (Nnamchi et al., 2021) from the outputs of 31 CMIP6 historical simulations (1979–2014), which were extended to 2020 with the Shared Socioeconomic Pathways (SSP) SSP5-8.5 simulations (O'Neill et al., 2016) (see Table S2 in Supporting Information S1). The historical simulations are forced by the historical anthropogenic and natural forcing, and the SSP5-8.5 with CO_2 concentrations reaching a radiative forcing of 8.5 W/m^2 at the end of the century. El Niño/La Niña events were defined based on the ±0.5 standard deviation of the Niño 3.4 index and the Atlantic Niño/Niña events were defined based on the ±0.5 standard deviation of the Atl3 index for each model.

3. Results

3.1. The Apparent Paradoxical Tropical Pacific/Atlantic Interaction

During the onset of a Pacific El Niño in boreal summer, an Atlantic Niña can often be observed to reach its mature phase. Similarly, a developing Pacific La Niña in boreal summer often coincides with Atlantic Niño conditions. In the subsequent months, the El Niño (or La Niña) further grows, maturing two seasons later in winter whereas the Atlantic Niña (or Niño) rapidly decays. Based on this seasonally-locked interannual evolution of Atlantic and Pacific SSTs during the satellite era, many studies concluded that summer equatorial Atlantic events favor the formation of opposite-signed Pacific ENSO events in the following winter (Ding et al., 2012; Keenlyside & Latif, 2007) (Figure 1b). This observed lead relationship can be reproduced in pacemaker experiments (Martín-Rey et al., 2012; Polo et al., 2015), however, seasonal forecast experiments initialized in early summer with observed equatorial Atlantic SST being nudged toward observed equatorial Atlantic SST afterward show that very limited additional predictive skill is achieved for the subsequent development of ENSO (Figure 3 in Exarchou et al., 2021). We also find that compared to a benchmark persistence-based prediction scheme (based on linear regression) for the Niño3.4 index, a statistical model with an additional consideration (based on multiple linear regression) of the equatorial Atlantic SST lacks additional skill. As shown in Figure 1c, the statistical model with an additional consideration of the equatorial Atlantic SST fails to outperform the persistence forecast in predicting the boreal winter Niño3.4 index when starting from any month after an equatorial Atlantic event has developed (Figure 1c).

In an attempt toward resolving the apparent paradox, we propose a new hypothesis for the inter-basin interaction between Pacific ENSO and Atlantic Niño/Niña, in which a Pacific event in its early stages of development can drive an opposite-signed equatorial Atlantic event but not vice versa. A much-overlooked fact when it comes to the inter-basin interaction is that the ENSO lifecycle itself is asymmetric with respect to the winter peak, that is, on average, the ENSO-associated central-to-eastern Pacific SST anomalies (as indicated by the Niño3.4 index) are already well-developed by the boreal summer, but quickly decay after they mature in winter (Figure 2a). Correspondingly, the ENSO autocorrelation structure shows that boreal winter ENSO SST anomalies are significantly correlated with its previous summer conditions ($R = 0.84$, statistically significant at the 95% confidence level) but loses statistical connection with the following summer condition (black line in schematic Figure 2a). In this context, an alternative explanation for the Pacific/Atlantic lead-lag correlation is that the Pacific SST anomalies during the summer onset stage of ENSO events generate pronounced equatorial Atlantic anomalies but the near-neutral ENSO conditions in the summer after the ENSO peak are accompanied with no statistically significant response over the equatorial Atlantic. The previously identified impacts of the equatorial Atlantic on ENSO could therefore be a statistical artifact resulting from ENSO driving the equatorial Atlantic event during its developing phase and the subsequent strong ENSO persistence from summer to winter seasons.

As shown in Figure 2b, the role of equatorial Atlantic variability in the Pacific-Atlantic connection is more likely to be the consequence of ENSO rather than a trigger. Analyzing the observed Atlantic lead correlation with the Pacific, the years in which winter ENSO events are preceded by opposite-signed summer equatorial Atlantic events (red dots in Figure 2b) constitute an essential part of their statistically significant negative correlation. For ENSO years preceded by opposite-signed summer Atlantic events, the amplitudes of summer equatorial Atlantic events and winter ENSO events are highly negatively correlated ($R = -0.94$, statistically significant at the 95% confidence level). However, these ENSO events peaking in winter have already been well-developed in the preceding summer, exhibiting a comparable strong correlation between summer and winter ENSO conditions ($R = 0.94$, statistically significant at the 95% confidence level). We further calculated the statistical contribution of summer equatorial Atlantic variability to winter ENSO amplitude, which is defined as the difference between the reconstructed winter Niño3.4 index obtained by incorporating both the previous summer Niño3.4 and Atl3 indices and that derived solely from summer Niño3.4 index. It is evident that the additional consideration of the equatorial Atlantic information associated with Atlantic Niño/Niña events in an ENSO persistence-based representation does not lead to significantly increased explained variance for these ENSO events (inset of Figure 2b).

