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ENSO Influence on the Atlantic Niño, Revisited: Multi-Year versus Single-Year ENSO Events

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ABSTRACT

The influence of El Niño–Southern Oscillation (ENSO) on the Atlantic Niño over the past 113 years is investigated by comparing multi-year and single-year ENSO events. Multi-year ENSO events sustain an anomalous zonal gradient of sea surface temperature (SST) in the equatorial western to central Pacific even during boreal spring and summer. This SST gradient is coupled with an anomalous Walker circulation and atmospheric deep convection through the Bjerknes feedback. During multi-year La Niñas, for example, a strengthened Pacific Walker circulation extends into the tropical Atlantic in boreal spring, a season when both the Pacific and Atlantic intertropical convergence zones become more symmetric about the equator. As a result, surface westerly wind anomalies appear over the equatorial Atlantic, triggering an Atlantic Niño. By contrast, such a teleconnection is not found in the spring following the peak of single-year ENSO events. A Pacific pacemaker model experiment reproduces the observed atmospheric response and its impact on the Atlantic Niño, further supporting the importance of prolonged ENSO forcing. The contrasting influence of multi-year and single-year events explains the fragile relationship between ENSO and the Atlantic Niño. An empirical orthogonal function (EOF) analysis shows that the leading EOF mode (EOF-1) for the spring tropical western to central Pacific SST anomalies captures the characteristics of multi-year ENSO events. EOF-1 is highly correlated with the summer Atlantic Niño over the past 113 years while the Niño-3 SST is not. These correlations indicate that ocean–atmosphere coupling in the equatorial western to central Pacific plays a major role in shaping ENSO teleconnections in boreal spring.

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1. Introduction

El Niño–Southern Oscillation (ENSO) exerts a considerable influence on global climate (Wallace et al. 1998; Trenberth et al. 1998; Klein et al. 1999; Alexander et al. 2002). El Niño suppresses atmospheric convection over the Indonesian Maritime Continent from boreal summer to the following winter, driving surface easterly anomalies over the equatorial Indian Ocean (Xie et al. 2002; Tokinaga and Tanimoto 2004). In response, the tropical Indian Ocean often develops a zonal dipole of sea surface temperature (SST) anomaly in boreal

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autumn (Ueda and Matsumoto 2000; Baquero-Bernal et al. 2002) and a basinwide warming in the following winter to spring (Tourre and White 1995; Chambers et al. 1999; Klein et al. 1999; Tokinaga and Tanimoto 2004). Over the tropical North Atlantic, northeasterly trade winds weaken in the winter and spring of El Niño events, warming SST through suppressed evaporative cooling (Curtis and Hastenrath 1995; Enfield and Mayer 1997; Alexander and Scott 2002; Chikamoto and Tanimoto 2006). These tropical Indian and North Atlantic ocean responses are evident in their significant lagged correlations with an SST anomaly index averaged over the equatorial eastern Pacific (Lanzante 1996), suggesting a seasonally phase locked influence of ENSO. Hereafter, seasons refer to those for the Northern Hemisphere.

The equatorial Atlantic has a mode of coupled ocean–atmosphere variability that is similar to the Pacific El Niño, known as the Atlantic Niño (Hisard 1980; Merle 1980). It starts to develop in spring, in response to an anomalous weakening of the trade winds over the equatorial Atlantic (Zebiak 1993; Ruiz-Barradas et al. 2000; Richter et al. 2013; Richter et al. 2014b; Lübbecke et al. 2018). Reinforced by the Bjerknes feedback, SST warming in the equatorial eastern Atlantic peaks in summer, when the climatological thermocline is shallowest. The equatorial SST warming shifts the intertropical convergence zone (ITCZ) southward (Ruiz-Barradas et al. 2000), sometimes causing floods in the West African countries along the Guinea coast (Paeth and Friederichs 2004; Balas et al. 2007). Therefore, clarifying the cause for the springtime trade wind variability over the equatorial Atlantic is of great importance for predictions of the Atlantic Niño and seasonal climate over the surrounding regions.

It has long been controversial whether and how ENSO affects the Atlantic Niño (Zebiak 1993; Latif and Barnett 1995; Ruiz-Barradas et al. 2000; Münnich and Neelin 2005; Chang et al. 2006; Lübbecke and McPhaden 2012). Historical climate records over the past century generally suggest an insignificant correlation between ENSO and the Atlantic Niño (Zebiak 1993; Ruiz-Barradas et al. 2000). On the other hand, satellite observations reveal an interdecadal strengthening of their correlation during the 1980s–90s, a change hypothesized due to enhanced ENSO activity (Münnich and Neelin 2005). Chiang et al. (2000) and Münnich and Neelin (2005) show that the ENSO-induced atmospheric convection over the equatorial eastern Pacific plays an important role in causing the springtime trade wind variability over the equatorial Atlantic and the occurrence of the Atlantic Niño. However, the equatorial Atlantic exhibited opposite

signs of SST anomalies between the two extreme El Niño events in 1982/83 and 1997/98 (Fig. 2 of Chang et al. 2006), implying that factors other than the ENSO intensity must contribute to the Atlantic Niño. The previous studies suggest that the Atlantic Niño after the 1997/98 El Niño may be due to counteracting responses of the equatorial Atlantic to El Niño (Chang et al. 2006) and a delayed negative feedback induced by the spring North Atlantic SST warming (Lübbecke and McPhaden 2012; Richter et al. 2013). In addition, Martin-Rey et al. (2014) suggest that the Atlantic multidecadal oscillation may modulate the connection between ENSO and the Atlantic Niño. The exact reason for the fragile ENSO–Atlantic Niño connection remains unclear.

The duration of ENSO events is another possible factor for the uncertain ENSO–Atlantic Niño relationship. Okumura and Deser (2010) identified that many La Niña events persist through the following year and often reintensify in the subsequent winter. While less frequent than La Niña, multi-year El Niño events have also occurred during the twentieth century. During multi-year La Niña events, anomalous atmospheric convection is anchored over the tropical Indo-Pacific oceans for 2 years or more, with a strengthened Walker circulation. Because of this persistent circulation anomaly, multi-year ENSO events presumably exert a lingering influence on the trade winds over tropical oceans, including the equatorial Atlantic. This possible atmospheric teleconnection leads us to hypothesize that a prolonged La Niña (El Niño) forcing can trigger an Atlantic Niño (Niña) by intensifying and sustaining surface westerly wind anomalies over the equatorial Atlantic from spring to early summer.

The present study revisits the ENSO influence on the Atlantic Niño by comparing seasonal evolution of ocean and atmospheric anomalies associated with multi-year and single-year ENSO events. Our study is the first to illustrate a robust and significant linkage between the Atlantic Niño and multi-year ENSO events over the past 113 years. We will show that ocean–atmosphere coupling in the equatorial western to central Pacific persists during multi-year ENSO events due to the Bjerknes feedback. The persistent coupling allows the Pacific Walker circulation to extend into the equatorial Atlantic in spring. Our hypothesis is tested by a coupled model pacemaker experiment, in which SST variations in the tropical eastern Pacific are restored to observations (Kosaka and Xie 2016). While previous studies focus on the equatorial eastern Pacific as a key region of ENSO forcing, our findings point to the importance of persistent ocean–atmosphere coupling in the equatorial

western to central Pacific that anchors anomalous atmospheric convection during multi-year ENSO events.

The rest of the paper is organized as follows. [Section 2](#) describes data and methods. [Section 3](#) compares seasonal developments of ocean and atmospheric anomalies during multi-year and single-year ENSO events. [Section 4](#) examines the spring SST variability in the equatorial western to central Pacific and its link with the multi-year ENSO and the Atlantic Niño. [Section 5](#) is a summary and discussion.

