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Key Points:

- Observed tropical Atlantic forced pacemaker experiments produce La Niña events, but not El Niño events, in unison with observations
- A warm Atlantic had a greater chance of leading to a La Niña event if the tropical Pacific was initially in neutral conditions
- There was a tropical-wide response to a warm Atlantic in the model, affecting western Pacific wind. This was not seen for a cold Atlantic

Supporting Information:

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

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The Tropical Atlantic's Asymmetric Impact on the El Niño-Southern Oscillation

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Abstract Using observations and Atlantic forced coupled model simulations, we show evidence for an asymmetry in the link between beginning of year tropical Atlantic sea surface temperature anomalies (SSTAs) and end of the year El Niño-Southern Oscillation events. We find a greater tendency for warm Atlantic SSTAs to lead to a La Niña than for cold anomalies to lead to El Niño. The model experiments showed that the Atlantic had a greater chance to force the tropical Pacific if the Pacific was initially in a neutral state. In the model, a warm Atlantic from March–May was able to produce an atmospheric response leading to easterly wind anomalies in the western Pacific. This in turn induces a subsurface oceanic response, leading to La Niña at the end of the year. The atmospheric response does not occur for a cold Atlantic, leading to no impacts in the Pacific.

Plain Language Summary It has been found that the tropical Atlantic can have an impact on an El Niño or La Niña events that form in the tropical Pacific at the end of the year. We show using observations and targeted model experiments that a warmer than normal Atlantic from March-May can lead to a La Niña, but a colder than normal Atlantic does not lead to an El Niño. The model shows a strong atmospheric response to warm Atlantic surface temperature, leading to wind changes in the Pacific that aid La Niña formation. This strong atmospheric response does not occur for cold Atlantic temperatures leading to no changes in the Pacific. The model also shows that the Atlantic has a greater chance of impacting the Pacific at the end of the year if the Pacific is already in near average conditions at the beginning of the year. These results may improve forecasts of La Niña events and may help in understanding past changes in the Atlantic-Pacific relationship.

1. Introduction

The El Niño-Southern Oscillation (ENSO) has a large influence on global weather, leading to significant human impacts, ranging from economic (Callahan & Mankin, 2023) and agricultural (Iizumi et al., 2014) to emergency management (Guimarães Nobre et al., 2019). Accurate forecasting of ENSO events provides a vital warning for these sectors, meaning any improvements to the forecast could have an appreciable human benefit. One avenue to improve forecasts is through understanding the influence of other tropical ocean basins on ENSO development in the Pacific (Cai et al., 2019). Studies have shown that the tropical Atlantic can have an impact on ENSO events, ranging from causing ENSO events (Ham et al., 2013; Polo et al., 2015) to modulating ENSO events (Chikamoto et al., 2020; Ding et al., 2012; Richter et al., 2021; Rodríguez-Fonseca et al., 2009).

The current leading theory for the Atlantic to impact the Pacific is associated with a Gill-type atmosphere response (Gill, 1980) originating in the Atlantic (Ding et al., 2012; Ham et al., 2013; Jiang & Li, 2021; Polo et al., 2015; Rodríguez-Fonseca et al., 2009). Sea surface temperature anomalies lead to a change in convection and upper-level heating, which is dissipated through the tropics through fast-moving eastward propagating Kelvin waves and slow, westward moving Rossby waves. The two waves converge over the Pacific leading to a changed circulation and surface wind anomalies. The Pacific wind anomalies influences the ocean subsurface through the Bjerknes feedback, potentially growing to an ENSO event.

It is also possible that the Atlantic to Pacific connection is the result of a spurious relationship between ENSO and the Atlantic (Zhang et al., 2021). The influence of the Atlantic on the Pacific could be a statistical artifact resulting from the combination of autocorrelation within the Pacific due to internal recharge oscillator dynamics, and ENSO variability also influencing Atlantic SSTAs. This suggests it will be challenging to investigate Atlantic—

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Pacific interactions using observations alone. However, studies using coupled models forced by Atlantic SSTs report changes in the modeled ENSO (Bi et al., 2022; Chikamoto et al., 2020; Ding et al., 2012; Polo et al., 2015), suggesting there is a pathway for the Atlantic to affect the Pacific in the model space.

It has been shown that cold SSTAs produce a weaker magnitude global atmospheric response compared to their opposite warm SSTAs (Williams et al., 2023). Whether this asymmetry in response can occur in the Atlantic has begun to be explored. A modeling study found that a cold Atlantic exerts a slightly stronger magnitude wind response over the Pacific than for a warm Atlantic (Richter et al., 2021). This raises the question whether there is an asymmetry in the Pacific response to cold and warm Atlantic SSTs and if it can be detected in observations and in other general circulation models.

