A Decadal Weakening in the Connection between ENSO and the Following Spring SST over the Northeast Tropical Atlantic after the Mid-1980s

WEI CHEN

State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

(Manuscript received 3 September 2021, in final form 24 December 2021)

ABSTRACT: The north tropical Atlantic (NTA) displays significant sea surface temperature anomalies (SSTA) during the ENSO decaying spring. This study identifies a largely weakened impact of ENSO on the SSTA concentrated over the northeast tropical Atlantic (NEA) after the mid-1980s, while the impacts on the SSTA over the northwest tropical Atlantic (NWTA) are stable during the whole period. Different SST datasets can recognize this weakened connection between ENSO and the NTA SSTA, suggesting the robustness in this decadal variation. The El Niño–related teleconnections shift westward after the mid-1980s, and thus the anomalous southwesterly, leading to the positive NTA SSTA via the wind–evaporation–SST feedbacks, is restricted over the NWTA without extending eastward. As a result, the positive SSTA rises only over the NWTA but is diminished over the NTA. The regime shift in these circulation anomalies is due to the westward shift in the El Niño–induced convection and circulation anomalies from the eastern equatorial Pacific (EEP) to the central equatorial Pacific (CEP). Further analysis indicates that the intensified zonal SST gradient over the equatorial Pacific leads to a westward shift of Pacific Walker circulation after the mid-1980s. The westward shift of Walker circulation contributes to the convergent circulation anomalies over the CEP and thus results in the El Niño–induced precipitation anomalies concentrated there.

SIGNIFICANCE STATEMENT: Previous studies have indicated a positive connection between ENSO and the succeeding spring SSTA over the north tropical Atlantic (NTA), and this connection tends to be unstable. This study identifies a decadal weakening in the connection between ENSO and the NTA SSTA, including the ENSO–NTA connection are due to the westward shift in the ENSO-related convection and teleconnections, resulting from the westward shift of Pacific Walker circulation, induced by the intensified zonal SST gradient over the equatorial Pacific after the mid-1980s. The result implies a decadal change in NTA SSTA structure, which may bring different climate anomalies in the surrounding area.

KEYWORDS: North Atlantic Ocean; ENSO; Decadal variability; Tropical variability; Atmospheric circulation

1. Introduction

As the most dominant mode on the interannual time scale, El Niño–Southern Oscillation (ENSO) is characterized as the sea surface temperature anomalies (SSTA) rising over the central and eastern tropical Pacific and generating atmospheric teleconnections to strongly affect the global weather and climate (e.g., Horel and Wallace 1981; Philander 1983; Deser et al. 2010). One of the most robust ENSO-related teleconnection is the impact of ENSO on the SSTA over the northeast tropical Atlantic (NTA). During the El Niño decaying spring, a broad significant positive SSTA arises over the NTA (Enfield and Mayer 1997; Klein et al. 1999; Saravanan and Chang 2000; Alexander and Scott 2002, Lee et al. 2008; Wu et al. 2020; Wu and He 2019). This broad SSTA has remarkable influence on climate phenomena over the surrounding and remote regions, such as Atlantic hurricane activity (Wang et al. 2006), anomalous precipitation over Northeast Brazil (Uvo et al. 1998), variability over the tropical Pacific (Ham et al. 2013; Chen et al. 2022), and climate anomalies over the western North Pacific (W. Chen et al. 2015) and South Asia (Yang and Huang 2021).

Previous studies have proposed the mechanisms involved in the connection between ENSO and the NTA SSTA, including both the ENSO-related extratropical teleconnection and tropical teleconnection (e.g., Enfield and Mayer 1997; Klein et al. 1999; Giannini et al. 2000; Czaja et al. 2002; García-Serrano et al. 2017; Jiang and Li 2019). The extratropical teleconnection is the Rossby wave train that propagates across the Pacific–North American (PNA) region (e.g., Wallace and Gutzler 1981; Enfield and Mayer 1997; Klein et al. 1999; Giannini et al. 2000; Alexander and Scott 2002). The tropical teleconnection is the remote Gill response associated with perturbations in Walker circulation (e.g., García-Serrano et al. 2017; Jiang and Li 2019). Both the ENSO-related extratropical teleconnection and the tropical teleconnection induce an anomalous southwesterly over the NTA, which weakens the northeasterly trade winds and in turn results in warming over the NTA via the wind–evaporation–SST feedback (e.g., Enfield and Mayer 1997; Klein et al. 1999; Giannini et al. 2000; Czaja et al. 2002; García-Serrano et al. 2017; Jiang and Li 2019).