2. Data and methods

a. Observational data

We analyze the following datasets: the Hadley Centre Sea Ice and SST, version 1.1 (HadISST1; <https://www.metoffice.gov.uk/hadobs/hadisst>) available on a $1^\circ \times 1^\circ$ grid ([Rayner et al. 2003](#)); wind velocity, sea level pressure (SLP), precipitation, and specific humidity from the National Oceanic and Atmospheric Administration (NOAA)-Cooperative Institute for Research in Environmental Sciences (CIRES) Twentieth Century Reanalysis, version 2 (20CRv2; https://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html), available on a $2^\circ \times 2^\circ$ grid ([Compo et al. 2011](#)); and ocean subsurface temperature from the Simple Ocean Data Assimilation version 2.2.4 (SODA; <http://www.atmos.umd.edu/~ocean/>) available on an approximately $0.5^\circ \times 0.5^\circ$ grid ([Giese and Ray 2011](#)). The 20CRv2 uses the HadISST1 data as a surface boundary condition for the atmospheric model while the wind stress of 20CRv2 is used in SODA2.2.4 to force the global ocean model. To validate the data quality of 20CRv2 precipitation, we use marine cloudiness from the International Comprehensive Ocean–Atmosphere Data Set release 3.0 (ICOADS; <https://rda.ucar.edu/datasets/ds548.0/>) gridded on a $4^\circ \times 4^\circ$ grid ([Freeman et al. 2017](#); [Tokinaga et al. 2017](#)); and gauge-based land precipitation from the Climate Research Unit (CRU; <https://crudata.uea.ac.uk/cru/data/precip>) available on a $3.75^\circ \times 2.5^\circ$ grid ([Hulme et al. 1998](#)). Both ICOADS cloudiness and CRU precipitation datasets are useful to infer the atmospheric convection variability before the satellite era, especially over tropical oceans and small islands located in the tropical western to central Pacific ([Deser et al. 2004](#); [Tokinaga et al. 2012](#)). The analysis period is for 1900–2012, except for SODA (1900–2010) and land precipitation (1900–98). Our conclusion does not change if we choose slightly different data periods or post-1950 only. Statistical significance is estimated using a two-tailed Student's *t* test and taking into account serial autocorrelation ([Zwiers and von Storch 1995](#)).

b. Model experiment

We analyze a 10-member Pacific Ocean-Global Atmosphere (POGA) pacemaker experiment by [Kosaka and Xie \(2016\)](#). This experiment was performed using the NOAA Geophysical Fluid Dynamics Laboratory Coupled Model, version 2.1 (GFDL-CM2.1; [Delworth et al. 2006](#)), with an atmospheric resolution of 2° latitude $\times$ 2.5° longitude $\times$ 24 vertical levels and an oceanic resolution of approximately 1° latitude (increasing from 30°N/S to $1/3^\circ$ at the equator) $\times$ 1° longitude $\times$ 50 vertical levels. Like many other coupled models, GFDL-CM2.1 has a warm bias of the climatological SST in the equatorial Atlantic ([Richter et al. 2014a](#)). In a qualitative sense, however, the model simulates well the observed characteristics of the Atlantic Niño, including an equatorial peak of SST variance in summer ([Yang et al. 2017](#)). While the interannual standard deviation of equatorial SST is about 60% larger than that of HadISST1, the seasonality and spatial pattern of the Atlantic Niño are reasonably reproduced in this model. As presented in the following sections, our model experiment shows quite consistent results with observational analyses.

In the POGA experiment, the tropical eastern Pacific SST was restored to the model climatology plus observed anomaly from the Extended Reconstructed SST, version 3b (ERSST; <https://www.ncdc.noaa.gov/data-access/marineocean-data/extended-reconstructed-sea-surface-temperature-ersst-v3b>; [Smith et al. 2008](#)), by overriding sensible heat flux to the ocean ([Kosaka and Xie 2016](#)). The SST restoring was applied from 15°S to 15°N , and from the date line to the American coast, with 5° buffer zones west, north, and south [see Fig. 2h of [Kosaka and Xie \(2016\)](#)]. While the SST restoring is confined in the tropical eastern Pacific, this POGA experiment well reproduces the pattern and variability of western to central Pacific SST anomalies associated with the multi-year ENSO events. It allows us to examine the influence of multi-year ENSO events on the Atlantic Niño/Niña. Each ensemble member was forced identically with the Coupled Model Intercomparison Project phase 5 historical radiative forcing for 1861–2005 and representative concentration pathway (RCP) 4.5 afterward but began from a slightly different initial condition. In this study, we analyze ensemble mean of 10-member model outputs for the period 1900–2012. To focus on interannual variability, linear trends are removed from all datasets including model output and observations.

c. ENSO and Atlantic Niño indices

We denote the ENSO-developing year as Year 0, the following year as Year 1, and so on. Thus, the March–May (MAM) and June–August (JJA) seasons after the first-year

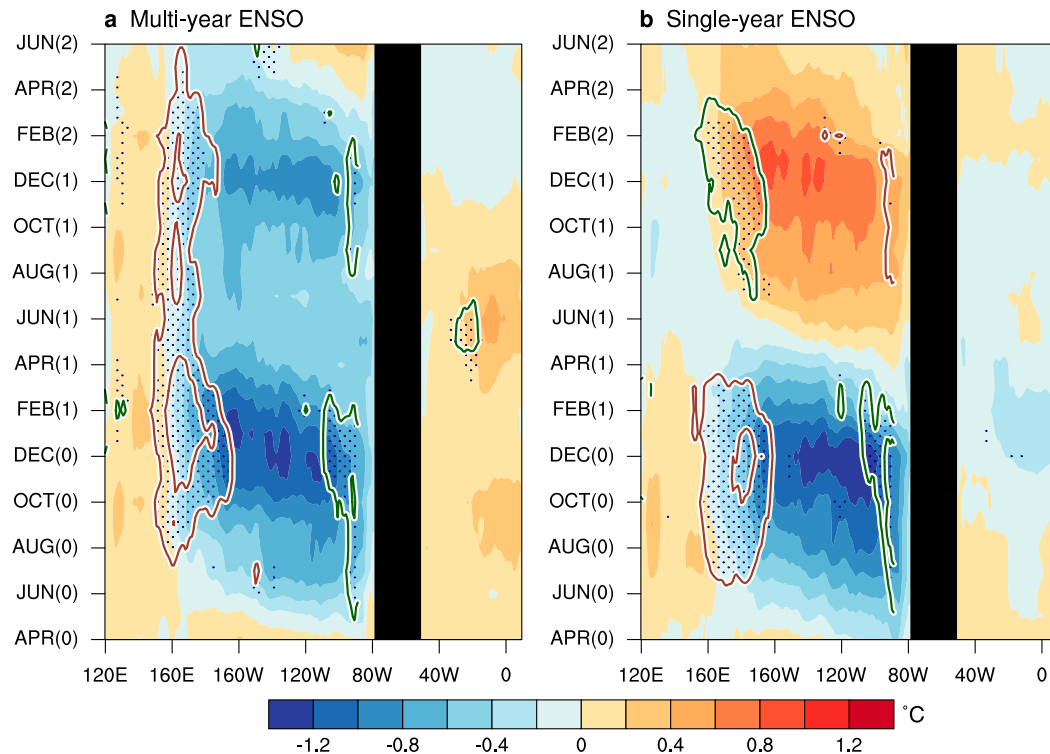


FIG. 1. Longitude–time sections of composite SST anomalies (shading; $^{\circ}\text{C}$) along the equator (3°S – 3°N) for (a) multi-year and (b) single-year ENSO events during 1900–2012, based on HadISST1. Green and brown contours indicate the eastward and westward gradient of SST anomalies (contours of $\pm 0.015^{\circ}$ and $\pm 0.03^{\circ}\text{C}$ per 1° longitude), respectively, with statistically significant values stippled at the 95% confidence level.

peak of ENSO are symbolized as MAM(1) and JJA(1), respectively. To appropriately capture the coupled variability of the zonal SST gradient and Walker circulation, our ENSO index is defined as the principal component (PC) of the first combined empirical orthogonal function (EOF) mode for SST, SLP, and surface zonal wind anomalies over the equatorial Pacific (5°S – 5°N , 120°E – 90°W). The correlation coefficient between our ENSO index and the Niño-3 is 0.94, statistically significant at the 99% confidence level.

The monthly ENSO index is linearly detrended and smoothed with a 3-month running mean filter (Fig. S1 in the online supplemental material). A multi-year ENSO event is identified when the ENSO index is over $+0.75$ (below -0.75) standard deviations in any month during October(0)–March(1), remains positive (negative) during April(1)–September(1), and becomes over $+0.5$ (below -0.5) standard deviations in any month during October(1)–March(2). Based on this criterion, we identify 16 multi-year La Niñas (1908, 1916, 1921, 1933, 1943, 1949, 1954, 1961, 1970, 1973, 1983, 1988, 1995, 1998, 2007, 2010 as Year 0) and 10 multi-year El Niños (1904, 1913, 1918, 1929, 1939, 1957, 1968, 1976, 1986, 1991 as Year 0). There are 9 single-year La Niñas

(1901, 1903, 1906, 1924, 1938, 1942, 1964, 1967, 2005 as Year 0) and 18 single-year El Niños (1900, 1902, 1911, 1923, 1925, 1935, 1951, 1963, 1965, 1972, 1979, 1982, 1994, 1997, 2002, 2004, 2006, and 2009 as Year 0). Not only major but also minor ENSO events are selected based on our criteria.

