An enhanced influence of sea surface temperature in the tropical northern Atlantic on the following winter ENSO since the early 1980s

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ABSTRACT
Previous studies have revealed a connection between springtime sea surface temperature (SST) in the tropical northern Atlantic (TNA) and the succeeding wintertime El Niño–Southern Oscillation (ENSO). The present analysis demonstrates that the linkage between springtime TNA SST and the following ENSO experiences an obvious interdecadal change around the early 1980s, with the connection being weak before but significant after. After the early 1980s, springtime positive TNA SST anomalies induce an anomalous cyclone over the northeastern subtropical Pacific and an anomalous Walker circulation with a descending branch over the tropical central-eastern Pacific. This leads to anomalous cold SST in the northeastern Pacific and an anomalous anticyclone over the western-central tropical Pacific, with anomalous easterlies to the equatorward side. As such, springtime TNA SST anomalies are followed by wintertime ENSO after the early 1980s. In contrast, before the early 1980s, anomalous cold SST in the northeastern Pacific and related anomalous easterlies over the western-central tropical Pacific are weak, corresponding to springtime positive TNA SST anomalies and resulting in a weak linkage between springtime TNA SST and the succeeding wintertime ENSO. Further investigation implies that the change in the TNA SST–ENSO relationship is probably due to a change in springtime mean precipitation over the tropical Atlantic and South America.

1. Introduction
The tropical northern Atlantic (TNA) sea surface temperature (SST) anomaly pattern is an important component of the tropical Atlantic SST variability, which is characterized by warm (or cold) SST anomalies in the TNA (e.g. Huang, Schopf, and Shukla 2004; Chen, Wu, and Chen 2015). Studies have reported that changes in TNA SST exert marked impacts on climate over many regions (e.g. Uvo et al. 1998; Cassou, Terray, and Phillips 2005; Hatzaki and Wu 2015; Huo et al. 2015). For instance, Uvo et al. (1998) showed that variations of April–May-averaged precipitation over northeastern Brazil are closely connected to the changes in the TNA SST. Hatzaki and Wu (2015) showed that wintertime precipitation over southeastern Europe is strongly impacted by TNA SST. The interannual variability of tropical cyclone frequency in the northwestern Pacific during boreal summer is also highly correlated with preceding springtime TNA SST (e.g. Huo et al. 2015).

A recent study reported that springtime TNA SST correlates well with El Niño–Southern Oscillation (ENSO) events...
in the succeeding winter (Ham et al. 2013). A La Niña event tends to appear in the succeeding winter when a warm SST anomaly occurs in the TNA in the preceding spring (Ham et al. 2013). However, studies have found that connections between TNA SST or ENSO and climate systems are unsteady (e.g. Wu and Wang 2002; Zhou et al. 2007; Chen, Chen, and Wei 2013; Chen, Wu, and Chen 2015; Chen, Yu, and Chen 2015; Cao et al. 2016). Chen, Wu, and Chen (2015) reported that the linkage between wintertime North Atlantic Oscillation and TNA SST underwent marked interdecadal shifts during 1870–2012. Cao et al. (2016) showed that the impact of springtime TNA SST on the succeeding summer northwestern Pacific tropical cyclone frequency has become significantly enhanced during recent decades. Hence, it is natural to question whether the springtime TNA SST–ENSO relationship has changed in the past. Our analysis demonstrates that the linkage between springtime TNA SST and the succeeding wintertime ENSO undergoes a marked interdecadal shift around the early 1980s. The present study investigates this change and the possible factors leading to this change.