3.2. Evidence for Pacific-To-Atlantic Impact

We further establish an unequivocal causal link between the developing ENSO and ensuing summer equatorial Atlantic events by analyzing the observed time evolution of atmosphere-ocean conditions for those ENSO years with opposite-signed summer equatorial Atlantic events (Figures 2c and 2d). The much earlier development of these ENSO events compared to the equatorial Atlantic events is clearly evident in the Hovmöller diagrams showing the time evolution of fundamental atmospheric and oceanic conditions (zonal wind, precipitation, and subsurface ocean temperature anomalies) over the equatorial Pacific and Atlantic (Figures 2c and 2d). During the early months of these El Niño years, warm water spreads from the western equatorial Pacific and zonal wind and precipitation anomalies are established in the central Pacific (Figures 2c and 2d). These early spring atmosphere-ocean anomalies set the stage for El Niño to develop, whereas the equatorial Atlantic basin at the

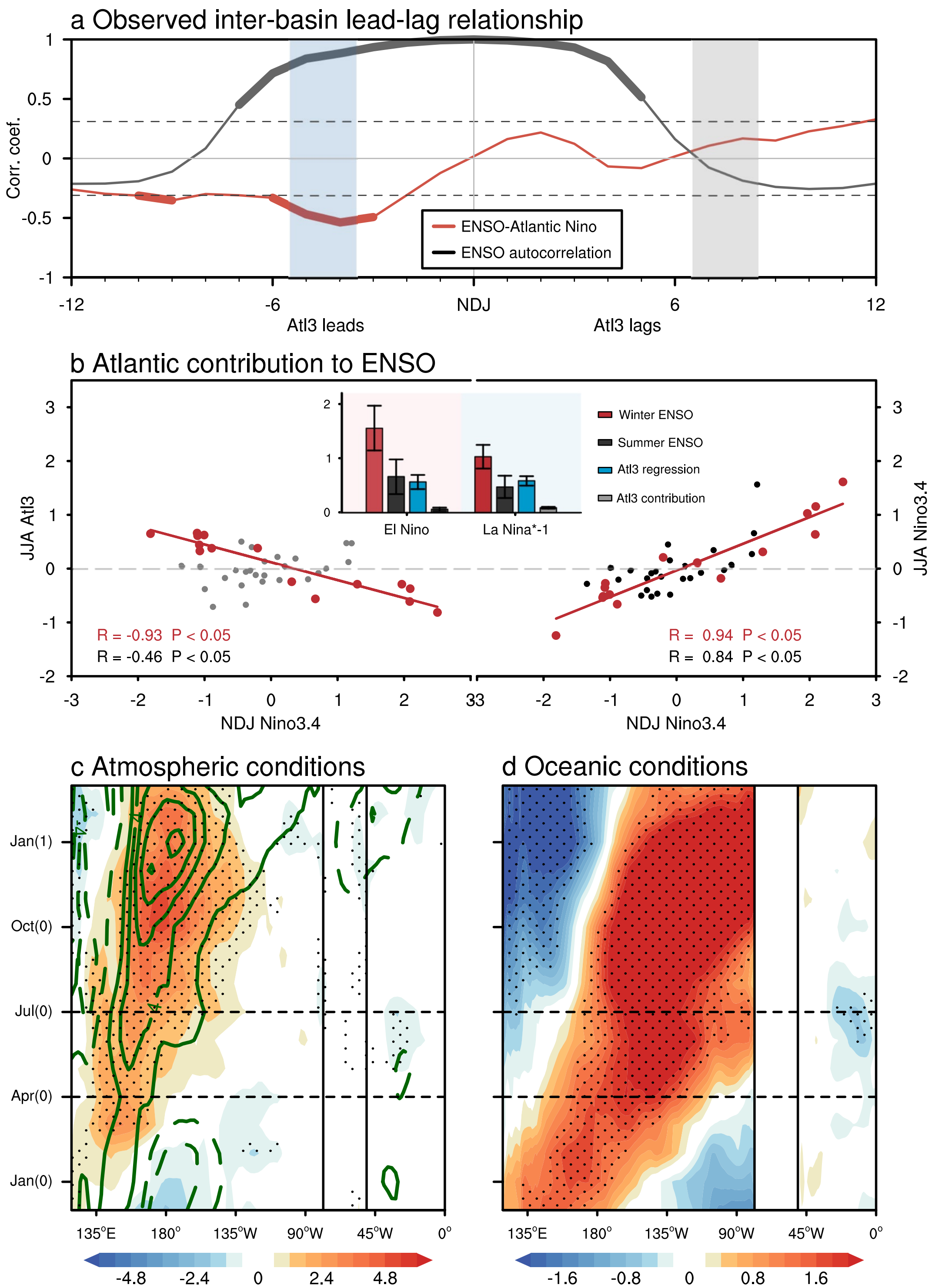

Figure 2.

same time is close to a neutral state. It is not until late spring (around May) that atmospheric anomalies start to emerge over the equatorial Atlantic as a response to the developing El Niño. The strengthened Atlantic trade winds act to activate the Bjerknes feedback, tilting the Atlantic thermocline down to the west, triggering the equatorial Atlantic SST cooling, and subsequently leading to the mature stage of an Atlantic Niña. The opposite works for a developing La Niña driving an Atlantic Niño event (Figure S1 in Supporting Information S1).

Most notably, the ENSO impact on the equatorial Atlantic SST operates only during a short time window over the course of the seasonal cycle, manifesting itself primarily in the late boreal spring and early summer season (April–June). The close linkage between the Pacific and the Atlantic in this specific season has been noticed in earlier studies (Latif & Grötzner, 2000; Münnich & Neelin, 2005), and we here demonstrate that the seasonal preference is related to the strong seasonal preconditioning by atmospheric and oceanic processes within the equatorial Atlantic (Keenlyside & Latif, 2007; Nnamchi et al., 2021; Zebiak, 1993). During these months, the equatorial eastern Atlantic thermocline is shallow enough for subsurface temperature anomalies to affect the SST (Richter et al., 2017), while the Atlantic Intertropical Convergence Zone (ITCZ) and associated diabatic heating are closest to the equator so that strong atmosphere-ocean coupling occurs in the equatorial Atlantic (Nnamchi et al., 2021). In this sense, the ENSO-associated