Previous studies have defined the Atlantic Niño index as SST anomalies averaged over the ATL3 region (3°S – 3°N , 20°W – 0°) (Zebiak 1993). However, this area-averaged index sometimes fails to capture the eastward gradient of SST anomalies associated with the warm Atlantic Niño. For this reason, we define our Atlantic Niño index as the PC time series of the leading EOF for the JJA-mean SST anomalies in the tropical Atlantic (15°S – 15°N , 50°W – 10°E). The correlation coefficient between this index and JJA-mean ATL3 is 0.97, statistically significant at the 99% confidence level.

3. Persistent forcing by multi-year ENSO events

This section presents a composite analysis to examine spatial patterns and seasonality of oceanic and atmospheric anomalies associated with multi-year and single-year

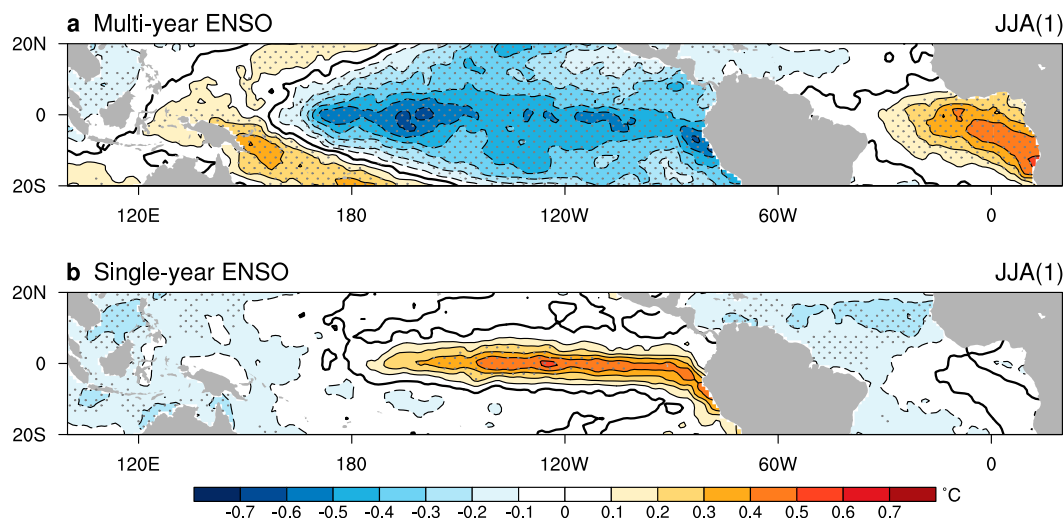


FIG. 2. Composite anomalies of JJA(1) SST (shading; °C) for (a) multi-year and (b) single-year ENSO events, based on HadISST1. Stippling indicates composite anomalies exceeding the 95% confidence level.

ENSO events. All composite anomalies are shown as the La Niña minus El Niño difference. Thus, the signs of the composite fields correspond to La Niña conditions. Our conclusions do not change even if we make separate composites for La Niña and El Niño.

a. Observed seasonal evolution

Figure 1 compares Hovmöller diagrams of composite SST anomalies averaged along the equator (3°S–3°N). Characterized by consecutive peaks of the Niño-3 SST anomaly in NDJ(0) and NDJ(1), the multi-year ENSO tends to sustain the same sign of SST anomaly between the first-year and second-year peaks (Fig. 1a). The single-year ENSO composite shows a comparable magnitude of the Niño-3 SST anomaly in NDJ(0) (Fig. 1b). However, it rapidly decays in MAM(1) and reverses the sign of the SST anomaly in JJA(1). Another important difference between the two composites is the zonal SST gradient in the equatorial western to central Pacific, a region where SST, trade winds, and atmospheric deep convection are tightly coupled. During multi-year ENSO events, strong anomalies of zonal SST gradient emerge in this region in September(0) and persist until March(2). During single-year ENSO events, on the other hand, anomalous zonal SST gradients appear only from August(0) to February(1), in sync with the seasonal development of the Niño-3 SST anomaly. This difference in zonal SST gradient between multi-year and single-year ENSO events is particularly large from MAM(1) to JJA(1), the season when Atlantic Niños typically start to develop. During this season the multi-year ENSO composite indeed exhibits a strengthening of

the equatorial eastern Atlantic warming with significant anomalies of the eastward SST gradient, a feature indicative of the Atlantic Niño (Fig. 1a). Given that the zonal SST gradient in the equatorial Pacific is strongly coupled with the Walker circulation, the multi-year ENSO probably has a prolonged influence on the tropical climate despite being weak in spring and summer. By contrast, the single-year ENSO composite does not show any sign of an Atlantic Niño in summer (Fig. 1b). The composites thus suggest that the Atlantic Niños (Niñas) tend to occur in the summer following the first peak of a multi-year La Niña (El Niño).

The JJA(1) SST composite map clarifies the differences in spatial pattern between multi-year and single-year ENSO events. The multi-year ENSO composite exhibits the typical Atlantic Niño pattern, with a significant SST warming in the equatorial Atlantic cold tongue region (Fig. 2a). As indicated by Fig. 1a, the cold SST anomalies are located to the west of the Niño-3 region. On the other hand, the single-year ENSO composite shows that the opposite phase of ENSO has already started in JJA(1) (Fig. 2b). Neither the Atlantic Niño pattern nor the strengthened zonal SST gradient in the equatorial western to central Pacific are found in the single-year ENSO composite, implying an important role of multi-year ENSO events in developing the Atlantic Niño.

Composite anomalies of MAM(1) precipitation and surface wind explain why the Atlantic Niño develops in JJA(1) during multi-year ENSO events. Over the tropical Pacific, the multi-year ENSO reduces (increases) precipitation over the equatorial central Pacific (western

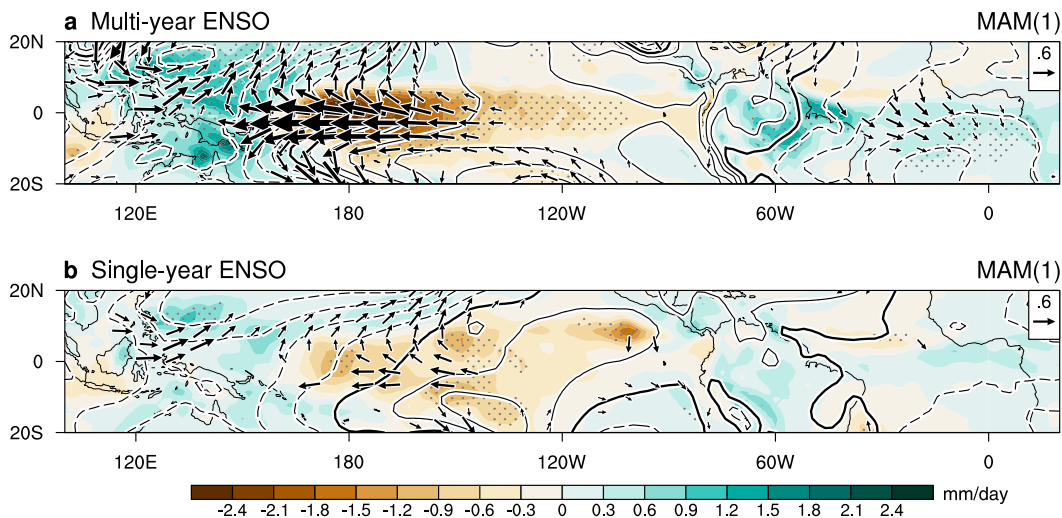


FIG. 3. Composite anomalies of MAM(1) surface wind (vectors; m s^{-1}), precipitation (shading; mm day^{-1}), and SLP (contours at 0.12-hPa intervals) for (a) multi-year and (b) single-year ENSO events, based on the Twentieth-Century Reanalysis product. Stippling (vector) indicates composite precipitation (surface wind) anomalies exceeding the 95% confidence level.