The ENSO teleconnections mentioned above are generated by the diabatic heating over the tropical Pacific corresponding
to the ENSO-induced tropical convections (e.g., Horel and Wallace 1981; Alexander and Scott 2002; García-Serrano et al. 2017). In response to El Niño forcing, positive precipitation anomalies emerge over the central and eastern tropical Pacific. The corresponding heating generates a pair of cyclonic circulation anomalies according to the Gill response, with the anomalous westerly extending from the west of the date line to the eastern equatorial Pacific. This anomalous westerly further generates the convergence of zonal wind anomalies, favoring the persistence of precipitation anomalies in situ (e.g., Wang et al. 2000; Chou et al. 2003; Chen et al. 2012, 2016).

The anomalous precipitation over the tropical Pacific, being in response to the ENSO forcing, has experienced a significant decadal change (Lyon et al. 2014; Jo et al. 2015; Guo et al. 2016). Jo et al. (2015) mentioned a westward shift in the location of the tropical convective heating after the 1990s. Guo et al. (2016) pointed out that the positive precipitation anomalies associated with El Niño shifted from the eastern equatorial Pacific to the central equatorial Pacific after the 1990s and contributed to the intensified zonal mean SST gradient. Han et al. (2020) further indicated that the zonal shift of ENSO-induced tropical convection is induced by the westward shift of Pacific Walker circulation, resulting from the enhanced zonal SST gradient over the tropical Pacific. Coinciding with the regime shift of the tropical Pacific convection activities, the North Pacific circulation (Jo et al. 2015) and the extratropical circulation (Guo et al. 2019) also exhibit remarkable decadal change. It is worthwhile to examine the decadal variations in the circulation teleconnections, linking the ENSO and the NTA SSTA, in response to the El Niño–induced tropical Pacific heating.

Some studies have noticed the decadal changes in the connection between ENSO and NTA SSTA (e.g., Amaya and Foltz 2014; S. Chen et al. 2015; Park and Li 2019; Yin and Zhou 2019). The increased occurrence of El Niño events with short period and weak amplitude after the 2000s (e.g., Hu et al. 2013; He et al. 2020) leads to weak impact on the NTA SSTA (e.g., Wu and He 2019). The growing frequency of central Pacific (CP)–El Niño since the late 1990s (e.g., Yeh et al. 2009; Lee and McPhaden 2010) produces insignificant warming over the NTA (e.g., Amaya and Foltz 2014; Taschetto et al. 2016). Besides the modulation of ENSO properties, the change in the mean state of polar vortex contributes to the decadal weakening in the influence of CP-ENSO on the NTA SSTA after the mid-1980s (Yin and Zhou 2019). The disturbance of enhanced impacts of North Atlantic Oscillation (NAO) to the NTA SSTA weakens the ENSO–NTA connection around the mid-1980s (S. Chen et al. 2015). The variation of Atlantic multidecadal oscillation (AMO) modulates the decadal changes in the ENSO–NTA relationship (Park and Li 2019).

Previous studies indicated the decadal changes in the impact of ENSO on the SSTA occurred over the entire NTA (e.g., Amaya and Foltz 2014; S. Chen et al. 2015; Park and Li 2019; Yin and Zhou 2019). However, the SSTA over the eastern and the western parts of the North Atlantic may feature differently and thus has different climate impacts (e.g., Liu et al. 2012; Wang et al. 2017). Do the decadal changes in the ENSO–NTA connection vary with different parts of the NTA? If so, what mechanism takes charge in the different decadal connection of ENSO with individual parts of NTA? These two questions have not been well addressed in previous studies. Therefore, we would like to further investigate the decadal variations in the connection between ENSO and the NTA SSTA and the physical mechanisms involved. In the following parts, section 2 inspects the observed characteristics of decadal changes in the impacts of ENSO on the SSTA over different parts of NTA. Section 3 demonstrates the physical processes behind this decadal change. Section 4 illustrates the role of change in topical convection in the decadal variations. A summary and discussion follow in section 5.

2. Decadal changes in the connection of ENSO with the SSTA over different parts of NTA

Figure 1 is the regression of SSTA in spring [March–May (MAM)] onto the Niño-3 index (defined as the SST anomalies averaged over 5°S–5°N, 90°–150°W) in the previous winter [December–February (DJF)] from 1948 to 2020 by using three SST datasets, including the Hadley Center Sea Ice and Sea Surface Temperature dataset (HadISST; Rayner et al. 2003); the National Oceanic and Atmospheric Administration (NOAA) Extended Recon-structed Sea Surface Temperature, version 5 (ERSSTv5; Huang et al. 2017); and the International Comprehensive Ocean–Atmosphere Data Set (ICOADS; Freeman et al. 2017). The linear trends have been removed first.