### 3. Results

#### 3.1. Interdecadal shift in the springtime TNA SST–ENSO connection

Figure 1(a) displays the standardized and detrended springtime (March–May, MAM) TNA SST index and succeeding winter (December–February, DJF) Niño-3.4 index. The correlation between these two indices reaches −0.35 during 1949–2013, significant at the 0.05 level. This result is in agreement with Ham et al. (2013), whose analysis was based on the period 1980–2010. However, the linkage between MAM TNA SST and the succeeding winter ENSO is unsteady. Figure 1(b) shows the 25-year moving correlation between the MAM TNA SST and DJF Niño-3.4 index. The correlation is significant since the year 1982, but weak before the year 1981 (Figure 1(b)). This indicates that the impact of springtime TNA SST on the succeeding wintertime ENSO experiences an enhancement around the early 1980s. Note that similar results are obtained when different lengths of windows (e.g. 19, 21, and 23 years) are used to calculate the moving correlation (figures not shown).

Next, we compare the anomalies in high- and low-correlation periods to confirm the interdecadal change. According to the moving correlation in Figure 1(b), we select one high-correlation period (1953–1977) and one in the preceding winter (Ham et al. 2013). A La Niña event tends to appear in the succeeding winter when a warm SST anomaly occurs in the TNA in the preceding spring (Ham et al. 2013). However, studies have found that connections between TNA SST or ENSO and climate systems are unsteady (e.g. Wu and Wang 2002; Zhou et al. 2007; Chen, Chen, and Wei 2013; Chen, Wu, and Chen 2015; Chen, Yu, and Chen 2015; Cao et al. 2016). Chen, Wu, and Chen (2015) reported that the linkage between wintertime North Atlantic Oscillation and TNA SST underwent marked interdecadal shifts during 1870–2012. Cao et al. (2016) showed that the impact of springtime TNA SST on the succeeding summer northwestern Pacific tropical cyclone frequency has become significantly enhanced during recent decades. Hence, it is natural to question whether the springtime TNA SST–ENSO relationship has changed in the past. Our analysis demonstrates that the linkage between springtime TNA SST and the succeeding wintertime ENSO undergoes a marked interdecadal shift around the early 1980s. The present study investigates this change and the possible factors leading to this change.

#### 2. Data and methods

The monthly SST data are from the National Oceanic and Atmospheric Administration’s ERSSST.v3b (Extended Reconstructed SST, version 3b) data-set (Smith et al. 2008). ERSSST.v3b is available from 1854 to the present day and has a horizontal resolution of 2° × 2°. The monthly sea level pressure (SLP), precipitation, geopotential height, vertical p-velocity, and horizontal winds are from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis from 1948 to the present day (Kalnay et al. 1996). The precipitation is available on a T62 Gaussian grid; the SLP, geopotential height, and winds are on 2° × 2° grids.

The TNA SST index is defined as region-averaged SST anomalies in the domain (0°–20°N, 60°W–20°E). ENSO variability is represented by the Niño-3.4 index (region-averaged SST anomalies in the domain (5°S–5°N, 120°–170°W)). Studies have demonstrated that the preceding winter ENSO is able to influence the following spring TNA SST via an anomalous atmospheric wave train or Walker circulation (e.g. Huang, Schopf, and Pan 2002). Following Ham et al. (2013) and Ham and Kug (2015), the variability of the spring TNA SST index, which is linearly related to the Niño-3.4 index in the previous winter, is removed as follows:

\[
TNA_{\text{res}} = TNA - r \times \text{Niño-3.4},
\]

where TNA and Niño-3.4 are standardized indices and \( r \) is the correlation coefficient between TNA and Niño-3.4. Removal of the signal related to Niño-3.4 from the spring TNA index ensures that the significant linkage between spring TNA SST and the succeeding winter ENSO is independent from the ENSO cycle. In addition, long-term trends of all-time series are removed before the analysis.