Pacific warm pool) with a strong acceleration of the equatorial trade winds (Fig. 3a). These atmospheric anomalies develop over the intensified zonal SST gradient (Fig. 1a), suggesting enhanced ocean–atmosphere coupling in the equatorial western to central Pacific. Composite anomalies of the ICOADS marine cloudiness and CRU land precipitation roughly capture the patterns of 20CRv2 precipitation anomalies with an equatorial peak (Fig. 4a), providing independent

support for the reliability of the reanalysis precipitation. Another notable feature is the westerly to northwesterly wind anomalies over the equatorial Atlantic (Fig. 3a). These wind anomalies act to suppress the equatorial upwelling and flatten the oceanic thermocline (Fig. 5), leading to the development of an Atlantic Niño that matures in JJA(1). Consistent with the anomalous trade winds, SLP anomalies are positive over the central to eastern Pacific and negative over the tropical Atlantic

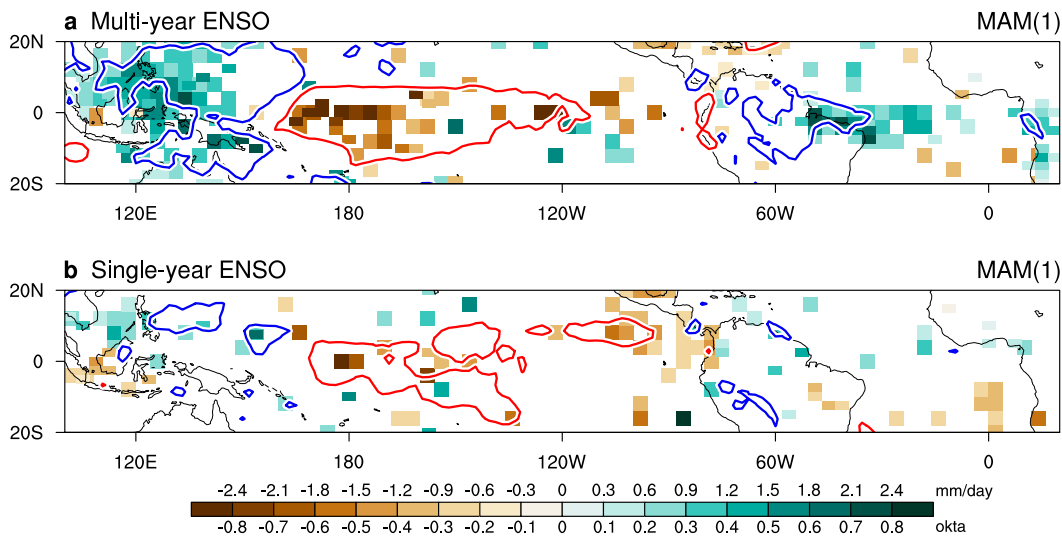


FIG. 4. As in Fig. 3, but for composite anomalies of rain gauge-based land precipitation (shading with scales above the color bar; mm day^{-1}) and marine cloud cover (shading with scales below the color bar; okta), based on CRU precipitation and ICOADS R3.0. Only significant composite anomalies exceeding the 90% confidence level are shaded in color. Precipitation contours of +0.6 (blue) and -0.6 (red) mm day^{-1} in Fig. 3 are repeated.

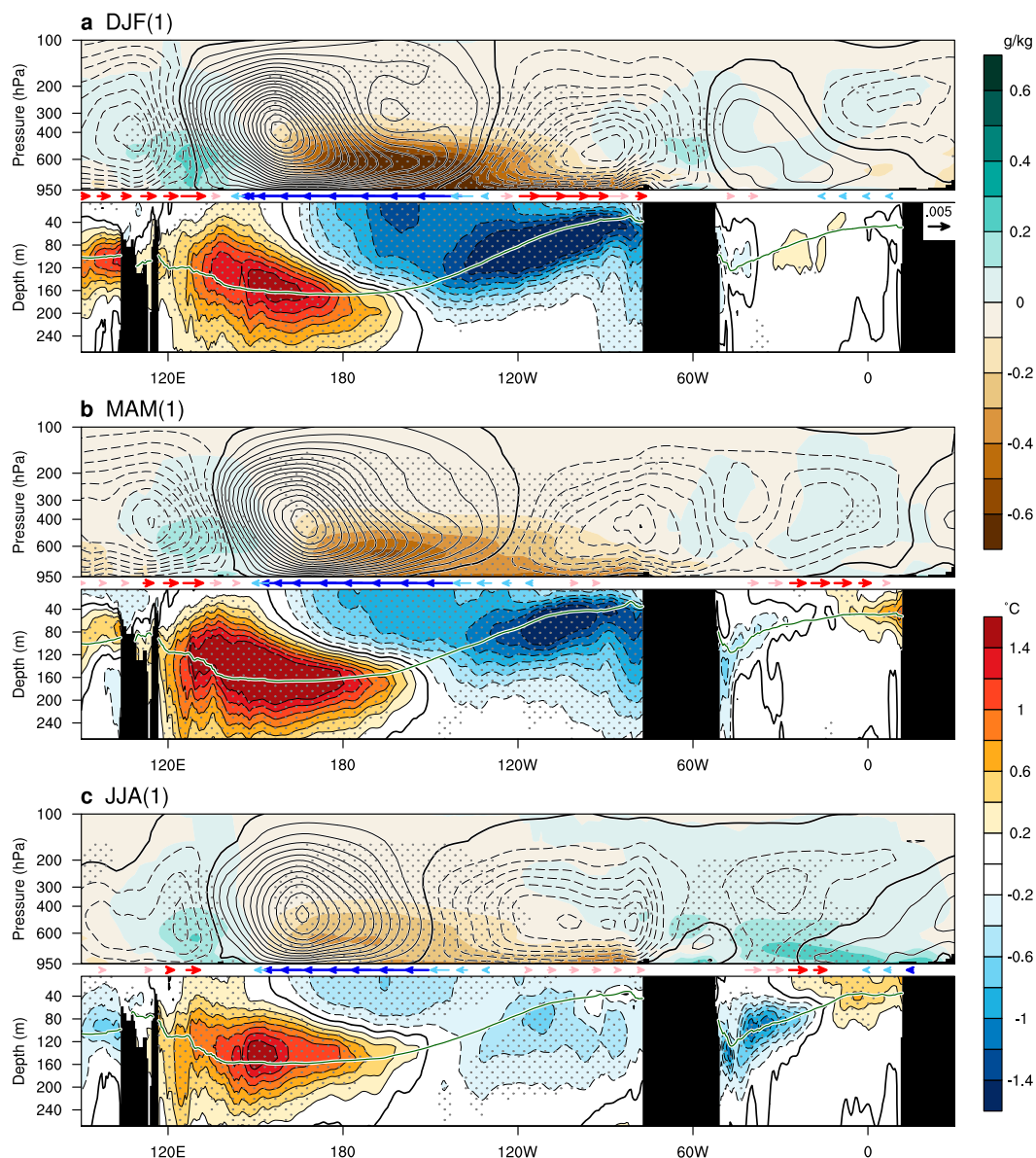


FIG. 5. Longitude–height section of multi-year ENSO composite anomalies of (top) mass streamfunction (contours at $4 \times 10^8 \text{ kg s}^{-1}$ intervals) and specific humidity (shading; g kg^{-1}), and (bottom) ocean subsurface temperature (shading; $^{\circ}\text{C}$) averaged in the equatorial regions. Vectors between the top and bottom panels indicate composite zonal wind stress anomalies (N m^{-2}). (a) DJF(1), (b) MAM(1), and (c) JJA(1). All variables are averaged along the equator (5°S – 5°N), except for the mass streamfunction, which is calculated over the tropics (20°S – 20°N). Stippling of top and bottom panels indicates composite specific humidity and ocean temperature anomalies exceeding the 95% confidence level. Significant wind stress vectors at the 95% confidence level are darkened. Green contours in the bottom panel indicate the climatological mean of the 22°C isothermal depth.

and the western Pacific warm pool, a tripole pattern suggestive of the tropical-wide atmospheric bridge through the Walker circulation. The single-year ENSO composite shows similar patterns of atmospheric anomalies over the tropical Pacific in MAM(1), but their magnitudes are much smaller than those of the multi-year ENSO composite (Figs. 3b, 4b).

Furthermore, an equatorial peak of anomalous precipitation is not pronounced over the Pacific. Surface zonal wind anomalies are also insignificant over the equatorial Atlantic, consistent with the absence of an Atlantic Niño pattern in JJA(1) (Fig. 2b). The precipitation patterns are again corroborated by the in situ observations (Fig. 4b).