trade wind changes over the equatorial Atlantic during this period, which is through direct modulation of Walker Circulation, the excited Pacific-South America wave train, or other mechanisms (Lübbecke et al., 2018; Richter et al., 2013; Rodrígues et al., 2011), are most effective in activating the positive Bjerknes feedback (Richter et al., 2017), which could be conducive to the subsequent development of Atlantic Niño/Niña events. As soon as the climatological upwelling in the eastern equatorial Atlantic weakens and the ITCZ migrates northward, the ENSO impact on equatorial Atlantic SST ceases to exist. Therefore, early-onset ENSO events are accompanied by opposite-signed equatorial Atlantic signals in summer (Figure S2 in Supporting Information S1), while late-onset ENSO events tend to be accompanied by near-neutral states in the equatorial Atlantic (Figure S3 in Supporting Information S1). The essential role of ENSO in the development of following equatorial events in late spring to early summer can also be well reproduced in pacemaker experiments (Figure S4 and Text S1 in Supporting Information S1).

On these bases, we extend the original recharge oscillator (RO) model (Jin, 1997) to an ENSO-forced seasonal-modulated model for Atlantic Niño (Text S2 in Supporting Information S1). RO model well captures the fundamental characteristics of observed Atlantic Niño, including its synchronization to the summer season and its statistically significant near-annual spectral peaks (Figure S5 in Supporting Information S1). And importantly, this conceptual framework does not allow for feedback from the equatorial Atlantic to the Pacific, yet the observed lead relationship of Atlantic Niño over ENSO can still be reproduced (Figure S6 in Supporting Information S1). The simulated lead relationship (Figures S6b, S6d, and S6e in Supporting Information S1) is fully consistent with ENSO's autocorrelation and the seasonally modulated equatorial Atlantic's response to ENSO. It provides compelling evidence to support our observational-based hypothesis of one-way ENSO-to-Atlantic Niño forcing.

3.3. Reconciling Observations and CMIP6 Model Simulations

While the observations and previous partially coupled experiments support a statistically significant correlation between Pacific and Atlantic Niño/Niña when the Atlantic leads by two seasons (Ding et al., 2012; Keenlyside & Latif, 2007; Martín-Rey et al., 2012), state-of-the-art CGCMs fail to capture this relationship (Figure 3). This failure is frequently interpreted as the result of long-standing systematic model biases in simulating the tropical Atlantic climatology (Richter et al., 2015).