In response to the previous winter El Niño forcing, three SST datasets all suggest a significant positive SST over the NTA oceanic basin south of 25°N (Fig. 1), including both the northeast tropical Atlantic (NETA; purple boxes) and the northwest tropical Atlantic (NWTA; blue boxes). The results indicate a modulation of ENSO to the NTA over the entire NTA in the succeeding spring, being consistent with previous studies (e.g., Enfield and Mayer 1997; Klein et al. 1999; Saravanan and Chang 2000; Alexander and Scott 2002; Wu and He 2019). The correlation coefficient between the spring NTA index (defined as the SSTA averaged over 0°–25°N, 15°–80°W) and the preceding winter Niño-3 index is 0.51 in HadISST, 0.55 in ERSSTv5, and 0.55 in ICOADS, all being significant at the 99% confidence level.

Figure 2 is the 25-yr sliding regression of spring SSTA over the NTA (zonal averaged over 0°–25°N) onto the previous winter Niño-3 index. The positive SST covers the entire NTA during the whole period. In regional scale, the intensity of SST over the NTA is stable (blue boxes), but the intensity of SST over the NETA clearly exhibits a decadal variation, which is strong before the mid-1980s (black boxes) but is largely weakened after that (purple boxes). The regressed SST averaged over the black box is 0.29°C in HadISST data set (0.30°C in ERSSTv5 and 0.31°C in ICOADS), being more than twice that over the purple box with a value of 0.13°C in HadISST (0.14°C in ERSSTv5 and 0.14°C in ICOADS). The decadal change in spring SSTA over the NETA associated with the previous winter ENSO can be obtained by different
SST datasets, suggesting that this decadal variation is a robust feature.

The decadal change in the connection of ENSO with the NETA SSTA is further illustrated by the 25-yr sliding correlation between the spring NETA index (defined as the SSTA averaged over 0°–25°N, 15°–45°W) and the preceding winter Niño-3 index (solid lines in Fig. 3a). The correlation coefficients vary from 0.5 to 0.8 before the mid-1980s, which are significant at the 99% confidence level. The correlation coefficients, however, decrease largely after the mid-1980s, with the values varying from 0.2 to 0.4. Different SST datasets show a

FIG. 1. Regression of spring SSTA (°C) onto the previous winter Niño-3 index from 1948 to 2020 by using (a) HadISST, (b) ERSSTv5, and (c) ICOADS. The anomalies inside the solid lines represent the regions where the regressions are significant at the 95% confidence level by using a t test. The purple and blue boxes denote the regions to define the NETA (0°–25°N, 15°–45°W) index and the NWTA (0°–25°N, 45°–80°W) index, respectively.

FIG. 2. The 25-yr sliding regression of spring SSTA over the north tropical Atlantic (zonal averaged over 0°–25°N) onto the previous winter Niño-3 index. The anomalies inside the solid lines represent the regions where the regressions are significant at the 95% confidence level by using a t test. The regions within the black (purple) boxes represent the anomalies over the NETA (15°–45°W) during the period of 1960–88 (1988–2008). The regions within the blue boxes represent anomalies over the NWTA (45°–80°W) during the period of 1960–2008.
consistent result of the sliding correlation, indicating the robustness in this decadal change. In addition, the time series of the Niño-3 index and the NETA index show a consistent change before the mid-1980s. But after that, this concurrence is broken (Fig. 3b). In the 31 years from 1990 to 2020, there are 14 years that the positive (negative) Niño-3 index is accompanied with the negative (positive) NETA index. This is consistent with the decadal weakening in the sliding correlations between the Niño-3 index and the NETA index after the mid-1980s (Fig. 3a). Hereafter, the period of 1955–85 with
Table 1. Correlation coefficients between the spring (MAM) NETA index and the preceding winter (DJF) Niño-3 index during different periods by using three SST datasets. The correlation coefficients that are significant at the 99% confidence level by using t test are in bold.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>HadISST</td>
<td>0.433</td>
<td>0.587</td>
<td>0.232</td>
</tr>
<tr>
<td>ERSSTv5</td>
<td>0.457</td>
<td>0.646</td>
<td>0.246</td>
</tr>
<tr>
<td>ICOADS</td>
<td>0.446</td>
<td>0.622</td>
<td>0.223</td>
</tr>
</tbody>
</table>

For comparison, the sliding correlation between the spring NWTA index (defined as the SSTA averaged over 0°–25°N, 45°–80°W) and the previous winter Niño-3 index is also shown (dashed lines in Fig. 3a). The correlation coefficients are above 0.5, being significant at the 99% confidence level, and keep stable during the whole period in all three SST datasets. The stable connection can also be seen from the coincident change of the Niño-3 index and the NWA index persisting during the whole period (Fig. 3c). The result suggests that the decadal change in the connection with ENSO is not over the NWTA but occurs only over the NETA.