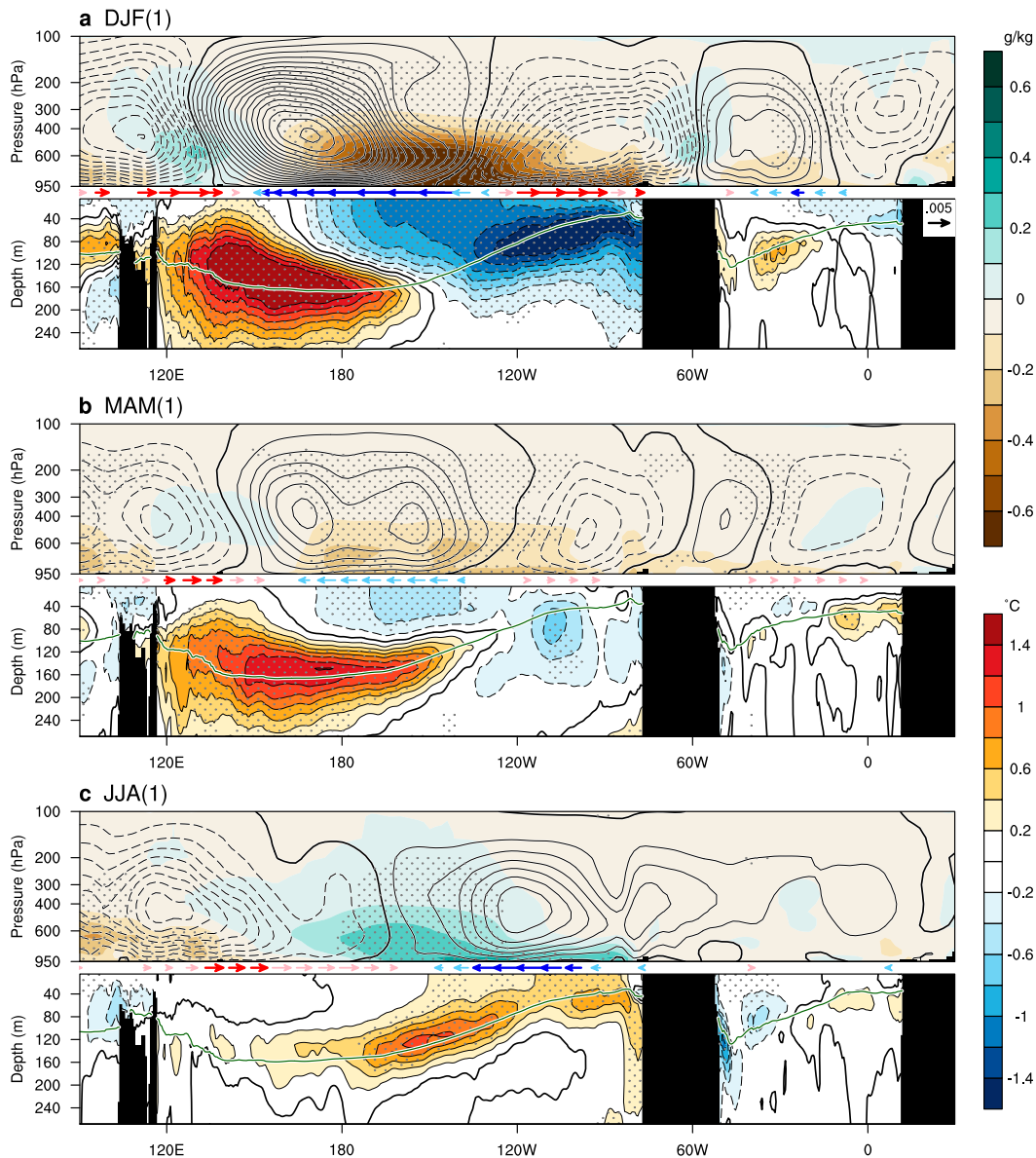


FIG. 6. As in Fig. 5, but for composite anomalies for single-year ENSO events.

Figure 5 gives a detailed view of ocean and atmosphere coupling during multi-year ENSO events. From DJF(1) to JJA(1), an anomalous Walker circulation with ascending branch over the western Pacific warm pool persists due to the Bjerknes feedback, with strengthened trade winds and east–west contrasts of both atmospheric convection and ocean temperature anomalies in the western to central Pacific. Cold SST anomalies in the central Pacific act to suppress atmospheric convection, contributing to form clockwise and counterclockwise anomalies of the Walker cell over the western and eastern Pacific, respectively. While the counterclockwise Walker cell anomaly is

confined to the west of South America in DJF(1) and JJA(1) (Figs. 5a,c), it extends eastward in MAM(1), causing significant surface westerly anomalies over the equatorial Atlantic (Fig. 5b). In response, a zonal dipole of subsurface ocean temperature anomalies starts to develop at the depth of the climatological thermocline in the equatorial Atlantic. This zonal dipole eventually outcrops to the sea surface in JJA(1) to form an Atlantic Niño SST anomaly pattern. The equatorial eastern Atlantic warming in turn enhances atmospheric convection, leading to a southward shift of the ITCZ in JJA(1) (Ruiz-Barradas et al. 2000).

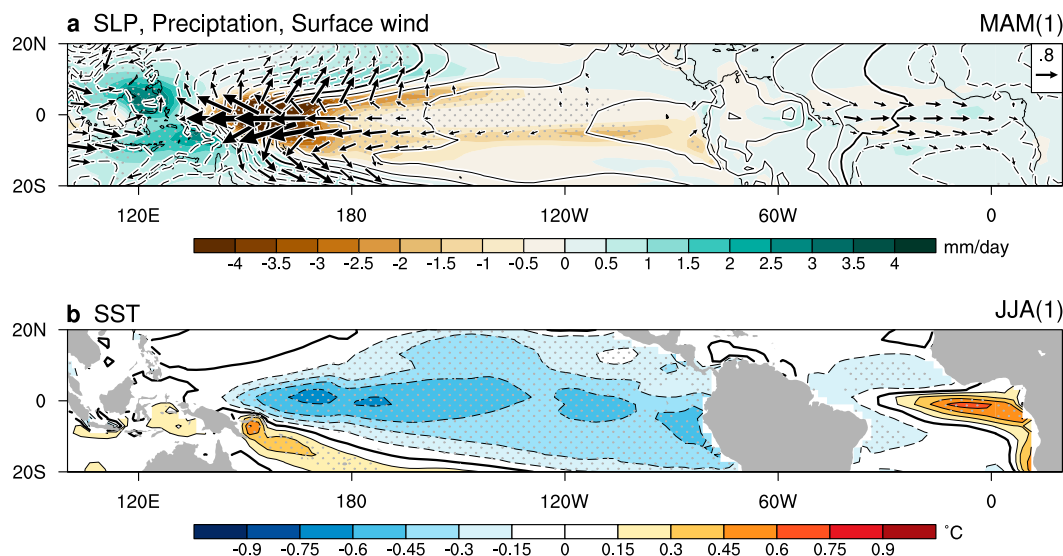


FIG. 7. As in Figs. 2a and 3a, but for (a) MAM(1) surface wind (vectors; m s^{-1}), precipitation (shading; mm day^{-1}), and SLP (contours at 0.12-hPa intervals), and (b) SST (shading; $^{\circ}\text{C}$) of multi-year ENSO composite based on a 10-member ensemble mean of GFDL CM2.1 POGA experiment.

The single-year ENSO composite exhibits similar vertical sections of ocean and atmospheric anomalies in DJF(1), whereas in MAM(1) and JJA(1), they are significantly different from those of the multi-year ENSO composite (Fig. 6). In the subsurface ocean, warm anomalies of the western Pacific start to propagate eastward as an equatorial Kelvin wave in MAM(1) (Fig. 6b), initiating the next El Niño in JJA(1) (Fig. 6c). Coinciding with this relaxation of east–west temperature contrast in the western Pacific, the anomalous Walker circulation significantly decays from DJF(1) to MAM(1), leading to a weak counterclockwise anomaly of the Walker cell over the eastern Pacific and insignificant surface westerly wind anomalies over the equatorial Atlantic in MAM(1). As a result, the Atlantic Niño cannot develop in summer after the decay of the single-year ENSO event.

b. POGA experiment

To test our hypothesis that a persistent ENSO forcing effectively causes an Atlantic Niño, we perform the same composite analysis using outputs from the POGA experiment by Kosaka and Xie (2016). The POGA experiment enables us to examine the effect of observed ENSO variability on the atmosphere and its effects on other ocean basins. Figure 7 presents a multi-year ENSO composite. Overall, the patterns of MAM(1) precipitation, surface wind, and SLP anomalies are quite similar to observations, though their magnitudes are slightly stronger (Fig. 7a). Interestingly, the POGA experiment successfully simulates the large-scale surface

divergence over the equatorial eastern Pacific and South America, sandwiched by strong easterly wind anomalies over the equatorial western Pacific and moderate westerly wind anomalies over the equatorial Atlantic. The Atlantic Niño SST pattern in JJA(1) is well reproduced (Fig. 7b), consistent with the MAM(1) westerly wind anomalies over the equatorial Atlantic.