Here we show that the multi-model simulations are generally consistent with our hypothesis, in which a developing El Niño forces an Atlantic Niña (and a developing La Niña forces an Atlantic Niño). We investigate this inter-basin relationship in CMIP6 model simulations over the period 1979–2020, extending historical simulations with future ScenarioMIP experiments (see details in Methods). We identified 20 out of 31 CMIP6 models that reasonably represent the seasonal synchronization behavior of interannual SST variability in terms of the

Figure 2. (a) Lead-lag correlations of the Niño 3.4 index (black line) and Atl3 index (red line) with the winter Niño3.4 index. Thick line marks the correlation coefficients that exceed the 95% confidence level. The blue and gray shadings indicate the El Niño-Southern Oscillation (ENSO) developing and decaying summer, respectively. (b) Scatterplot of winter Niño 3.4 index against previous summer Atl3 index (the left panel) and previous summer Niño3.4 index (the right panel). Red dots denote ENSO years with opposite-signed preceding summer equatorial Atlantic events and gray dots denote other years. The linear fit for the red dots is displayed together with the correlation coefficients R and P values for the red and black dots respectively. The inset shows the composite winter Niño3.4 index (red bar; °C), previous summer Niño3.4 index (black bar; °C), the winter Niño3.4 index reconstructed based on previous summer Atl3 index using linear regression (blue bar; °C) and the equatorial Atlantic's statistical contribution to the winter Niño3.4 index (gray bar; °C) for these ENSO years, with error bars corresponding to 1 standard deviation respectively. The composites for La Niña are scaled by a factor of −1. (c) Hovmöller diagrams for the composited temporal evolution of zonal wind (shading; m/s) and precipitation anomalies (contours; mm/day) for ENSO years with opposite-signed summer equatorial Atlantic events (El Niño minus La Niña). The contour interval is 2 mm/day and the zero value is omitted. (d) Similar to (c) but for the upper ocean (averaged over 5–250 m) temperature anomalies (shading; °C). All variables in (c) and (d) are averaged over 3°S–3°N. Dots in (c) and (d) indicate wind and heat content anomalies that are statistically significant at the 95% confidence level, respectively.