Table 1 examines the correlation coefficients between the winter Niño-3 index and the following spring NETA index during different periods. In HadISST, the correlation coefficient is 0.43 during the whole period. It rises to 0.59 in the P1 but only 0.23 in the P2. The strong (weak) correlation in the P1 (P2) also can be obtained by using ERSSTv5 and ICOADS datasets, further indicating that the decadal change in the connection between ENSO and the NETA SSTA around the mid-1980s is a robust feature. On the contrast, the correlation coefficients of the winter Niño-3 index with the succeeding spring SSTA over the NWTA vary from 0.57 to 0.60 in the whole period, 0.54 to 0.62 in the P1, and 0.53 to 0.56 in the P2 among the different SST datasets, which are all being significant at the 99% confidence level. The results suggest a stable connection of ENSO with the NWTA SSTA in the past decades, but a decadal weakening in the connection of ENSO with the NETA SSTA after the mid-1980s. The decadal weakening in the ENSO–NETA connection also can be obtained by using winter Niño-3.4 index or Niño-4 index, indicating the robustness in the decadal variation. In the following sections, the physical processes behind this decadal change are demonstrated by using HadISST dataset, and the similar results can be obtained by using other two SST datasets.

Previous studies noticed a weakened connection between ENSO and the SSTA over the entire NTA (e.g., Amaya and Foltz 2014; S. Chen et al. 2015; Taschetto et al. 2016; Park and Li 2019; Yin and Zhou 2019). Our study identifies that the decadal variation in the connection of ENSO with the SSTA actually concentrates over the NETA. In addition, Park and Li (2019) presented that the connection between ENSO and the NTA SSTA is along with the phase of AMO. We further examine the sliding correlation between ENSO and the NETA SSTA with long-term records and compared with the decadal changes in AMO (figures not shown). The results indicate that the decadal variations in the ENSO–NETA connection do not coincide with the decadal changes of AMO, being different with Park and Li (2019). This is possibly due to the differences in the region and the season that are used to define the tropical Atlantic SSTA. We focus on the SSTA that concentrates over the NTA (0°–25°N, 15°–45°W) during spring (MAM) rather than the SSTA over the entire NTA (0°–30°N; 20°–100°W), which lagged ENSO by 3–7 months in their study. In addition, we use four SST datasets including HadISST, ERSSTv5, ERSSTv3, and ICOADS to examine the robustness of the results instead of the one SST dataset of ERSSTv3 in their study.

3. Physical processes in response to this decadal change

Figure 4 is the lead–lag regression of SSTA from the simultaneous winter D(0)JF(1) to the following spring MAM(1) with respect to the Niño-3 index fixed in winter during the two periods [here, (0) and (1) represent the seasons in the preceding year and in the following year, respectively]. During winter, the SSTA exhibits a typical spatial pattern of El Niño mature phase with the strongest positive SSTA over the central and eastern tropical Pacific in both periods (Figs. 4a, c). Over the NTA, the weak positive SSTA is mainly limited over the Caribbean Sea without eastward extending, indicating that ENSO hardly affects the NTA SSTA during the simultaneous winter in both periods. The differences in regressions between the two periods show little anomaly over the tropical Pacific and tropical Atlantic (Fig. 4e), implying that the ENSO amplitude and its impacts are similar during winter between the two periods.

During spring, the positive SSTA over the tropical Pacific declines (Figs. 4b, d). The intensity of the SSTA over the Niño-3 region is 0.38°C in the P1, and 0.40°C in the P2, indicating that the intensity of El Niño during the decaying spring is comparable in the two periods. Large differences in the SSTA between the two periods occur over the NTA. The positive SSTA is over the entire NTA, including both the NWTA and the NETA, in the P1, but restricts over the NWTA in the P2. The intensity of the NETA SSTA is 0.28°C in the P1, but only 0.09°C in the P2. The differences in regressions between the P2 and the P1 show the negative SSTA over the NETA (Fig. 4f), with a value of −0.19°C, which is consistent with the weakened connection between ENSO and the NETA SSTA in the P2 (Figs. 2 and 3). In addition, the differences between the two periods display little change over the NWTA (Fig. 4f).
being consistent with the stable connection between ENSO and the NWTA SSTA (Figs. 2 and 3).