This paper addresses this issue by first detailing the methods and data sets used (Section 2), then explore the asymmetry in observations (Section 3), and Atlantic pacemaker experiments (Section 4). We then explore the dependence of the Pacific initial state to the ability for the Atlantic to have an impact (Section 5), and propose a mechanism for the asymmetry (Section 6).

2. Methods

2.1. Observed Analysis

For SST observations we used HadISST (Rayner, 2003) and ERSSTv3b (Smith et al., 2008) depending on the model used for comparison (see Section 2.4). We used the time period from December 1978 to February 2014, and we linearly detrend the data before performing regressions.

2.2. Definition of Events

We used the mean (0 anomaly) value to split between warm or cold SSTA groups. For composites, La Niña and El Niño events were defined as DJF Niño3.4 less than −1 and greater than 1 standard deviation, respectively. We used all members of the model experiment to calculate the model standard deviation.

2.3. Models Utilized

Two versions of the Australian Community Climate and Earth System Simulator (ACCESS) were used. ACCESS CM2 (Bi et al., 2020), which is the latest version submitted to CMIP6 (Coupled Model Intercomparison Project Phase 6), and ACCESS 1.0 (Bi et al., 2013), which is an older version submitted to CMIP5 (see Text S1 in Supporting Information S1 for details).

The models share a similar base, but the fully coupled control simulations have different dynamics in their representation of ENSO and Atlantic—Pacific relationship. The correlation between MAM Atlantic basin wide mean (10°N–10°S, 60°W–15°E) and the following DJF Pacific basin wide mean (10°N–10°S, 130°E–80°W) in an ACCESS 1.0 control run is −0.14, weaker than for all five ACCESS CM2 control runs (ranging from −0.15 to −0.48). Both models are weaker than that observed in HadISST (−0.54) and ERSST (−0.53) over the same period from 1979 to 2014. The fully coupled ACCESS CM2 model had the strongest North Tropical Atlantic—ENSO relationship of all CMIP6 models analyzed in Zhang et al. (2021), making it the closest to the relationship observed from 1990 to 2019.

There are numerous differences in the modeled representation of ENSO statistics and dynamics between ACCESS 1.0 and ACCESS CM2 (Planton et al., 2021). For example, whereas ACCESS CM2 produces a better ENSO pattern close to that observed, ACCESS 1.0 produces a more accurate ENSO lifecycle than ACCESS CM2 (Planton et al., 2021).

2.4. Pacemaker Experiment Details

We analyzed results from pacemaker experiments where the model Atlantic SSTs were prescribed to observed SSTs, while the atmosphere and remaining oceans were free to evolve. The two ACCESS model versions used two different Atlantic pacemaker experiment configurations, as they were originally developed independently. The three key differences are the Atlantic meridional extent used as a pacemaker (ACCESS 1.0: 30°S–30°N; ACCESS CM2: 20°S–20°N), the observational data set used to restore the observed SSTs (ACCESS 1.0: ERSSTv3b; ACCESS CM2: HadISST), and the method used to restore the SSTs (ACCESS 1.0: SSTs nudged to observations using a 3-day restoring timescale—for further details, see Purich et al. (2021); ACCESS CM2: SSTs are bypassed and completely replaced with observations—see Bi et al. (2022)). The integration time for ACCESS 1.0 and ACCESS CM2 was from 1961–2014 and 1970–2014, respectively, but we only used data from 1979 to 2014. Five runs were available for ACCESS CM2 and 10 runs for ACCESS 1.0.

2.5. Statistical Significance

Statistical significance for the regression analysis was calculated using the Student's *t*-test with a confidence interval of 0.05 p-value or less. For the statistical significance in the Venn diagrams, we used Theiler surrogates to produce random timeseries of the observed DJF Niño3.4 with similar spectral properties (Prichard & Theiler, 1994; Theiler et al., 1992), using the phaseran tool (Khider et al., 2022). We then perform the same analysis 1000 times to calculate the 5%–95% statistical significance bounds.

3. Observations Show a Stronger Relationship Between MAM Atlantic and La Niña Than El Niño

First, using observations, we detect if regions of the Atlantic SST in MAM are coherent with Niño3.4 in the following DJF, showing many regions of significant correlation (Figure 1a). We focus on the western tropical Atlantic (WTA), due to its strong coherence and tropical location. A scatter plot shows an asymmetry in this relationship, where warm (positive) anomalies in this region favors La Niña conditions, but cold (negative) anomalies do not favor El Niño conditions (Figure 1b).