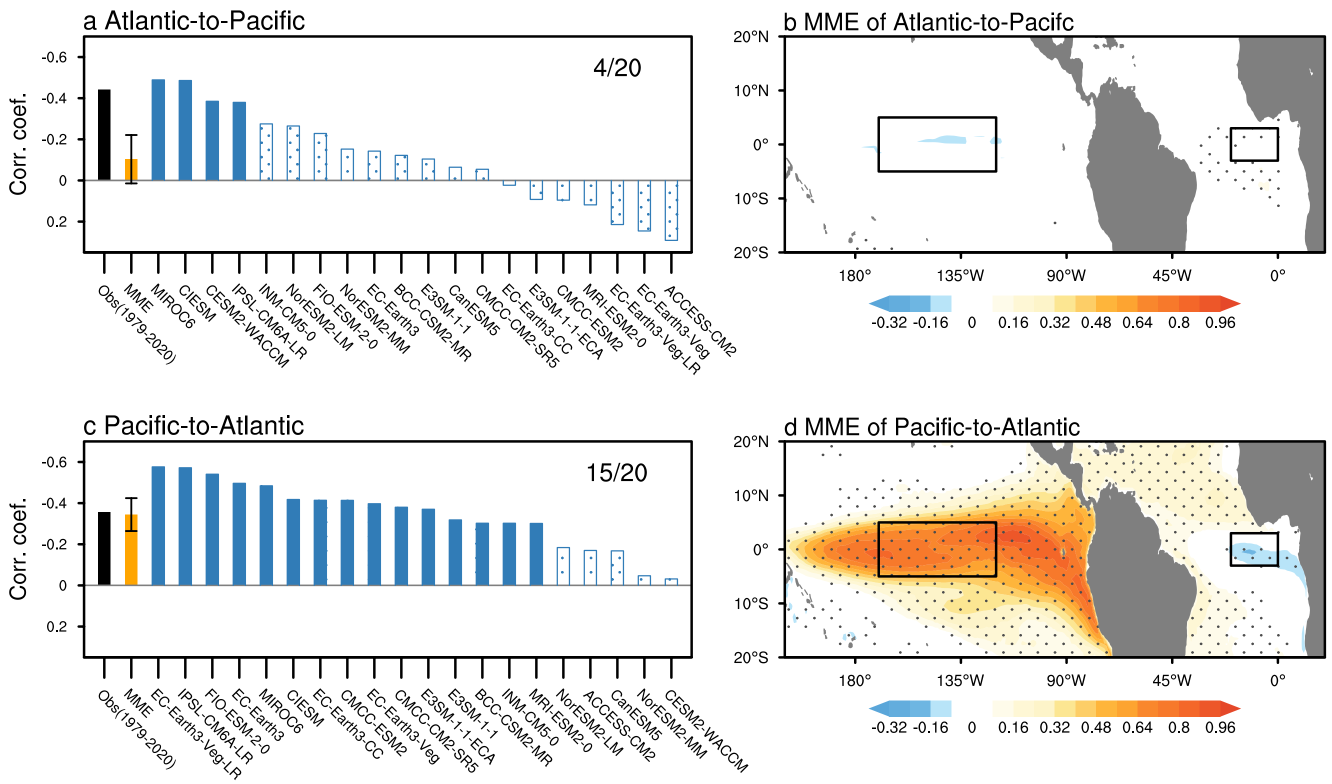

Figure 3. (a) Correlation coefficients of the winter Niño3.4 index with the preceding summer Atl3 index for 20 CMIP6 models which simulate the seasonal synchronization behavior of both Pacific El Niño and Atlantic Niño realistically. Note that the *y*-axis is reversed, and the models are ranked by the correlation coefficients in a descending order. The error bar for the multi-model ensemble (MME) mean corresponds to 1 standard deviation. The observed value is shown for reference. (b) Composite of the regressed winter sea surface temperature (SST) anomalies (°C) upon the previous summer Atl3 index for 20 models. (c) Similar to (a) but for the correlation coefficient of late spring and early summer (April–June) Niño 3.4 index with the subsequent summer Atl3 index. (d) Composite of the regressed summer SST anomalies (°C) upon the early spring Niño 3.4 index for 20 models. Dots in (b) and (d) indicate anomalies that are statistically significant at the 95% confidence level.

preferred SST variance maximum in both Pacific and Atlantic basins (Table S1 and Figure S7 in Supporting Information S1). Among these 20 models, however, only four models are capable of reproducing the observed Atlantic statistical lead relationship over the Pacific by two seasons during the past four decades. In contrast, the majority of models (15/20) reproduce the historical observations of Pacific impacts on the equatorial Atlantic, using the lead relationship of Pacific over Atlantic SST as a rough representation (Figure 3c). The earlier development of oceanic anomalies associated with ENSO events compared to those of Atlantic events can also be realistically reproduced (Figure S8 in Supporting Information S1). The agreement of CMIP6 extended historical simulations on the causal role of developing ENSO events on Atlantic Niño/Niña variability (Figure 3d), rather than vice versa (Figure 3b), further lends support to our interpretation of the observational record. According to Figure S9 in Supporting Information S1, the inability of most climate models to reproduce the observed statistical relationship could be partly attributed to a systematic model bias in simulating ENSO autocorrelation features with a much lower persistence from early summer to winter seasons compared to the observations. Nevertheless, we are still left with much uncertainty in understanding the specific reason for the discrepancies between the observed inter-basin linkage and that in each individual model, and future efforts are needed to achieve a more comprehensive understanding.

4. Conclusions

Previous studies concluded that, based on the lead-lag relationship between tropical Atlantic and Pacific interannual variability, equatorial Atlantic SST variability could act as a precursor for ENSO prediction. This argument, though appearing promising, is confronted with serious challenges associated with its practical utility for enhancing climate predictability. Here, we show that the inter-basin equatorial Pacific/Atlantic relationship is consistent

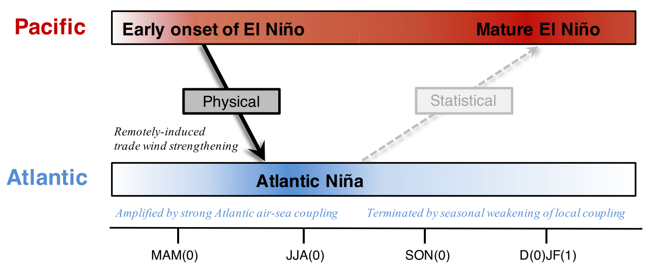

Figure 4. Schematic illustration explaining the inter-basin Pacific El Niño and Atlantic Niño relationship. An early-onset El Niño event during late boreal spring to early summer drives an ensuing summer Atlantic Niña event. Subsequently, the El Niño event shows full manifestation in winter, which is automatically correlated with the previous summer equatorial Atlantic sea surface temperature variability. The same mechanism works for a developing La Niña driving a summer Atlantic Niño.