### Figure 1

(a) Standardized and detrended TNA (tropical North Atlantic) SST index in spring (March–May, MAM) and the following winter (December–February, DJF) Niño-3.4 index. (b) The 25-year moving correlation between the MAM TNA SST index and DJF Niño-3.4 index. The dashed line in (b) denotes the correlation is significant at the 0.05 level.
low-correlation period (1986–2010) to conduct comparative analysis. These two periods are selected because the difference in correlation between them is the largest in the study period. Figure 2 displays the wintertime SST, SLP, 850 hPa winds, and 300 hPa geopotential height (Hgt; units: gpm), in December–February, regressed on the standardized spring TNA (tropical North Atlantic) SST index during (a, c, e, g) 1953–1977 and (b, d, f, h) 1986–2010. Anomalies significantly different from zero at the 0.05 level are shaded in (a, b) and (e, h). The shading in (c, d) indicates wind anomalies significantly different from zero at the 0.05 level in either direction.

During 1986–2010, anomalous SST and atmospheric circulation are highly similar to those related to a La Niña event. In particular, significant anomalous cold SST appears in the tropical central-eastern Pacific and a pronounced warm SST anomaly occurs in the western tropical Pacific (Figure 2(b)). The anomalous SLP pattern over the tropical Pacific during 1986–2010 bears a close resemblance to

Figure 2. Anomalies of (a, b) SST (units: °C), (c, d) SLP (units: hPa), (e, f) 850 hPa winds, and (g, h) 300 hPa geopotential height (Hgt; units: gpm), in December–February, regressed on the standardized spring TNA (tropical North Atlantic) SST index during (a, c, e, g) 1953–1977 and (b, d, f, h) 1986–2010. Anomalies significantly different from zero at the 0.05 level are shaded in (a, b) and (e, h). The shading in (c, d) indicates wind anomalies significantly different from zero at the 0.05 level in either direction.
that associated with the Southern Oscillation (e.g. Wang, Wu, and Fu 2000), with pronounced negative and positive SLP anomalies over western and eastern tropical Pacific, respectively (Figure 2(d)). In addition, significant positive SLP anomalies are apparent over the midlatitude North Pacific (Figure 2(d)). At 850 hPa, pronounced anomalous easterlies appear over the central-eastern tropical Pacific (Figure 2(f)). An obvious anomalous anticyclone appears over the Aleutian region, extending eastward to the eastern North Pacific, indicating a weakened Aleutian low. This is in good agreement with previous findings that the intensity of the Aleutian low is below normal during La Niña winters (Wang, Wu, and Fu 2000). In addition, a significant anomalous cyclone occurs over the western tropical Pacific, accompanied by pronounced westerly wind anomalies over the tropical eastern Indian Ocean and easterly wind anomalies over the tropical western-central Pacific (Figure 2(f)). Studies have reported that an anomalous cyclone (anticyclone) over the Northwest Pacific plays a critical role in connecting La Niña (El Niño) events to East Asian climate (e.g. Wang, Wu, and Fu 2000). At 300 hPa, anomalous negative geopotential height appears over the tropical Pacific as a response to anomalous cold SST related to La Niña (Figure 2(h)). In addition, a Pacific–North American teleconnection pattern (Wallace and Gutzler 1981) occurs over the extratropical Pacific (Figure 2(h)).

In contrast, during 1953–1977, significant positive SST anomalies are limited to small regions in the tropical western Pacific and midlatitude North Pacific (Figure 2(a)). In particular, negative SST anomalies in the tropical central-eastern Pacific are much weaker compared to those during 1986–2010 (Figure 2(a) and (b)). The anomalous SLP over the Pacific are weak and insignificant (Figure 2(c)). In addition, a cyclonic circulation anomaly cannot be observed over the tropical western Pacific and an anomalous anticyclone over the midlatitude North Pacific and easterlies over the tropical western-central Pacific are very weak (Figure 2(e)). Furthermore, upper-level geopotential height anomalies are extremely weak over the tropical Pacific (Figure 2(g)). The above results suggest that the MAM TNA SST correlates significantly with the succeeding winter ENSO variability during 1986–2010, whereas the TNA SST–ENSO connection is insignificant during 1953–1977.