We can perform the same analysis as Figure 1b for each grid point of the SST data set, whereby for each grid point we select the years of negative anomalies of MAM SSTs and correlate with the corresponding year of DJF Niño3.4 (Figure 1c), likewise for positive anomalies (Figure 1d). This reveals the regions of anomalously cold or warm MAM SSTs that may lead to a change in end of year DJF Niño3.4.

Cold tropical Pacific DJF SSTA (La Niña) were affected by earlier MAM SSTAs in more regions of the globe than warm tropical Pacific DJF SSTA (El Niño) (compare blue regions to red regions in Figures 1c and 1d). Cold MAM SSTAs in the central tropical Pacific and southwest tropical Indian Ocean were related to La Niña conditions later in DJF (Figure 1c). The central tropical Pacific signal is consistent with the tendency for La Niña to extend over multiple years (Okumura & Deser, 2010).

Positive MAM SSTAs show many well-defined regions that were related to end of year La Niña conditions (Figure 1d). The western tropical Atlantic showed a high coherence, along with the eastern off-equatorial Indian Ocean and western north Pacific. A patchy region in the eastern tropical Pacific could be remnants from a preceding El Niño (Figure 1d), consistent with the tendency for El Niño to be followed by La Niña (Okumura & Deser, 2010). These findings can be reproduced using another observational data set (Figure S1 in Supporting Information S1), however, the possibility that these features are an artifact similar in nature to that described by Zhang et al. (2021) (i.e., a confounding of ENSO autocorrelation and ENSO teleconnections) cannot be ruled out.

4. La Niña in Atlantic Pacemakers Are More Likely to Occur in Unison With Observations Than El Niño

To overcome the effects of autocorrelation and Atlantic teleconnection within the observed Pacific variability, we examined the results of pacemaker experiments. In these experiments the Atlantic SSTs were prescribed to observed SSTs, while the atmosphere and remaining oceans were free to evolve. This means that an El Niño or La Niña was not able to change the Atlantic SSTs, breaking the Pacific-Atlantic teleconnection route described by Zhang et al. (2021).

The model ensemble mean Niño3.4 region SSTA possessed a synchronisation with the observed Niño3.4 region SSTA. In both climate models, this synchronisation was stronger for cold Pacific SSTA only, indicating that the modeled and observed La Niña events tend to coincide (Figure 2a). This suggests that the Atlantic had a more robust impact on the formation of La Niña events than El Niño events in these models.

Focusing on the spread between the individual ensemble members in any given year can also give an indication of the statistical significance of this interbasin connectivity and any other factors affecting this relationship. For instance, there were six La Niña events in the observations during 1979–2014–which equates to 30 possible years