Figure 5 is the spatial patterns of precipitation and lower-tropospheric wind anomalies associated with the winter Niño-3 index in the two periods. The circulation and precipitation datasets are from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis, version 1 (NCEP-1; Kalnay et al. 1996). In the El Niño mature winter, the positive precipitation anomalies are over the central and eastern tropical Pacific, which coincide with the anomalous westerly extending from 150°E to 90°W in both periods (Figs. 5a,c). The remote response over the NTA is relatively weak during winter.

The positive precipitation anomalies over the tropical Pacific persist during the El Niño decaying spring in both periods, but the centers with the strongest precipitation anomalies are different (Figs. 5b,d). In the P1, the precipitation anomalies averaged over the eastern equatorial Pacific (EEP; 5°S–5°N, 90°–120°W) are 1.08 mm day$^{-1}$, which is greater than those over the central equatorial Pacific (CEP; 5°S–5°N, 150°W–180°W; with a value of 0.71 mm day$^{-1}$). This indicates that the El Niño–related positive precipitation anomalies center is over the EEP in the P1. On the contrary, in the P2, the intensity of precipitation anomalies is 2.32 mm day$^{-1}$ over the CEP, which are twice that over the EEP (with a value of 1.13 mm day$^{-1}$), indicating that the anomalous precipitation center concentrates to the CEP. The differences in the regressions show positive precipitation anomalies over the CEP (Fig. 5f; with a value of 1.61 mm day$^{-1}$), indicating an enhanced convection over the CEP during the P2. The result suggests that the center with the largest value of positive precipitation anomalies in response to El Niño forcing shifts westward from the EPP in the P1 to the CEP in the P2.

The location of positive precipitation anomalies coincides with the extension of anomalous westerly over the equatorial Pacific. On the one hand, the diabatic heating induced by the positive precipitation anomalies generates cyclonic circulation anomalies with anomalous westerly over the equatorial Pacific. On the other hand, the convergence of this anomalous westerly results in the persistence of precipitation anomalies (e.g., Wang et al. 2000; Chou et al. 2003; Chen et al. 2014). Therefore, the decadal shift in the center of precipitation anomalies agrees with the decadal shift in the extension of anomalous westerly.

The anomalous westerly over the central and eastern equatorial Pacific extends to 90°W in the P1 (Fig. 5b) but retreats to 120°W in the P2 (Fig. 5d). The zonal wind anomalies averaged over the EEP are 0.79 m s$^{-1}$ in the P1 but are largely declined in the P2 with a value of 0.08 m s$^{-1}$. Over the CEP, however, the anomalous westerly maintains in both periods,
with the values of 1.31 m s\(^{-2}\) in the P1 and 1.17 m s\(^{-2}\) in the P2. The results suggest that the anomalous westerly extends to the EEP in the P1 but withdraws westward to the CEP in the P2. The differences in the regressed zonal wind anomalies between the two periods show anomalous easterly from the EEP to the east of the CEP (Fig. 5f), implying the weakened anomalous westerly during the El Niño decaying spring in the P2. The extension of anomalous westerly determines the location of convergence in zonal wind anomalies. In the P1, the anomalous zonal wind is convergence over the EEP (with the zonal gradient of anomalous zonal wind of \(-1.33 \times 10^{-7} \text{ s}^{-1}\)) but divergence over the CEP (with the zonal gradient of anomalous zonal wind of \(0.89 \times 10^{-7} \text{ s}^{-1}\)). In the P2, the strong convergence shifts to the CEP with the zonal gradient of anomalous zonal wind of \(-0.90 \times 10^{-7} \text{ s}^{-1}\), which is close to twice that over the EEP (\(-0.56 \times 10^{-7} \text{ s}^{-1}\)).

Since the location of the strongest convergence corresponds to the center with the largest value of precipitation anomalies, the extension of anomalous westerly to the CEP (EEP) favors the precipitation center maintains over the CEP (EEP) through inducing convergence of anomalous zonal wind in situ. Thus, the westward shift of precipitation centers from the EEP in the P1 to the CEP in the P2 results from the westward retreat of anomalous westerly. The results are consistent with Guo et al. (2016), who pointed out that the strongest precipitation anomalies over the tropical Pacific agree with the position of extending anomalous zonal wind. In their study, the center of anomalous precipitation over the CEP (EEP) is associated with the appearance of anomalous westerly in situ.