3.2. Factors involved in the interdecadal change

The above analyses show that springtime positive TNA SST anomalies are followed by different states in the tropical eastern Pacific in the succeeding winter before and after the early 1980s. In this subsection, we analyze the temporal evolution of SST and atmospheric circulation anomalies related to the spring TNA SST index to understand the factors contributing to this change. Figure 3 shows the springtime SST, 850 hPa winds, 500 hPa omega, and 850 hPa velocity potential anomalies regressed on the simultaneous springtime TNA SST index during 1953–1977 and 1986–2010 separately. Superposed on Figure 3(e) and (f) are the corresponding divergent winds. Figure 4 displays the anomalies of SST and 850 hPa winds in the following summer (June–August, JJA) and autumn (September–November, SON) during 1953–1977 and 1986–2010 separately.

The spatial distributions of SST and wind anomalies during 1986–2010 are similar to those obtained by Ham et al. (2013) for the period 1980–2010. Notable SST warming occurs in the tropical Atlantic, midlatitude North Atlantic and western tropical Pacific, and anomalous cold SST appears in the northeastern subtropical to tropical Pacific (Figure 3(b)). Ham et al. (2013) demonstrated that SST cooling (warming) over the northeastern Pacific is critical to forming and sustaining anomalous easterlies (westerlies) over the western-central tropical Pacific, which further excite a La Niña (El Niño) event via coupled processes (Chen, Yu, and Chen 2014; Chen et al. 2016). The suppressed convection (indicated by downward motion) induced by anomalous cold SST in the northeastern Pacific leads to an anomalous anticyclone over the western-central tropical Pacific, with anomalous easterlies to the equatorward side (Figure 3(b) and (d)), via a Gill-type response (Gill 1980). According to Ham et al. (2013), the formation of anomalous cold SST is due to the anomalous cyclone over the northeastern Pacific induced by the warm SST anomaly in the TNA (Figures 2(b) and 3(b)). From Figure 3(b), a pair of anomalous cyclones appears over the tropical eastern Pacific as a Gill-type atmospheric response to anomalous heating (indicated by upward motion) over the equatorial Atlantic and South America. Note that this anomalous heating is related to anomalous warm SST in the TNA. The anomalous cyclone over the subtropical eastern Pacific further leads to SST cooling and suppressed convective activity through enhancing total wind speed (Ham et al. 2013).

During 1953–1977, SST warming occurs in the tropical Atlantic and western tropical Pacific (Figure 3(a)). However, SST cooling is very weak in the northeastern Pacific, which may be attributable to the weak anomalous cyclone (Figure 3(a)). Correspondingly, anomalous downward motion over the subtropical Pacific and the induced anomalous easterlies over the western-central tropical Pacific are much weaker than those during 1986–2010 (Figure 3(a) and (c)). Hong, Chang, and Hsu (2014) reported that tropical Atlantic SST warming might induce anomalous easterlies over the western-central tropical Pacific via anomalous Walker circulation, with an upward branch over the tropical Atlantic and a downward branch over the tropical
In the tropical Pacific. During 1953–1977, easterly wind anomalies and SST cooling in the tropical Pacific are weak and insignificant in JJA and SON (Figure 4(a) and (c)). In contrast, during 1986–2010, significant negative SST anomalies appear in the tropical central-eastern Pacific in JJA, accompanied by pronounced easterly wind anomalies extending from the tropical western Pacific to central Pacific (Figure 4(b)). The formation of significant negative SST anomalies in the tropical central-eastern Pacific in the following summer is attributable to the easterly wind anomalies over the tropical western-central in the preceding spring through oceanic dynamics (e.g. Ham et al. 2013; Chen et al. 2015). Note that positive feedback exists between the easterly wind and negative SST anomalies in the tropical Pacific during 1986–2010. Via this positive feedback, an apparent La Niña–like SST cooling forms in the tropical central-eastern Pacific in the following autumn (Figure 4(d)), and the easterly wind anomalies over the tropical Pacific (Hong, Chang, and Hsu 2014). The downward branch helps maintain a low-level anticyclone and anomalous easterlies over the western-central tropical Pacific. During 1986–2010, notable low-level (i.e. 850 hPa) convergence anomalies occur over the tropical eastern Atlantic and western tropical Pacific, and marked divergence anomalies appear over the tropical central-eastern Pacific (Figure 3(f)). A pair of anomalous anticyclones occurs over the tropical western-central Pacific (Figure 3(b)). As such, obvious anomalous easterlies form over the western-central tropical Pacific (Figure 3(b)). In contrast, the anomalous low-level divergence over the tropical central-eastern Pacific is much weaker during 1953–1977 than during 1986–2010 (Figure 3(e) and (f)). As a result, the anomalous anticyclone and easterlies over the western-central tropical Pacific are weaker during 1953–1977 than during 1986–2010 (Figure 3(a) and (b)).