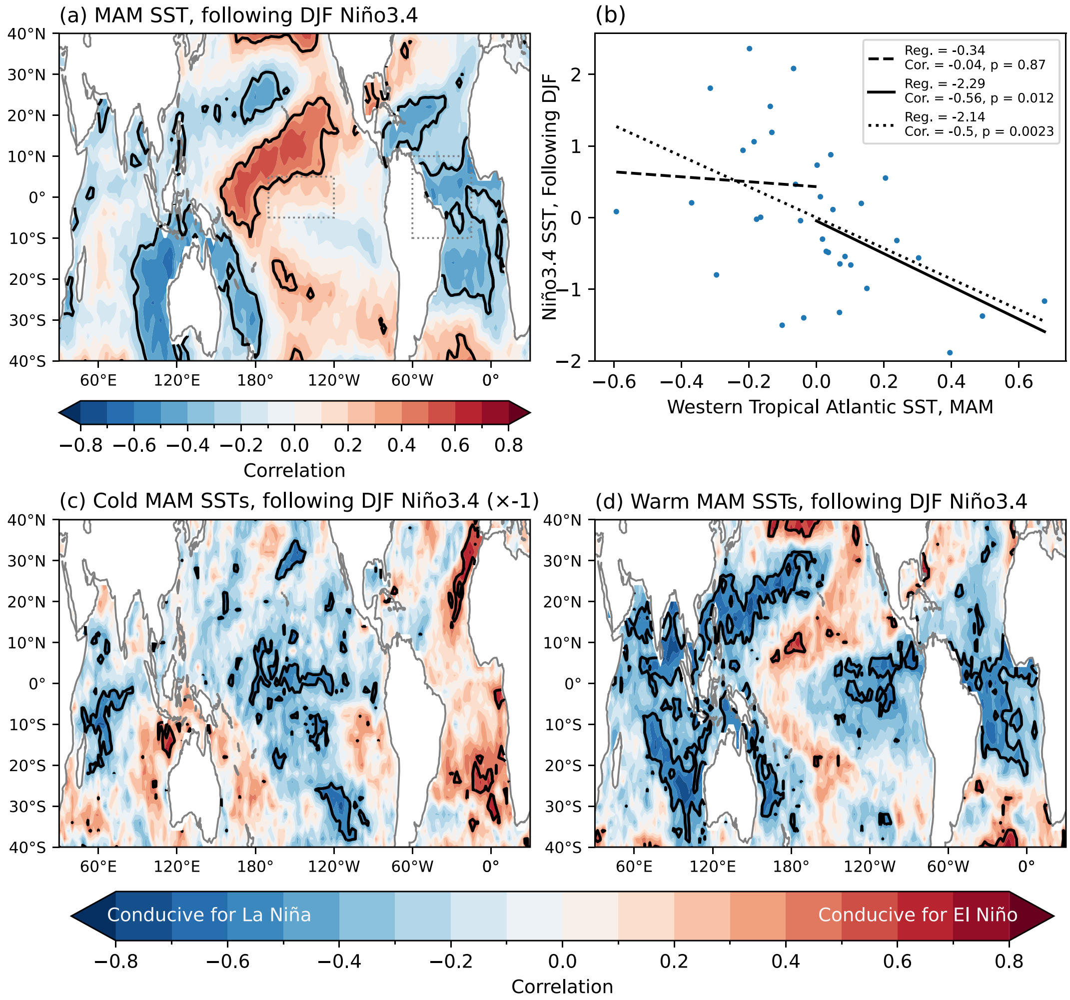

Figure 1. (a) Correlation of DJF Niño3.4 with preceding MAM SSTAs. Black contours show 95% significant values using Student's *t*-test. Gray dotted boxes show the Niño3.4 (5°N–5°S, 170°W–120°W) and WTA (10°N–10°S, 60°W–15°W) regions. (b) Observed scatterplot of DJF Niño 3.4 versus the preceding MAM WTA SSTA with linear regressions using all, only cold and only warm Atlantic SSTs. (c) Correlations with DJF Niño3.4 using only negative MAM SSTAs at each grid point. (d) As (c) but using only positive MAM SSTAs. We multiply (c) by −1 so the blue shades show regions related to end-of-year cool Niño3.4 and the red shades show regions related to end-of-year warm Niño3.4. This figure only used data from HadISST.

in the five-member ensemble of ACCESS CM2 that could coincide with the observations (six observed La Niña times five realizations).

Of the 31 La Niña events that occurred in the ACCESS CM2 ensemble during 1979–2014, there were 13 instances in which there was both a La Niña in the model and a La Niña in the observations (Figure 2b). This is outside the range expected by random chance defined by the 95th confidence level (see Section 2.4). Further to this, when the ACCESS CM2 pacemaker ensemble exhibited a La Niña, there was a 42% chance that it occurred in the same year as observed. Whereas the number of El Niño events in the ACCESS CM2 pacemaker that cooccurred with the observations could be explained by random chance (Figure 2b, bottom row).

Carrying out the same analysis for ACCESS 1.0 pacemaker, we find that the co-occurrence of La Niña events only occurred 15% of the time—which is within the possibility of random chance (Figure 2c). This weak result could be expected given the ACCESS 1.0 control exhibited a limited interbasin connection than that seen in both observations and ACCESS CM2 (see Section 2.3), with SSTAs leading up to the formation of ENSO events largely limited to the Pacific Ocean (Figure S1 in Supporting Information S1). ENSO in ACCESS 1.0 is less biennial compared to ACCESS CM2, which may also be a factor in the Atlantic-Pacific interaction (e.g., Zhang et al., 2021).