The positive precipitation anomalies over the equatorial Pacific generate anticyclonic circulation anomalies over the NTA (Figs. 5b,d) via a remote Gill response (García-Serrano et al. 2017; Jiang and Li 2019) and a PNA wave train (e.g., Enfield and Mayer 1997; Giannini et al. 2000). The anomalous southwesterly in the north edge of the anticyclonic circulation anomalies over the north equatorial Atlantic (result from the remote Gill response) and in the south edge of cyclonic circulation over the North Atlantic (result from the PNA wave train) weakens the climatological northeasterly trade winds and result in decrease of surface heat flux loss and warming over the NTA (Figs. 4b,d), being consistent with previous studies (e.g., Enfield and Mayer 1997; Giannini et al. 2000; Saravanan and Chang 2000; García-Serrano et al. 2017; Jiang and Li 2019).

The decadal shift in the anomalous precipitation centers from the EEP to the CEP leads to the decadal changes in the ENSO-related atmospheric circulation response over the NTA. In the P1, the anomalous southwesterly extending from the NWTA to the NETA leads to positive SSTA over the entire NTA (Fig. 4b). In the P2, however, the circulation anomalies are shrunk, and the anomalous southwesterly is restricted over the NWTA (Fig. 5d). As a result, the positive SSTA is limited over the NWTA, and no significant signals over the NETA (Fig. 4d).

Figure 6 suggests the circulation anomalies in response to the El Niño forcing shift westward in the P2, compared to those in the P1. During the El Niño decaying spring, there is a pair of cyclonic circulations in the lower troposphere over the
tropical Pacific that occupies the entire central and eastern tropical Pacific from the date line to 90°W in the P1 (Fig. 6b) but withdraws to 120°W in the P2 (Fig. 6d). In the upper troposphere, the anomalous divergence and ascent are over the eastern tropical Pacific in the P1 (Fig. 6b) but shift westward to the central tropical Pacific in the P2 (Fig. 6d). Over the north equatorial Atlantic, the anticyclonic circulation anomalies occur across the Atlantic oceanic basin in the P1 (Fig. 6b) but are restricted over the western side in the P2 (Fig. 6d), indicating the westward shift of the teleconnections in response to El Niño forcing. The differences in the regressed circulation patterns further indicate a westward shift in the El Niño–related teleconnections between the two periods (Fig. 6f).

Figure 7 is the spatial pattern of 500-hPa geopotential height anomalies in response to the El Niño forcing, illustrating the El Niño–induced extratropical response exhibiting as a PNA pattern. During the P2, with the El Niño–related precipitation center being over CEP, the regression of 500-hPa geopotential height anomalies features a typical PNA pattern with a positive center in the tropical North Pacific, a negative center in the North Pacific, a positive center in northwest United States and a negative center in the eastern United States and the North Atlantic (Fig. 7d). During the P1, although the maximal heating is over the EEP, the associated geopotential height anomalies exhibit as an eastward shift of PNA pattern (Fig. 7b), which is consistent with Taschetto et al. (2016). The negative center of PNA over the North Atlantic extends eastward to the northeast Atlantic during the P1 but shrinks westward over the northwest Atlantic during the P2. Thus, the impact of ENSO can be conveyed to the NETA in the P1 but limited in the NWTA in the P2.

4. Role of the shift in equatorial Pacific convection

Figure 8 is the evolution of SSTA over the equatorial Pacific associated with the winter Niño-3 index in the two periods. The positive SSTA is over the central and eastern equatorial Pacific, which peaks during winter, declines during the following spring, and disappears during the following summer in both periods (Figs. 8a,b). The difference in SSTA patterns between the two periods suggests that the intensity and decaying phase of El Niño are comparable (Fig. 8c), indicating no significant decadal changes in ENSO properties between the two periods.

The evolution of precipitation anomalies and lower-tropospheric zonal wind anomalies over the equatorial Pacific in response to the winter Niño-3 index shows different patterns in the two periods (Figs. 9 and 10), although the El Niño properties are similar (Fig. 8). During the El Niño decaying spring, a large proportion of precipitation anomalies are concentrated in the EEP in the P1 (Fig. 9a), which is consistent with the eastward extension of an anomalous westerly in the P1.
In contrast, the precipitation anomalies maintain in the CEP in the P2 (Fig. 9b), corresponding to the persistence of anomalous westerlies in situ (Fig. 10b). The differences between these two periods suggest a westward shift in the positive precipitation center as well as a westward retreat in the anomalous westerly (Figs. 9c and 10c).