Substantial differences in SST and 850 hPa wind anomalies are further observed in the subsequent JJA and SON in the tropical Pacific. During 1953–1977, easterly wind anomalies and SST cooling in the tropical Pacific are weak and insignificant in JJA and SON (Figure 4(a) and (c)). In contrast, during 1986–2010, significant negative SST anomalies appear in the tropical central-eastern Pacific in JJA, accompanied by pronounced easterly wind anomalies extending from the tropical western Pacific to central Pacific (Figure 4(b)). The formation of significant negative SST anomalies in the tropical central-eastern Pacific in the following summer is attributable to the easterly wind anomalies over the tropical western-central in the preceding spring through oceanic dynamics (e.g. Ham et al. 2013; Chen et al. 2015). Note that positive feedback exists between the easterly wind and negative SST anomalies in the tropical Pacific during 1986–2010. Via this positive feedback, an apparent La Niña–like SST cooling forms in the tropical central-eastern Pacific in the following autumn (Figure 4(d)), and the easterly wind anomalies over the tropical Pacific.
the latter than former period (Figure 3(a), (b), (e) and f). Northeasterly wind anomalies to the west of the anomalous cyclone over the subtropical eastern Pacific lead to strong SST cooling via the enhancement of total wind speed during 1986–2010, as the anomalous winds and mean winds are nearly in the same direction (Figure 3(b)). Strong SST cooling and downward motion anomalies during 1986–2010 further induce obvious anomalous easterlies over the tropical western-central Pacific, which contribute to the development of La Niña events in the succeeding winter through positive feedback.

From Figure 3(a) and (b), the magnitude and spatial pattern of warm SST anomalies in the TNA are similar in the two periods. On the other hand, the atmospheric response over the tropical Pacific is stronger during 1986–2010 than during 1953–1977. Next, we investigate why the atmospheric anomalies induced by the springtime TNA SST are stronger during 1986–2010 than during 1953–1977. By calculating the differences in the climatological mean SST in the tropical Atlantic between 1986–2010 and 1953–1977, we find that the difference is small in the tropical Atlantic. As such, the change in the climatological mean SST in the tropical Atlantic cannot explain the interdecadal increase in the linkage between springtime TNA SST and the succeeding winter ENSO around the early 1980s.

The above results imply that anomalous atmospheric circulation related to springtime TNA SST is stronger during 1986–2010 than during 1953–1977. In particular, the anomalous cyclone over the tropical eastern Pacific and anomalous Walker circulation with downward motion over the tropical central-eastern Pacific is stronger during the latter than former period (Figure 3(a), (b), (e) and f). Northeasterly anomalies to the west of the anomalous cyclone over the subtropical eastern Pacific lead to strong SST cooling via the enhancement of total wind speed during 1986–2010, as the anomalous winds and mean winds are nearly in the same direction (Figure 3(b)). Strong SST cooling and downward motion anomalies during 1986–2010 further induce obvious anomalous easterlies over the tropical western-central Pacific, which contribute to the development of La Niña events in the succeeding winter through positive feedback.