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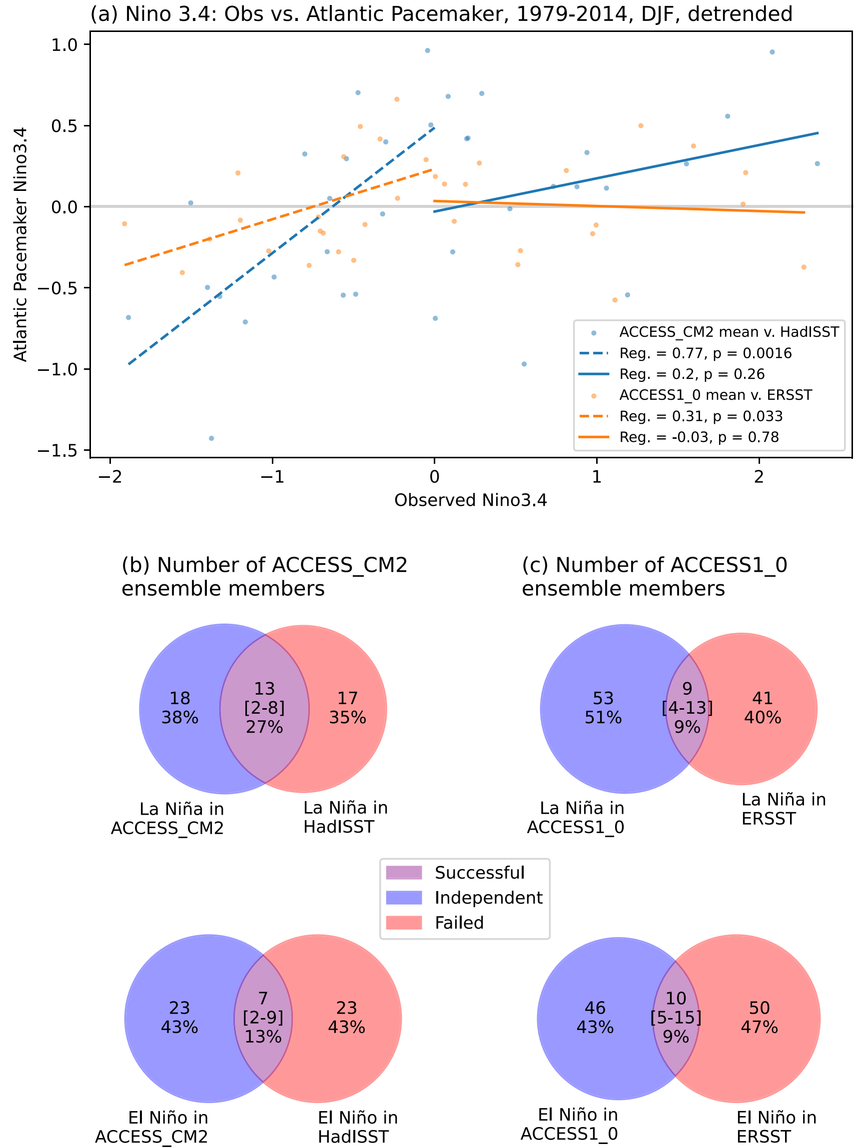

Figure 2. Synchronisation of Atlantic pacemaker to observations in the Pacific. (a) Multi-run mean of Atlantic pacemaker DJF Niño3.4 versus the observed DJF Niño3.4 from 1979 to 2014. ACCESS CM2 and HadISST are blue, ACCESS 1.0 and ERSST are orange. Regressions for both positive and negative observed Niño3.4 are shown in solid and dashed lines, respectively (see legend). All timeseries were linearly detrended. (b) Venn diagram showing the total number of ACCESS CM2 pacemaker years in all runs that correspond with a La Niña in the model and/or HadISST (events with Niño3.4 standard deviation of −1 or less). The size of the circles are proportional to the sample size. (c) As for (b) but using ACCESS 1.0 pacemaker years and ERSSTv3b for observations. The bottom row shows the same but for El Niño events. The range shown in the Successful group is the 5th–95th confidence interval (see Section 2.5), meaning counts outside this range are statistically significant.

5. Pacific Initial State May Determine if a Warm Atlantic Can Lead to La Niña

The ACCESS CM2 ensemble showed that while a warm Atlantic on average forces a La Niña-like Pacific response, it does not force a La Niña on all occasions. Here we used composite analysis to explore possible reasons why modeled La Niña events successfully occurred at the same time as observations, why they occurred independently of the observations, and why they failed to occur at the same time as observations, as characterized in Figure 2b (Figure 3).