The POGA experiment also shows similar patterns of MAM(1) precipitation and surface wind anomalies during single-year ENSO events (Fig. 8a). However, the magnitudes of the composite anomalies are much smaller than those of the multi-year ENSO composite. Over the tropical Atlantic, no significant westerly wind anomaly is simulated, consistent with the weak atmospheric response over the equatorial western Pacific. In JJA(1), SST anomalies in the equatorial Atlantic are weakly positive but not statistically significant. These results from the POGA experiment support our hypothesis that the tropical Pacific variability associated with the multi-year ENSO has a strong influence on the Atlantic Niño through the persistent Walker circulation anomaly.

4. Spring ENSO variability and its link to the Atlantic Niño

The tropical western Pacific appears to be a key region to sustain the anomalous Walker circulation from spring to early summer during multi-year ENSO events. In this section, we apply EOF analysis to identify the dominant pattern of spring SST anomalies in the tropical western

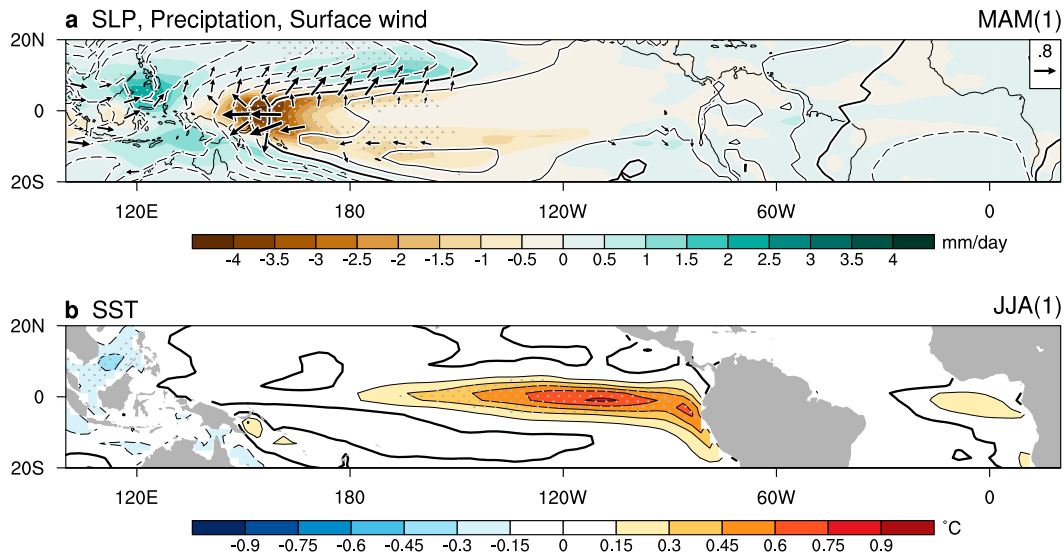


FIG. 8. As in Fig. 7, but for composite anomalies for single-year ENSO events.

Pacific (20°S–20°N, 120°E–170°W; denoted by a box in Fig. 9a) and its link to the multi-year ENSO and the Atlantic Niño.

Figure 9a displays SST anomalies regressed onto the PC time series of the first EOF mode (EOF-1) that accounts for 32.2% of the total variance. This mode features a central Pacific La Niña-like SST pattern with an intensified zonal gradient around 170°E. In fact, the EOF-1 PCs are highly correlated with the MAM-mean central Pacific ENSO index ($r = 0.89$) defined by Ren and Jin (2011) (not shown). This pattern is also similar to that of the SST composite during multi-year ENSO events (Fig. 2a), suggesting that the multi-year ENSO tends to have a central Pacific ENSO-like pattern in spring. Lead-lag regressions of the Niño-3 index with the EOF-1 PCs show consecutive winter peaks in December(0) and December(1) (Fig. 9b). In addition, regressed anomalies of zonal SST difference between the equatorial central and western Pacific are also significant from August(0) to January(2), suggesting that the EOF-1 mode captures the spring SST variability associated with the multi-year ENSO.

Figure 10 compares the Atlantic Niño index with three time series in the equatorial Pacific. Note that we apply a 3-yr running average to all time series to suppress high-frequency variations of single-year ENSO events. The PC time series of EOF-1 (PC1) is significantly correlated with the JJA-mean Atlantic Niño index, with a correlation coefficient of 0.57 (Fig. 10a). Figure 10b shows the time series of precipitation anomaly averaged over the equatorial central Pacific (3°S–3°N, 170°E–130°W), a region where atmospheric convection is strongly suppressed (enhanced) in

MAM(1) during multi-year La Niña (El Niño) events (Fig. 3a). This precipitation index is also significantly correlated with the Atlantic Niño index, with a correlation coefficient of -0.53 (Fig. 10b). These significant correlations mean that the tropical western to central Pacific variability explains about 30% of the variance associated with the Atlantic Niño/Niña. Figure S2 shows the unfiltered raw time series of the same indices. Correlation coefficients for the PC1 ($r = 0.3$) and precipitation ($r = -0.31$) indices are also statistically significant at the 98% confidence level, supporting the robust linkage between the equatorial western to central Pacific and Atlantic. On the other hand, the correlation coefficients between the MAM-mean Niño-3 SST and the Atlantic Niño indices are insignificant (Fig. 10c; $r = -0.16$, Fig. S2; $r = -0.12$), implying that the Niño-3 SST is not the best index to capture the forcing from the equatorial Pacific in spring.

Another notable feature is the decadal fluctuations of the observed time series (Fig. 10). The decadal variability is particularly obvious in the 1970s–90s, a period when multi-year ENSO events frequently occurred. In fact, 9 out of 15 ENSO events in this period were actually multi-year events (Fig. S1). As suggested by previous studies, the Niño-3 index is strongly correlated with the Atlantic Niño in this period (Münich and Neelin 2005) presumably due to the enhanced ENSO activity and frequent occurrence of multi-year ENSO events.

We conduct the same EOF analysis for SST outputs from the POGA experiment by applying a 3-yr running mean filter. The ensemble mean of EOF-1, accounting

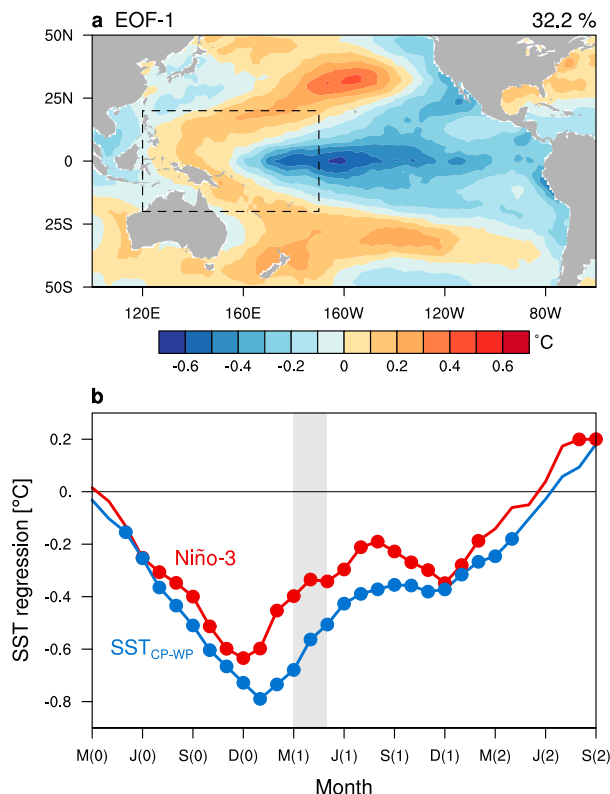


FIG. 9. (a) Regression coefficients of MAM-mean SST anomalies ($^{\circ}\text{C}$) onto the EOF-1 PC time series. The EOF domain is indicated with a dash line. (b) Lead-lag regression of Niño-3 index and zonal SST difference between the equatorial central (5°S – 5°N , 180° – 150°W) and western (5°S – 5°N , 120° – 150°E) Pacific with the EOF-1 PC. Significant regression coefficients at the 95% confidence level are marked with filled circles. A gray bar denotes March–May, a season when the EOF-1 is calculated.

for 35% of the variance, exhibits a similar central Pacific La Niña-like pattern as the observed EOF-1, with an intensified zonal SST gradient between the equatorial western and central Pacific (Fig. 11a). Ensemble means of the PC1 and simulated Atlantic Niño index are significantly correlated (Fig. 11b; $r = 0.56$), strongly supporting the observational findings. These results from the POGA experiment confirm that the equatorial western to central Pacific plays an important role in the occurrence of the Atlantic Niño.