Figure 11 is the spatial patterns of variables associated with the CEP_preca index (defined as the spring precipitation anomalies averaged over 5°S–5°N, 150°W–180°W) in the P2. The patterns are quite similar with those in response to El Niño forcing in the P2 (Figs. 4d, 5d, 6d and 7d). Besides the central and eastern tropical Pacific, the significant positive SSTA occurs only over the NWTA, but is extremely diminished over the NETA (Fig. 11a), which are consistent with the weakened connection between ENSO and the NETA SSTA in the P2. The positive precipitation anomalies over the CEP (Fig. 11b) lead to a pair of cyclonic circulation over the western and central tropical Pacific (Fig. 11c), with anomalous westerly extending from 150°E to 150°W (Fig. 11b). The remote response to the CEP_preca index exhibits as anticyclonic circulation anomalies over the north equatorial Atlantic (Fig. 11c) with an anomalous southwesterly being restricted west of 50°W (Fig. 11b) and negative geopotential height anomalies centering over the northwest Atlantic but positive ones over the northeast Atlantic (Fig. 11d). The westward shrink of these circulation anomalies results in positive SSTA rising only over the NWTA but vanishing over the NETA.

The variables associated with EEP_preca index (defined as the spring precipitation anomalies averaged over 5°S–5°N, 90°W–120°W) in the P1 are shown in Fig. 12. The spatial patterns are similar to those related to the previous winter Niño-3 index in the P1 (Figs. 4b, 5b, 6b, and 7b). The EEP precipitation anomalies coincide with a pair of cyclonic circulation over the central and eastern tropical Pacific (Fig. 12c), with the anomalous westerly extending to 90°W (Fig. 12b). The atmospheric teleconnection propagates eastward, exhibiting as the anticyclonic circulation anomalies over the north equatorial Atlantic (Fig. 12c) with anomalous southwesterlies across the Atlantic Ocean (Fig. 12b) and negative geopotential height anomalies extending to the east side of the North Atlantic (Fig. 12d). These circulation anomalies cover the entire NTA, leading to the strong connection of ENSO with the SSTA over both the NWTA and the NETA in the P1. Noting the eastward shift PNA pattern, triggered by the heating over the EEP, has been suggested by Taschetto et al. (2016) via performing the sensitivity experiments.
The variable anomalies in response to the EEP_preca (CEP_preca) index are also examined by using partial regression analysis in order to exclude the impact of precipitation over other equatorial Pacific regions (figures not shown). The partial regressions are quite similar with the regressions obtained by the original variables, although with a slight weak amplitude, which further supports the role of El Niño–related equatorial Pacific convection in the ENSO–NETA connections. The decadal westward shift in the El Niño–induced precipitation center leads to a westward shrinking of circulation teleconnections with anomalous southwesterly restricting over the NWTA, and in turn results in the decadal weakened connection between ENSO and the NETA SSTA after the mid-1980s.

Figure 13 is the 25-yr sliding correlation between the winter Niño-3 index with the succeeding spring CEP_preca index (red line) and with the NETA SSTA (black line; the correlation coefficients are multiplied by −1.0). The result suggests...
that the correlation between ENSO and the CEP precipitation anomalies exhibits a decadal variation that has been intensified after the mid-1980s (red line), which agrees with the weakened connection between ENSO and the NETA SSTAs (black line), with the correlation coefficient between the red and black lines of 0.89. Moreover, after the mid-1980s, the correlation between the CEP precipitation anomalies and local zonal wind anomalies is strengthened (blue line), which is consistent with the decadal intensification in the El Niño–related CEP precipitation anomalies (red line) as well as the decadal weakening in the El Niño–related NETA SSTAs (black line). The correlation coefficient between the red and blue (black) lines is 0.85 (0.64), indicating that the extension of anomalous westerly over the CEP leads to the precipitation
center located there and in turn favors the decreased NETA SSTA in response to El Niño forcing.