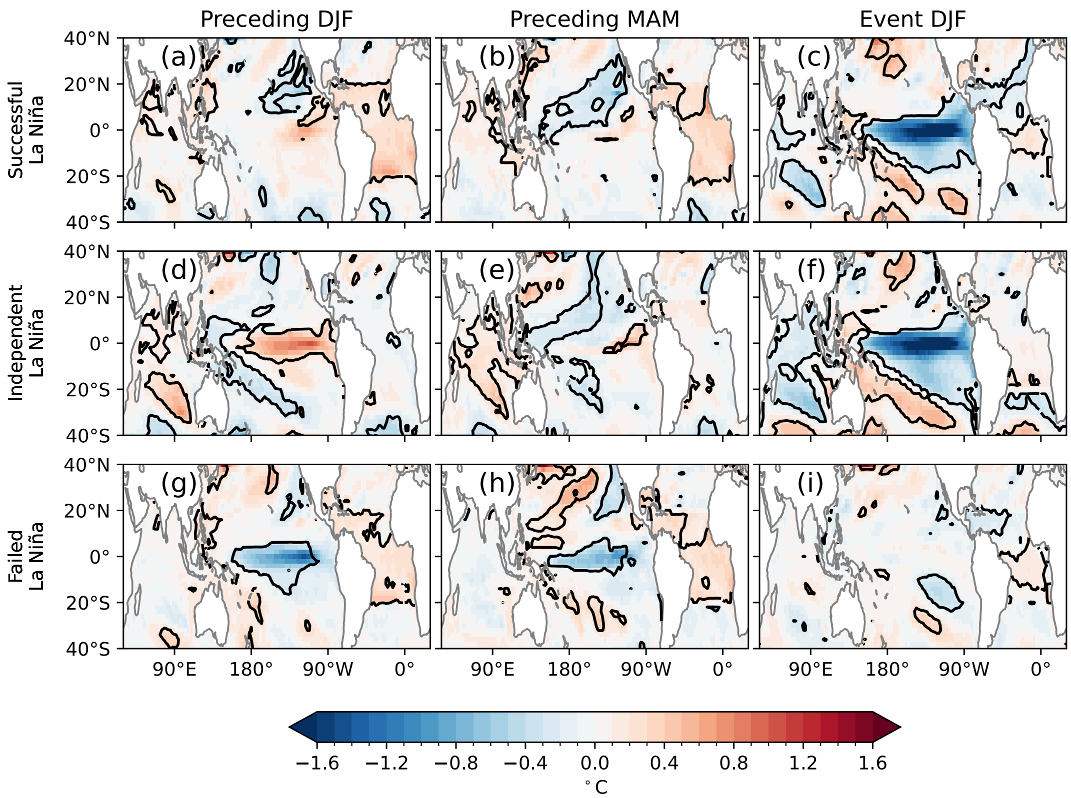

Figure 3. Composite mean of SSTAs for the (top row) successful, (middle row) independent, (bottom row) failed La Niña for ACCESS CM2, as defined in Figure 2b. Each column from left to right shows the time progression leading to the event: DJF and MAM before the event with the event occurring in DJF.

The composite analysis reveals that successful La Niña events show a widespread warm SSTA in the Atlantic in the preceding DJF that largely persists into MAM (Figures 3a and 3b), indicating the Atlantic was a strong driver for the La Niña synchronisation with observations. Further to this, there is an indication that the equatorial Pacific was ENSO neutral at the beginning of the year (Figure 3a), with robust neutral conditions forming by April (Figure S2a in Supporting Information S1). This follows a weak equatorial Pacific subsurface temperature anomaly during this time (sea surface height anomaly, Figure S2a in Supporting Information S1), indicating the Pacific may have been more open to external influences during MAM.

Independent La Niña events did not tend to have an Atlantic SSTA during the lead up, indicating that Atlantic SSTAs had little systematic impact on these events (Figures 3d and 3e). Rather, independent La Niña events tended to have a strong El Niño anomaly in the preceding DJF (which discharged heat throughout the year leading to La Niña, e.g. Jin (1997), Figure S2b in Supporting Information S1) and a warm Indian Ocean in MAM, both of which were not widely seen in the successful and failed (see below) groups. While ACCESS CM2 has improved in other ENSO metrics, it displays a higher frequency ENSO cycle compared to observations and most other CMIP5 and CMIP6 models (Planton et al., 2021). Thus, the evolution of SSTA in the independent La Niña group appears consistent with the typical ENSO evolution of the fully coupled model, and in terms of the El Niño transition to La Niña, the observations (e.g., Okumura & Deser, 2010). Further to this, a warm Indian Ocean has also been highlighted as a precursor for La Niña events (e.g., Izumo et al., 2016), it is possible this may play a role in the development and/or amplification of the event in this model.

Like the successful La Niña events, failed La Niña events also had a persistent warm SSTA in the Atlantic in MAM, but these events also displayed a La Niña-like anomaly in the preceding DJF and MAM (Figures 3g and 3h) and a Pacific subsurface that was recharging heat since the previous year (Figure S2c in Supporting Information S1). The tendency in the Pacific subsurface was to warm, potentially to prime an El Niño event later in the event year following ENSO Recharge Oscillator dynamics (Jin, 1997), and also the biennial ENSO tendency of