Figure 12a shows regression coefficients of observed MAM-mean precipitation, 850-hPa velocity potential and wind anomalies with the PC1 time series. Associated with the SST anomaly pattern of EOF-1, precipitation anomalies form a horseshoe-like pattern over the tropical western Pacific. Especially, precipitation broadly decreases over the equatorial Pacific east of 170°E , resulting in large-scale divergence over the central and eastern Pacific. Over the equatorial Atlantic and South America, on the other hand, precipitation

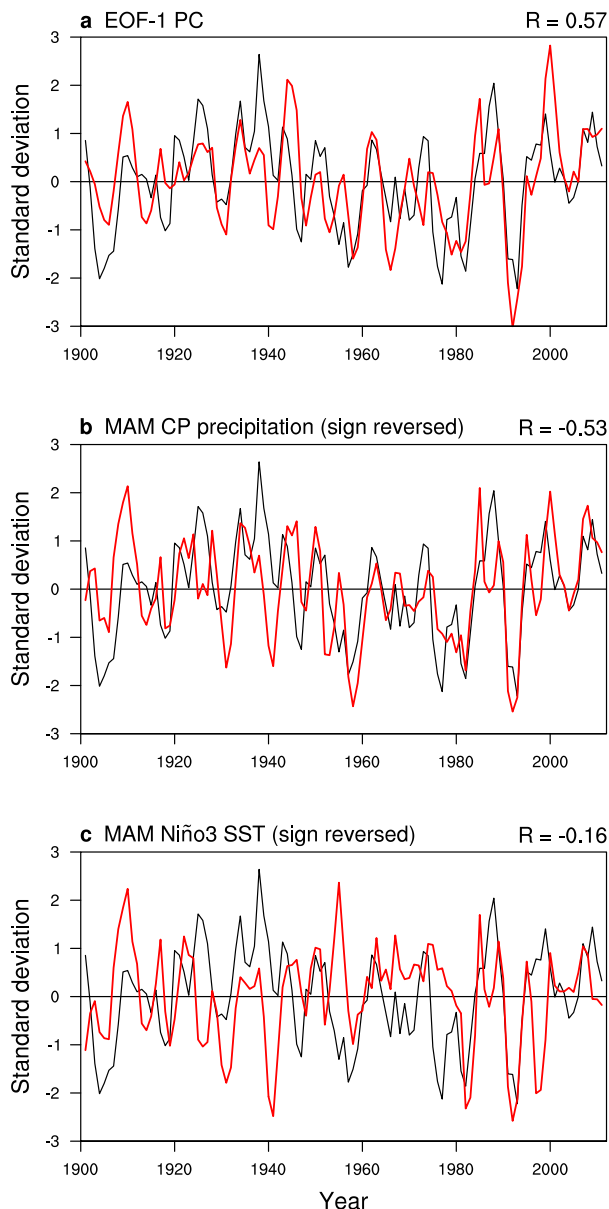


FIG. 10. MAM-mean time series (red lines) of (a) the EOF-1 PC, (b) a sign-reversed precipitation anomaly averaged in the tropical central Pacific (3°S – 3°N , 170°E – 130°W), and (c) the sign-reversed Niño-3 SST index. The JJA-mean Atlantic Niño index is indicated with black lines on all panels. All time series are normalized and smoothed with a 3-yr running mean filter. A correlation coefficient with the Atlantic Niño index is shown at the top-right corner of each panel.

zonally increases, along with convergence anomalies. The 850-hPa westerly wind anomalies over the equatorial Atlantic are consistent with an east–west dipole of velocity potential anomalies between the Pacific and Atlantic, acting to trigger the Atlantic Niño. These regressed anomalies are indicative of cross-basin changes in the Walker circulation, as illustrated in the multi-year

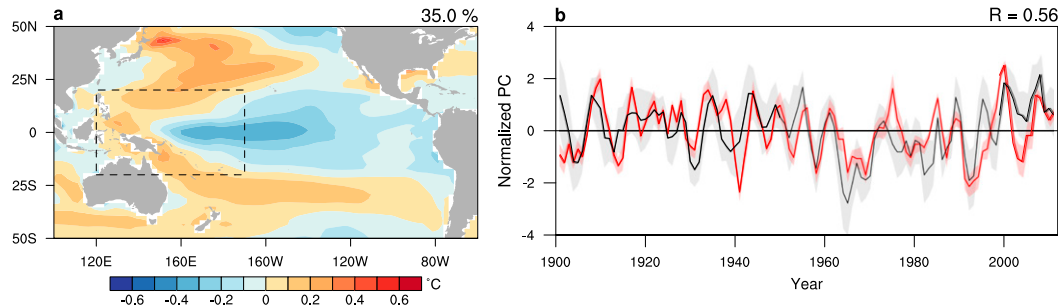


FIG. 11. (a) As in Fig. 9a, but for the regression coefficient of 3-yr running mean SST anomalies onto the EOF-1 PC time series based on a 10-member ensemble mean of GFDL CM2.1 POGA experiment. (b) As in Fig. 10a, but for the EOF-1 PC (red line) and JJA Atlantic Niño index (black line) from the POGA experiment. Shading indicates ± 1 intermember standard deviation. A correlation coefficient between the two ensemble-mean time series is 0.56, significant at the 95% confidence level.

ENSO composite for MAM(1) (Fig. 5b). In the POGA experiment, the centers of anomalous precipitation and convergence over the tropical western Pacific are biased slightly westward relative to the observation, but the model reproduces a similar Walker circulation change including surface westerly wind anomalies over the equatorial Atlantic (Fig. 12b). This robust pattern in the observation and POGA experiment provides strong support for the prolonged ENSO influence on the Atlantic Niño through a cross-basin change in the Walker circulation.

5. Summary and discussion

Synthesizing reanalysis products, in situ observations, and a Pacific pacemaker experiment, we have shown that the springtime forcing associated with multi-year ENSO events is crucial for the development of Atlantic Niños in summer. While single-year ENSO events rapidly decay after their winter peak, multi-year ENSO events sustain ocean-atmosphere coupling in the equatorial western to central Pacific even in spring and summer. This persistent coupling is characterized by

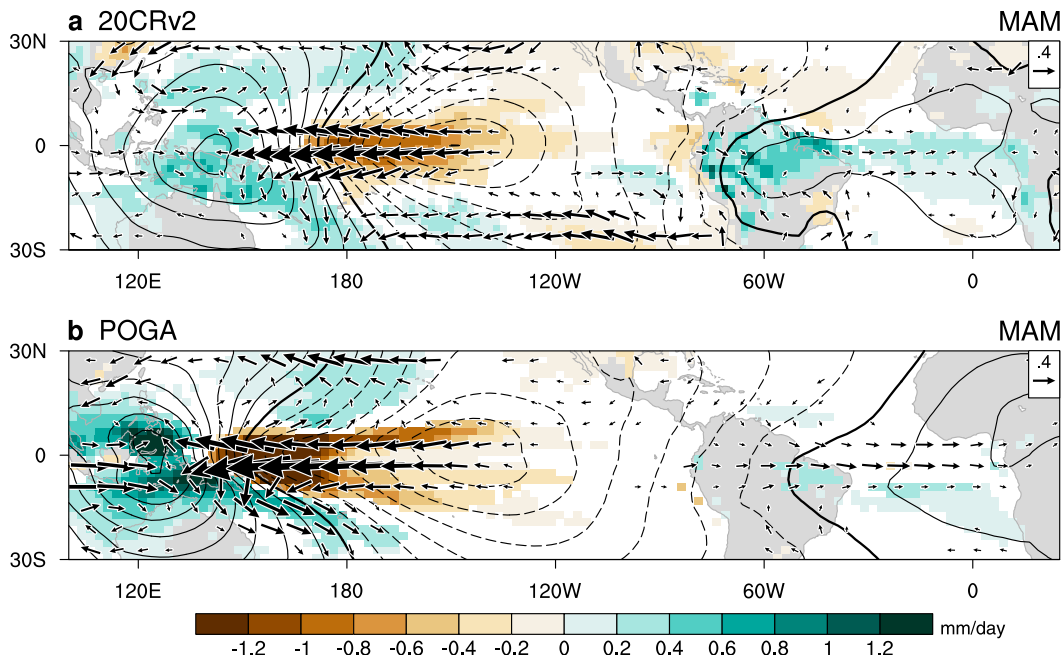


FIG. 12. Regression coefficients of MAM-mean precipitation (color; mm day^{-1}), 850-hPa velocity potential (contours at $0.8 \text{ m}^2 \text{ s}^{-1}$ intervals), and 850-hPa horizontal wind (vectors; m s^{-1}) with the EOF-1 PC, based on (a) 20CRv2 and (b) the POGA experiment. In (a), only significant precipitation and wind anomalies exceeding the 95% confidence level are shown. In (b), precipitation and 850-hPa wind anomalies are indicated on grid points where at least 7 ensemble members exceed the 95% confidence level.