with the following causal chain of events: an early-onset and strong enough El Niño event rapidly drives the ensuing summer Atlantic Niña event in late spring to early summer when the equatorial Atlantic atmosphere-ocean coupling is strongest; after that, the equatorial Atlantic coupling rapidly weakens, and the Atlantic event soon peaks and decays—while the Pacific ENSO event continues to grow, eventually peaking near the end of the calendar year. Analogously, a developing La Niña event drives an ensuing summer Atlantic Niño event and then matures to its peak later in winter (Figure 4). After they mature, ENSO events typically decay quickly and the tropical Pacific returns to a near-neutral state by the following summer. In this sense, the statistical relationship between summer equatorial Atlantic and winter Pacific SST is guaranteed once an ENSO event drives an opposite-signed summer equatorial Atlantic event during its developing phase, and no statistically significant response in the equatorial Atlantic would be anticipated during the summer following the decay of an ENSO event. Within this conceptual framework, the apparent contradiction between the statistically significant Atlantic lead relationship and the fact that the inclusion of Atlantic information does not lead to improvement of ENSO potential predictability can be resolved.

In the real world, no two El Niño events are exactly alike in terms of their onset timing, duration, and other fundamental characteristics (Quinn et al., 1971; Timmermann et al., 2018). Some ENSO events might have not yet developed by boreal summer (Neelin et al., 2000), and other events, especially cold La Niña events, could persist beyond a year, often re-intensifying in the following winter (Okumura & Deser, 2010). In the former case, an ENSO event commencing its development later than early summer would miss the optimal timing to exert its impact on the equatorial Atlantic SST. And for the latter case, these multi-year ENSO events are often accompanied by the opposite-signed equatorial Atlantic events in the intervening summer (Tokinaga et al., 2019), also in line with the hypothesis we proposed here. These highly complicated ENSO properties involving the ENSO onset timing and duration, offer a plausible explanation for the observed Pacific/Atlantic inter-basin linkages, without assuming that the relatively weak Atlantic variability is a major trigger for Pacific ENSO events.

In a rapidly changing climate, we have no alternatives but to rely on climate models to make predictions and projections across all timescales. The results here provide a reason for optimism, considering that state-of-the-art models are capable of simulating the fundamental dynamics that govern inter-basin linkages in spite of some long-standing biases, at least with regard to the ENSO and Atlantic Niño/Niña interaction.

Data Availability Statement

The data sets used to reproduce the results of this paper are located at https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html, https://psl.noaa.gov/data/gridded/data.cmap.html, https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.html, https://psl.noaa.gov/data/gridded/data.godas.html and https://esgf-node.llnl.gov/projects/cmip6/.

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References

Behringer, D., & Xue, Y. (2004). Evaluation of the global ocean data assimilation system at NCEP: The Pacific Ocean. In *Proceedings of the eighth symposium on integrated observing and assimilation systems for atmosphere, oceans, and land surface*. AMS 84th annual meeting.

Bjerknes, J. (1969). Atmospheric teleconnections from the equatorial Pacific. *Monthly Weather Review*, *97*(3), 163–172. https://doi.org/10.1175/1520-0493(1969)097<0163:ATFTEP>2.3.CO;2

Cai, W., Wu, L., Lengaigne, M., Li, T., McGregor, S., Kug, J.-S., et al. (2019). Pantropical climate interactions. *Science*, *363*(6430), eaav4236. https://doi.org/10.1126/science.aav4236

Carton, J. A., & Huang, B. (1994). Warm events in the tropical Atlantic. *Journal of Physical Oceanography*, *24*(5), 888–903. https://doi.org/10.1175/1520-0485(1994)024<0888:WEITTA>2.0.CO;2

Chang, P., Fang, Y., Saravanan, R., Ji, L., & Seidel, H. (2006). The cause of the fragile relationship between the Pacific El Niño and the Atlantic Niño. *Nature*, *443*(7109), 324–328. https://doi.org/10.1038/nature05053

Chikamoto, Y., Johnson, Z. F., Wang, S.-Y. S., McPhaden, M. J., & Mochizuki, T. (2020). El Niño–Southern Oscillation evolution modulated by Atlantic forcing. *Journal of Geophysical Research: Oceans*, *125*(8). https://doi.org/10.1029/2020JC016318