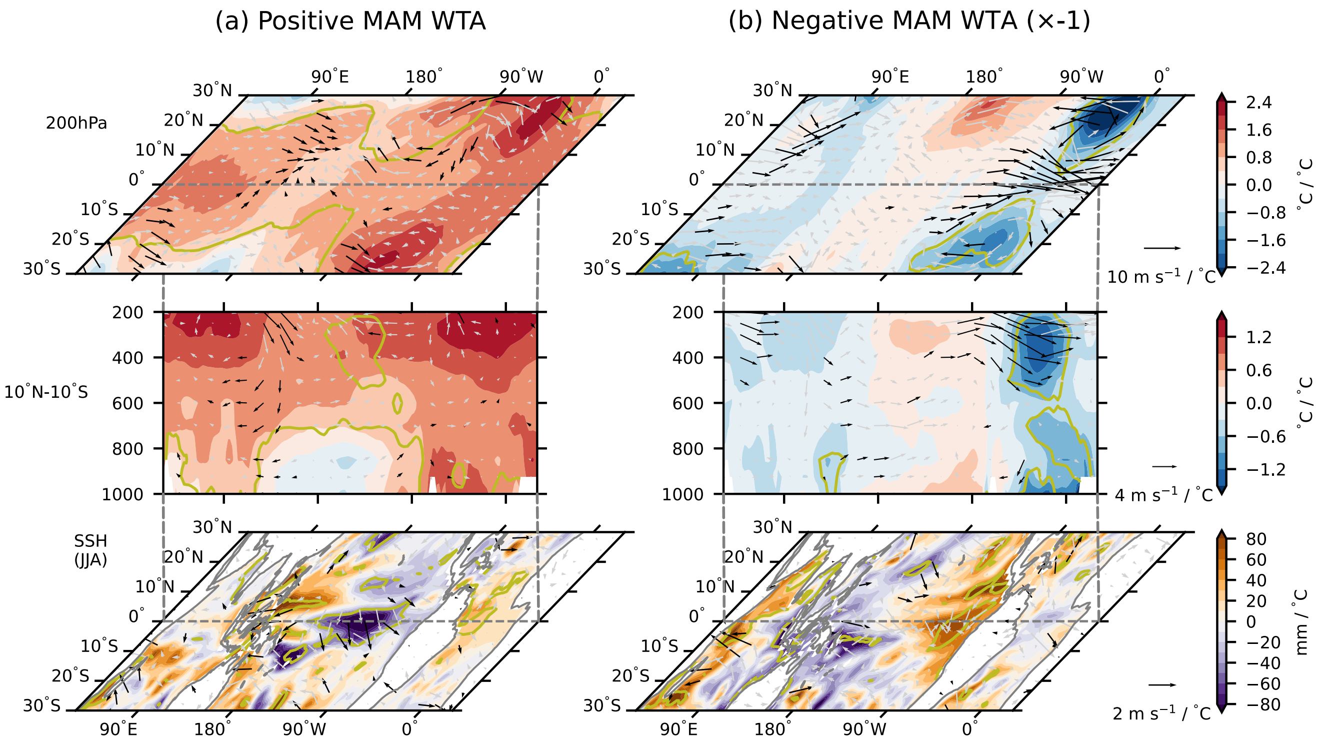

Figure 4. (a) Regressions of (top) MAM 200 hPa temperature and winds, (center) MAM vertical temperature and winds averaged 10N–10S and (bottom) JJA sea surface height and MAM surface winds onto positive values of MAM western tropical Atlantic SSTA. Green contours indicate 0.05 *p*-values for the regression coefficient. Vertical velocity is multiplied by 1000. (b) As (a), but for negative values of MAM WTA SSTA; we multiply the negative WTA regressions by −1 for easier comparison to positive WTA regressions in (a).

this model (Bi et al., 2022). Potentially, the warm Atlantic SSTs were not enough to maintain a La Niña event, but may have prevented the transition from a La Niña to El Niño, which is typical in this model, however, there is a large range to these values (Figure S2c in Supporting Information S1). This could also be another interpretation of the results of Bi et al. (2022), where not only a more realistic Atlantic mean state improved ENSO periodicity, the suppression of these El Niño events also reduced the ENSO frequency.

The ACCESS 1.0 pacemaker showed similar progressions within the groups, despite not exhibiting a significant successful La Niña count (Figure 2c; Figure S3 in Supporting Information S1). The successful and failed groups showed a warm Atlantic in the build-up (Figures S3a, S3b, S3g, and S3h in Supporting Information S1). The failed group tended to show La Niña conditions in the year prior to the event (Figure S3g in Supporting Information S1). Whereas the independent La Niña show a weak indication of an El Niño occurring the year before (Figure S3d in Supporting Information S1). Furthermore, the El Niño case for ACCESS CM2 does not show a similar progression as the La Niña case (Figure S4 in Supporting Information S1), supporting the hypothesis that the Atlantic preferentially forces La Niña events than El Niño events.