Figure 14 is the climatological mean of SST and lower-tropospheric zonal wind in the two periods and their differences. SST mean states are warm over the western tropical Pacific and relatively cold over the eastern tropical Pacific in both periods (Figs. 14a,b). In particular, the differences in the climatological SST between the two periods suggest an intensified zonal SST gradient between east and west equatorial Pacific, displaying as strengthened cold tongue and warm pool (Fig. 14c). The decadal enhancement in the zonal SST gradient leads to a westward shift of Pacific Walker circulation with the easterly trade winds being strengthened over the western tropical Pacific but being weakened over the eastern tropical Pacific (Fig. 14f). The zonal shift of Pacific Walker circulation, coinciding with the intensified zonal SST gradient on the decadal time scale, is consistent with previous studies (e.g., Ma and Zhou 2016; Li et al. 2021).

The zonal shift in Pacific Walker circulation affects the location of the El Niño-related convection (Han et al. 2020). In their study, the westward shift of Walker circulation results in a westward shift in the convergent moisture transport through enhancing the ENSO-induced lower-level vertical velocity variability, and in turn causing the westward shift in ENSO precipitation and circulation. According to their result, the westward shift of Walker circulation after the mid-1980s contributes to the convergent circulation anomalies shifting from the EEP to the CEP and thus results in the El Niño-induced precipitation anomalies concentrated over the CEP. Our result implies that the westward shift in ENSO-related convection and teleconnection occurs with the westward shift in Pacific Walker circulation and the intensified zonal SST gradient after the mid-1980s.

5. Summary and discussion

The NTA presents a significant positive SSTA during the El Niño decaying spring. The intensity of El Niño-induced NTA warming is unstable, exhibiting a decadal variation. Our results identify that the decadal variation occurs only with the SSTA concentrated over the NETA. The 25-yr sliding correlation between ENSO and the NETA SSTA is significant at the 99% confidence level before the mid-1980s but largely weakened and insignificant after that. This decadal weakening
in the connection can be recognized by different SST datasets, indicating that this decadal variation is a robust feature. On the contrast, the sliding correlation between ENSO and the SSTA over the NWTA is significant and stable during the whole period, indicating that the decadal change in the connection of ENSO and the NTA SSTA occurs only over the NETA, but not over the NWTA.

The decadal weakening in the ENSO–NETA connection is due to the westward shift in the ENSO-related circulation teleconnections. Before the mid-1980s, the anomalous southwesterly, induced by these remote circulation responses, weakens the climatological northeasterly trade winds and results in positive SSTA over the entire NTA. After the mid-1980s, the circulation responses and the anomalous southwesterly are limited over the NWTA without extending eastward. Therefore, the positive SSTA appears only over the NWTA but is extremely diminished over the NETA.

The regime shift of these remote circulation responses over the North Atlantic is due to the westward shift in El Niño–induced tropical Pacific convection. After the mid-1980s, the El Niño–induced precipitation center shift westward to the CEP. Both the tropical teleconnection and the extratropical teleconnection generated by the El Niño–induced tropical Pacific convection shrink westward. Further analysis suggests that the zonal SST gradient between the east and west equatorial Pacific is intensified after the mid-1980s, which leads to a westward shift of Pacific Walker circulation. The latter contributes to the westward shift in El Niño–induced tropical Pacific convection via enhancing the convergent circulation anomalies and moisture transport over the CEP.

Previous studies have argued decadal changes in the impacts of ENSO on the SSTA over the entire NTA due to the decadal variations in ENSO properties after the late-1990s (e.g., Amaya and Foltz 2014; Taschetto et al. 2016). Our result identifies the decadal weakening in the connection of ENSO with the SSTA actually concentrated over the NETA after the mid-1980s. The present results indicate that the decadal variations in the ENSO–NETA connection tend to not necessarily occur with the changes in ENSO properties but can be induced by a westward shift in the El Niño–induced tropical convection, resulting from the decadal changes in the zonal SST gradient and Walker circulation over the equatorial Pacific.

Acknowledgments. This study was supported by the National Key R&D Program of China (Grant 2019YFA0606703), the National Natural Science Foundation of China (Grant 41675078), and the Youth Innovation Promotion Association of CAS (2018102).

Data availability statement. The HadISST dataset is available at https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html. The ERSSTv5 dataset is available at https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html. The ICOADS dataset is available at https://icoads.noaa.gov/data.icoads.html. The NCEP–NCAR reanalysis, version 1, is available at https://psl.noaa.gov/data/gridded/data.ncep.reanalysis.html. Any other data are available upon request from the corresponding author.
REFERENCES


———, R. Lu, and H. Ding, 2022: A decadal intensification in the modulation of spring west tropical Atlantic sea surface temperature to the following winter ENSO after the mid-1980s. Climate Dyn., in press.