Ding, H., Keenlyside, N. S., & Latif, M. (2012). Impact of the equatorial Atlantic on the El Niño Southern Oscillation. *Climate Dynamics*, *38*(9–10), 1965–1972. https://doi.org/10.1007/s00382-011-1097-y

Exarchou, E., Ortega, P., Rodríguez-Fonseca, B., Losada, T., Polo, I., & Prodhomme, C. (2021). Impact of equatorial Atlantic variability on ENSO predictive skill. *Nature Communications*, *12*(1), 1612. https://doi.org/10.1038/s41467-021-21857-2

Grodsky, S. A., Carton, J. A., & McClain, C. R. (2008). Variability of upwelling and chlorophyll in the equatorial Atlantic. *Geophysical Research Letters*, *35*(3), L03610. https://doi.org/10.1029/2007GL032466

Jansen, M. F., Dommenget, D., & Keenlyside, N. (2009). Tropical atmosphere–ocean interactions in a conceptual framework. *Journal of Climate*, *22*(3), 550–567. https://doi.org/10.1175/2008JCLI2243.1

Jin, F.-F. (1997). An equatorial ocean recharge paradigm for ENSO. Part I: Conceptual model. *Journal of the Atmospheric Sciences*, *54*(7), 811–829. https://doi.org/10.1175/1520-0469(1997)054<0811:AEORPF>2.0.CO;2

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., et al. (1996). The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society*, *77*(3), 437–471. https://doi.org/10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2

Keenlyside, N. S., Ding, H., & Latif, M. (2013). Potential of equatorial Atlantic variability to enhance El Niño prediction: Atlantic Nino enhances ENSO prediction. *Geophysical Research Letters*, *40*(10), 2278–2283. https://doi.org/10.1002/grl.50362

Keenlyside, N. S., & Latif, M. (2007). Understanding equatorial Atlantic interannual variability. *Journal of Climate*, *20*(1), 131–142. https://doi.org/10.1175/JCLI3992.1

Latif, M., & Grötzner, A. (2000). The equatorial Atlantic oscillation and its response to ENSO. *Climate Dynamics*, *16*(2–3), 213–218. https://doi.org/10.1007/s003820050014

Lübbecke, J. F., & McPhaden, M. J. (2012). On the inconsistent relationship between Pacific and Atlantic Niños. *Journal of Climate*, *25*(12), 4294–4303. https://doi.org/10.1175/JCLI-D-11-00553.1

Lübbecke, J. F., Rodríguez-Fonseca, B., Richter, I., Martín-Rey, M., Losada, T., Polo, I., & Keenlyside, N. S. (2018). Equatorial Atlantic variability—Modes, mechanisms, and global teleconnections. *WIREs Climate Change*, *9*(4). https://doi.org/10.1002/wcc.527

Martín-Rey, M., Polo, I., Rodríguez-Fonseca, B., & Kucharski, F. (2012). Changes in the interannual variability of the tropical Pacific as a response to an equatorial Atlantic forcing. *Scientia Marina*, *76*(S1), 105–116. https://doi.org/10.3989/scimar.03610.19A

Münnich, M., & Neelin, J. D. (2005). Seasonal influence of ENSO on the Atlantic ITCZ and equatorial South America. *Geophysical Research Letters*, *32*(21), L21709. https://doi.org/10.1029/2005GL023900

Neelin, J. D., Jin, F.-F., & Syu, H.-H. (2000). Variations in ENSO phase locking. *Journal of Climate*, *13*(14), 2570–2590. https://doi.org/10.1175/1520-0442(2000)013<2570:VIEPL>2.0.CO;2

Nnamchi, H. C., Latif, M., Keenlyside, N. S., Kjellsson, J., & Richter, I. (2021). Diabatic heating governs the seasonality of the Atlantic Niño. *Nature Communications*, *12*(1), 376. https://doi.org/10.1038/s41467-020-20452-1

Okumura, Y. M., & Deser, C. (2010). Asymmetry in the duration of El Niño and La Niña. *Journal of Climate*, *23*(21), 5826–5843. https://doi.org/10.1175/2010JCLI3592.1

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., et al. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. https://doi.org/10.5194/gmd-9-3461-2016

Philander, S. G. H. (1983). El Niño Southern Oscillation phenomena. *Nature*, *302*(5906), 295–301. https://doi.org/10.1038/302295a0

Polo, I., Martin-Rey, M., Rodríguez-Fonseca, B., Kucharski, F., & Mechoso, C. R. (2015). Processes in the Pacific La Niña onset triggered by the Atlantic Niño. *Climate Dynamics*, *44*(1–2), 115–131. https://doi.org/10.1007/s00382-014-2354-7

Quinn, W. H., David, O., Short, S., & Yang, R. T. K. (1971). Southern Oscillation, El Niño, and Indonesian droughts. *Fishery Bulletin*, *76*(3), 663.