6. Mechanism for an Asymmetric Response From Atlantic SSTAs

Our results show the Atlantic has the capacity to influence the formation of La Niña events in the Pacific Ocean, but less so for El Niño events. Here we explore a possible mechanism in the ACCESS CM2 pacemaker ensemble mean for a warm Atlantic to influence the Pacific, that was not seen for a cold Atlantic. We analyze atmospheric fields in MAM and sea surface height in JJA (as a metric for subsurface heat content) by regressing onto both positive and negative MAM WTA (Figure 4). The importance of Atlantic SSTA in MAM or JJA seasons to force the Pacific is still under debate (e.g., Jiang et al., 2022), we show MAM as we can begin to see anomalies that grow into JJA, but our pacemaker experiments were forced by the observed Atlantic SSTs in every month.

Warm MAM WTA SSTAs were consistent with a Gill-type response (Gill, 1980), characterized by a Rossby wave-like pattern with anticyclonic rotation at about 20° latitude in both hemispheres, and a Kelvin wave-like pattern with warm upper-level temperature anomalies extending eastward along the equator (Figure 4a). The eastward extension appeared to converge over the western Pacific with a warm anomaly extending west from the Atlantic. Subsidence was enhanced where these signals converge leading to easterly wind anomalies at the surface in the western Pacific. These easterly wind anomalies induced a cool ocean subsurface temperature response that propagated to the east leading into JJA, activating the Bjerknes feedback and resulting in a La Niña signal at the end of the year (Figure 4a).

On the other hand, the cold MAM WTA SSTA had a limited tropospheric temperature response (Figure 4b), consistent with the results of Williams et al. (2023) which showed a weaker convection response for cold SST anomalies. The Rossby wave-like patterns straddling the equator were detected for the cold WTA, but the Kelvin wave-like eastward extension was not evident compared to the warm WTA case (cf. Figures 4a and 4b). The lack of the eastward extension appears responsible for the lack of response over the Pacific (Figure 4b), but why this did not occur is not known. One potential avenue to explore is the sensitivity of the height of the tropospheric temperature anomaly over the equatorial Atlantic for Kelvin wave-like responses (cf. Figures 4a and 4b).

7. Summary and Discussion

In this study we utilized observations and models to provide evidence that anomalously cold and warm Atlantic SSTAs exhibit an asymmetric relationship with tropical Pacific SSTAs. This suggests that there is potential for the Atlantic to be used to improve La Niña forecast, but not for El Niño forecast. The Atlantic had a greater chance of influencing La Niña events if the Pacific was in a neutral state in MAM, and the tropical Atlantic had a widespread warm pattern. The asymmetry from the Atlantic SSTAs was due to the lack of an upper-level atmospheric response for cool SSTAs, therefore leading to no wind anomalies at the surface in the western Pacific, whereas this was evident for warm Atlantic SSTAs.

Our observed and modeled results also showed an asymmetry in the influence of the Indian Ocean on the Pacific, where a warm Indian Ocean had a greater signal in forcing La Niña events than El Niño. The influence of the Indian Ocean on ENSO has been well documented in the literature (Cai et al., 2019; Izumo et al., 2016), but could be explored further using similar methodology to that showed here.

In the last two decades there has been a tendency for a warming Atlantic and a cooling Pacific (Cai et al., 2019; Li et al., 2016; McGregor et al., 2014; Naha et al., 2023; Ruprich-Robert et al., 2017, 2021). A warming Atlantic and an asymmetric relationship between the Atlantic and Pacific may lead to a cooling Pacific due to the occurrence of La Niña events, while still allowing for the Pacific to exhibit some autonomy to cause El Niño events, for example, the 2015–2016 event.

Subsequent studies could focus on asymmetries not only in the developing phase of ENSO, but also in the decaying phase (e.g., Richter et al., 2023). However, there remains some uncertainty in the precise mechanism for which the Atlantic can influence the Pacific in the developing phase alone. Model biases in the Atlantic mean state (McGregor et al., 2018) and the response to the Atlantic (Ruprich-Robert et al., 2021) likely hinders this pursuit. The effects of ENSO autocorrelation and teleconnection also cannot be ignored in the observations (e.g., Zhang et al., 2021), therefore a diverse set of analyses in numerous modeling configurations are likely required.

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Data Availability Statement

HadISST version 1.1 (Rayner, 2003) and ERSST version 3b (Smith et al., 2008) was used for observed SST. ACCESS 1.0 (Bi et al., 2013) and ACCESS CM2 (Bi et al., 2020) were used to produce the model results. For analysis and plotting we used xarray version 2023.4.2 (Hoyer et al., 2023), matplotlib version 3.5.3 (Hunter, 2007), numpy version 1.23.5 (Harris et al., 2020), PyleoClim version 0.7.2 (Khider et al., 2022).

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