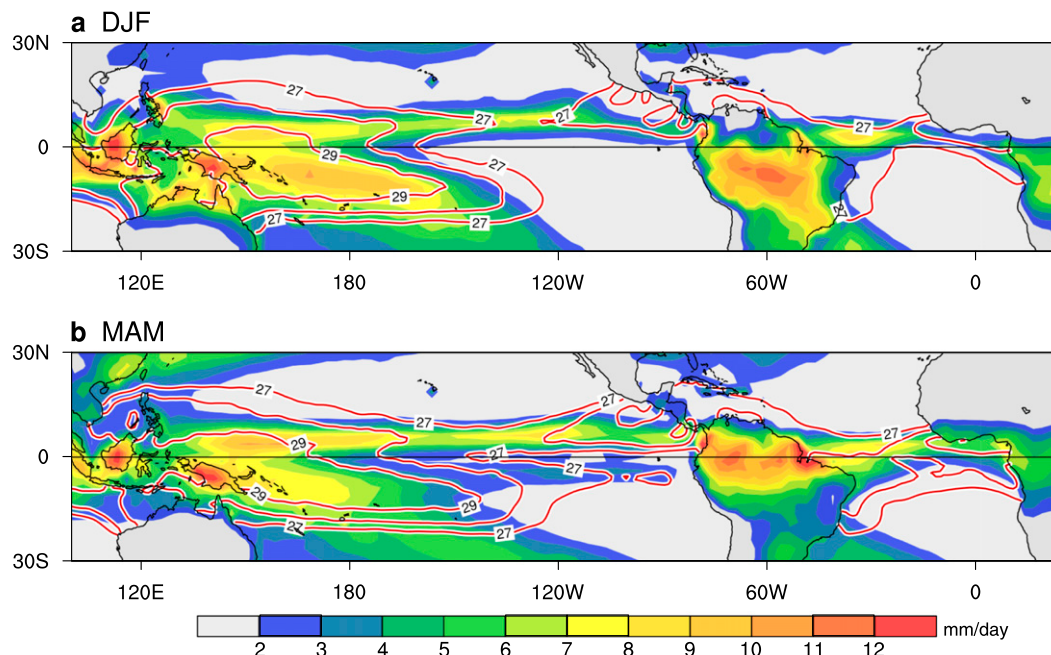


FIG. 13. (a) DJF and (b) MAM-mean climatologies of SST (red contours of 27°, 28°, and 29°C) and precipitation (color; mm day⁻¹), based on HadISST1 and the Global Precipitation Climatology Project datasets for 1979–2012.

anomalous zonal gradients of SST, ocean subsurface temperature, and atmospheric deep convection, a feature indicative of the Bjerknes feedback. Coupled with these changes, an ENSO-induced Walker circulation anomaly extends into the Atlantic, leading to westerly wind anomalies over the equatorial Atlantic in spring. In response, a zonal dipole of ocean subsurface temperature anomalies starts to develop in the equatorial Atlantic, and thus an Atlantic Niño develops in summer. Such a cross-basin ocean–atmosphere coupling is not found in the spring and summer of single-year ENSO events. Our study is the first to detect a significant correlation between the Atlantic Niño and long-lived ENSO events over the past 113 years, highlighting the importance of remote influences from the equatorial Pacific. Despite slightly asymmetric patterns of multi-year La Niñas and El Niños in the equatorial eastern Pacific, similar SST, surface wind, and precipitation anomalies with opposite sign are found in the equatorial western Pacific and the equatorial Atlantic (Figs. S3 and S4). These results are also consistent with the previous study by [Rodrigues et al. \(2011\)](#), which found that the long-lasting El Niño events intensify the southeasterly trade winds and northward displacement of the ITCZ over the tropical Atlantic.

Spring is the only season when the multi-year ENSO can cause significant surface westerly anomalies over the equatorial Atlantic, although the ENSO-induced Walker circulation anomaly is apparently stronger in winter

(Fig. 5). We speculate that the seasonal migration of the climatological ITCZ may modulate the influence of ENSO on the equatorial Atlantic. [Figure 13](#) shows DJF and MAM climatologies of precipitation and SST. Closely following the 27°C isotherm, both the Pacific and Atlantic ITCZs are displaced to the north of the equator in DJF ([Fig. 13a](#)), a well-known pattern maintained by the wind–evaporation–SST feedback ([Xie and Philander 1994](#)). Meanwhile, the South American ITCZ is displaced to the south of the equator due to land surface heating in austral summer ([Tanimoto et al. 2010](#)). The interannual variance of the DJF-mean precipitation roughly follows this climatological pattern with the off-equatorial peaks (not shown), making it difficult for the equatorial Pacific and Atlantic to interact through the Walker circulation. In MAM, on the other hand, warm SSTs greater than 27°C extend southward into the equatorial regions in both the Pacific and Atlantic, accompanied by ITCZs that are located closer to the equator ([Fig. 13b](#)). The South American ITCZ also migrates equatorward, resulting in a zonal alignment of ITCZs from the equatorial eastern Pacific to the equatorial Atlantic. These concurrent ITCZ shifts probably allow the Walker circulation to bridge the cross-basin interaction between the equatorial Pacific and Atlantic, and thus effectively cause westerly wind anomalies over the equatorial Atlantic in spring. Additionally, [Richter et al. \(2017\)](#) have shown how the proximity of deep convection is crucial to intensifying air–sea interaction over the equatorial Atlantic in spring.

ENSO diversity and its impact on regional climate variability are an important subject of active research (e.g., Ashok et al. 2007; Okumura et al. 2017; Xie et al. 2018). While the Niño-3 and Niño-3.4 indices have been used as the main measure of ENSO fluctuation in the tropical eastern Pacific, they are not always appropriate to capture different patterns of ENSO and their influence on climate (e.g., Ashok et al. 2007; Ren and Jin 2011; Xie et al. 2018). Our EOF analysis reveals that a central Pacific ENSO-like pattern dominates in the spring following the first peak of multi-year ENSO events. This EOF-1 mode can be used as a measure of the tropical Pacific influence in spring, and therefore, as a statistical precursor for predicting the summer Atlantic Niño/Niña events. This has important implications given strong impacts of the Atlantic Niño/Niña on regional climate and socioeconomy over equatorial Brazil and West African countries.

Previous studies have suggested that Atlantic Niños can force a La Niña-like SST pattern in the equatorial central Pacific in the following autumn to winter (Wang 2006; Keenlyside and Latif 2007; Rodríguez-Fonseca et al. 2009; Ding et al. 2012). As illustrated in our composite analysis (Fig. 5c), the equatorial Atlantic warming enhances atmospheric convection in summer. This may reinforce the surface divergence anomaly over the equatorial eastern Pacific through the Walker circulation (Wang 2006). The enhanced divergence intensifies surface trade winds over the equatorial central Pacific, generating favorable conditions for La Niña to develop through the Bjerknes feedback. Given our findings regarding the ENSO influence on the Atlantic Niño, the summertime Atlantic–Pacific forcing would imply the presence of a two-way interaction between the two modes. In addition, Chikamoto et al. (2015) recently identified a tropical transbasin SST/SLP variability (TBV) between the central Pacific and Atlantic/Indian Ocean dominating on decadal time scales. We found that the TBV mode is correlated with the decadal component of our EOF-1 PC time series for the tropical western to central Pacific SST anomalies (not shown), suggesting that the decadal interbasin interaction and multi-year ENSO events are strongly linked to each other. To clarify the causality between them, we need longer observational records and more reliable model simulations.

While the present study has shown a robust influence of multi-year ENSO events on the Atlantic Niño, the timing of ENSO onset and decay may also be important for the equatorial Atlantic response. For example, the 1965/66 El Niño started to develop in spring, a few months earlier than usual, followed by the summertime Atlantic Niña in the same year. Another single-year El

Niño in 1982/83 started earlier and lasted longer, accompanied by consecutive occurrences of Atlantic Niña events before and after the El Niño peak. These events may imply the sensitivity of the equatorial Atlantic response to the timing of ENSO onset and decay. Meanwhile, other factors, such as internal ocean and atmospheric variability over the Atlantic, may also be important for the occurrence of the Atlantic Niño. For example, the strong Atlantic Niño events in 1991 and 1995 cannot be explained by the mechanism proposed in this study. These events are strongly linked with the Benguela Niño that is forced by interannual variations of the South Atlantic anticyclone (Lübbecke et al. 2010; Richter et al. 2010). In addition, wind-induced equatorward warm advection (Richter et al. 2013) and stochastic atmospheric forcing and its effects on surface heat fluxes (Nnamchi et al. 2015) may also contribute to the occurrence of Atlantic Niños. Further research is needed to study the relative importance of these contributions.

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