Rayner, N. A. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, *108*(D14), 4407. https://doi.org/10.1029/2002JD002670

Richter, I., Behera, S. K., Masumoto, Y., Taguchi, B., Sasaki, H., & Yamagata, T. (2013). Multiple causes of interannual sea surface temperature variability in the equatorial Atlantic Ocean. *Nature Geoscience*, *6*(1), 43–47. https://doi.org/10.1038/ngeo1660

Richter, J. H., Deser, C., & Sun, L. (2015). Effects of stratospheric variability on El Niño teleconnections. *Environmental Research Letters*, *10*(12), 124021. https://doi.org/10.1088/1748-9326/10/12/124021

Richter, I., Xie, S.-P., Morioka, Y., Doi, T., Taguchi, B., & Behera, S. (2017). Phase locking of equatorial Atlantic variability through the seasonal migration of the ITCZ. *Climate Dynamics*, *48*(11–12), 3615–3629. https://doi.org/10.1007/s00382-016-3289-y

Rodrígues, R. R., Haarsma, R. J., Campos, E. J. D., & Ambrizzi, T. (2011). The impacts of Inter–El Niño variability on the tropical Atlantic and Northeast Brazil climate. *Journal of Climate*, *24*(13), 3402–3422. https://doi.org/10.1175/2011JCLI3983.1

Rodríguez-Fonseca, B., Polo, I., García-Serrano, J., Losada, T., Mohino, E., Mechoso, C. R., & Kucharski, F. (2009). Are Atlantic Niños enhancing Pacific ENSO events in recent decades? *Geophysical Research Letters*, *36*(20), L20705. https://doi.org/10.1029/2009GL040048

Timmermann, A., An, S.-I., Kug, J.-S., Jin, F.-F., Cai, W., Capotondi, A., et al. (2018). El Niño–Southern Oscillation complexity. *Nature*, *559*(7715), 535–545. https://doi.org/10.1038/s41586-018-0252-6

Tokinaga, H., Richter, I., & Kosaka, Y. (2019). ENSO influence on the Atlantic Niño, revisited: Multi-year versus single-year ENSO events. *Journal of Climate*, *32*(14), 4585–4600. https://doi.org/10.1175/JCLI-D-18-0683.1

Wang, C. (2004). ENSO, Atlantic climate variability, and the walker and Hadley circulations. In H. F. Diaz & R. S. Bradley (Eds.), *The Hadley circulation: Present, past and future* (Vol. 21, pp. 173–202). Springer Netherlands. https://doi.org/10.1007/978-1-4020-2944-8_7

Xie, P., & Arkin, P. A. (1997). Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. *Bulletin of the American Meteorological Society*, *78*(11), 2539–2558. https://doi.org/10.1175/1520-0477(1997)078<2539:GPAYMA>2.0.CO;2

Yadav, R. K., Srinivas, G., & Chowdary, J. S. (2018). Atlantic Niño modulation of the Indian summer monsoon through Asian jet. *Npj Climate and Atmospheric Science*, *1*(1), 23. https://doi.org/10.1038/s41612-018-0029-5

Zebiak, S. E. (1993). Air–sea interaction in the equatorial Atlantic region. *Journal of Climate*, *6*(8), 1567–1586. https://doi.org/10.1175/1520-0442(1993)006<1567:AIITEA>2.0.CO;2

References From the Supporting Information

Delworth, T. L., Broccoli, A. J., Rosati, A., Stouffer, R. J., Balaji, V., Beesley, J. A., et al. (2006). GFDL's CM2 global coupled climate models. Part I: Formulation and simulation characteristics. *Journal of Climate*, *19*(5), 643–674. https://doi.org/10.1175/JCLI3629.1

Stuecker, M. F., Timmermann, A., Jin, F.-F., Chikamoto, Y., Zhang, W., Wittenberg, A. T., et al. (2017). Revisiting ENSO/Indian Ocean Dipole phase relationships. *Geophysical Research Letters*, *44*(5), 2481–2492. https://doi.org/10.1002/2016GL072308