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Ham and Kug (2015) investigated a climate model’s ability in reproducing the TNA SST–ENSO linkage. Their results indicated that the model’s ability in capturing the TNA SST–ENSO relationship correlates highly with the model’s ability in simulating the climatological mean precipitation. Specifically, they found that springtime TNA SST can significantly impact the succeeding wintertime ENSO in climate models that have larger climatological mean precipitation over the tropical Atlantic. They indicated that larger climatological mean precipitation provides more beneficial conditions to induce anomalous convection and associated circulation anomalies. Weaker climatological mean precipitation prevents the generation of anomalous convection because climatological downward motion can offset anomalous upward motion to induce convective activity. By contrast, positive SST anomalies can easily lead to anomalous convection when there is larger climatological mean precipitation (i.e. stronger upward motion) (Ham and Kug 2015). For this reason, larger climatological mean precipitation can result in a stronger convective activity response to a given SST anomaly in the TNA, which further leads to a stronger atmospheric circulation response over the tropical Pacific and Atlantic (Ham and Kug 2015).

To confirm whether the climatological mean precipitation change could be a factor for the interdecadal increase in the linkage between springtime TNA SST and the succeeding winter ENSO around the early 1980s, we show in Figure 5 the difference in springtime climatological mean precipitation between 1986–2010 and 1953–1977. Springtime climatological precipitation over the tropical Atlantic and South America is significantly larger during 1986–2010 than during 1953–1977. According to Ham and Kug (2015), larger springtime climatological mean precipitation over the tropical Atlantic and South America leads to stronger atmospheric convection over the east coast of South America, which further results in a larger cyclonic anomaly over the tropical eastern Pacific during 1986–2010 (Figure 3(a) and (b)). Hence, the induced anomalous cold SST over the northeastern subtropical Pacific, easterlies over the western tropical Pacific, and anomalous Walker circulation with a downward branch over the tropical central Pacific, are much stronger during 1986–2010 than during 1953–1977. As a result, the linkage between springtime TNA SST and the succeeding winter ENSO is stronger during 1986–2010 than during 1953–1977.

4. Summary

The present study reveals that the relationship between springtime TNA SST and the succeeding wintertime ENSO undergoes an obvious interdecadal change around the early 1980s. Springtime TNA SST correlates highly with the succeeding winter ENSO after the early 1980s. In contrast, the linkage between the springtime TNA SST and ENSO is not clear before the early 1980s.

A springtime TNA SST–related anomalous cyclone over the northeastern subtropical Pacific and anomalous Walker circulation with a descending branch over the tropical central-eastern Pacific, are stronger during 1986–2010 than during 1953–1977. A stronger anomalous cyclone over the northeastern subtropical Pacific during 1986–2010 contributes to stronger anomalous cold SST, and further leads to a stronger anomalous anticyclone and easterlies over the western-central tropical Pacific. In addition, stronger anomalous descending motion over the tropical central-eastern Pacific induced by the anomalous Walker circulation also contributes to the stronger anticyclone and easterlies anomalies over the western-central tropical Pacific during 1986–2010 than during 1953–1977.

Further investigation indicates that the change in anomalous atmospheric circulation related to springtime TNA SST anomalies may be due to a change in climatological mean precipitation over the tropical Atlantic and South America. Specifically, springtime climatological mean precipitation over most regions of the tropical Atlantic and South America is larger during 1986–2010 than during 1953–1977. Given similar SST anomalies, stronger climatological mean precipitation during the latter period may explain the stronger atmospheric response to the warm SST in the TNA. The present analysis implies that we should take the interdecadal shift into account when employing springtime TNA SST anomalies to forecast ENSO events in the succeeding winter.

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