Enhanced Influences of Tropical Atlantic SST on WNP–NIO Atmosphere–Ocean Coupling since the Early 1980s

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ABSTRACT

This paper reports a new finding and related mechanism: the forcing effect of the tropical Atlantic (TA) sea surface temperature (SST) on the atmosphere–ocean coupling in the western North Pacific (WNP) and northern Indian Ocean (NIO). Since the early 1980s, the TA SST has increased and, notably, exhibited an enhanced interannual statistical relationship with the WNP subtropical high and NIO SST in boreal summer. Empirical diagnostics reveal the following spatial pattern linking the TA SST and the atmosphere–ocean coupling in the Pacific and Indian Ocean: 1) a cyclonic (anticyclonic) circulation pair straddling the equator over the eastern Pacific, 2) an anticyclonic (cyclonic) circulation pair straddling the equator in the WNP and Indian Ocean, 3) overturning circulation with ascending (descending) and descending (ascending) anomalies over the TA and tropical western Pacific, respectively, and 4) positive (negative) SST anomaly in the TA and NIO. The characteristics of this pattern are consistent with those of a WNP–NIO coupling pattern identified in a previous study. Empirical diagnostics and numerical simulations indicate that the TA SST serves as a forcing to induce low-level divergence and streamfunction anomalies in the Indian Ocean and the western Pacific. The latter in turn induces anomalous heat storage in the NIO and enhances the WNP–NIO coupling system, which is an intrinsic pattern engendered by the atmosphere–ocean interaction in the region. Without the remote influence of the TA SST forcing, the WNP–NIO coupling pattern and its impacts on the summer monsoon and TC variability in South Asia, East Asia, and the WNP would be considerably less significant than observed.

1. Introduction

The western North Pacific subtropical high (WNPSH) strongly influences climate variability and tropical cyclone (TC) activity in the western North Pacific (WNP; Hsu et al. 2014). Several mechanisms have been proposed for explaining the interannual variability of the WNPSH. Wang et al. (2000) proposed a wind–evaporation–sea surface temperature (WES) feedback mechanism for explaining the occurrence of an enhanced WNPSH following a mature El Niño phase. During a mature El Niño phase in boreal winter, the northeasterly anomaly triggered by the negative subtropical SST anomaly in the WNP (i.e., the horseshoe structure surrounding the warm SST in the tropical eastern Pacific) enhances the mean northeasterly trade winds and triggers positive feedback between the induced anticyclonic anomaly and the cooling of the WNP SST. The WNPSH becomes self-sustained and persists into the following summer. Xie et al. (2009) proposed that the warmer tropical Indian Ocean acts as a thermal capacitor following an El Niño event (Yang et al. 2007) to force equatorial Kelvin waves into the subsequent summer, consequently inducing Ekman divergence and enhancing the subtropical high in the WNP. Furthermore, Xie et al. (2010) suggested that the enhanced influence of El Niño after the mid-1970s led to a larger SST response in the Indian Ocean and therefore a stronger influence on the WNPSH. Other studies (e.g., Shen et al. 2001; Wu et al. 2010; Chowdary et al. 2011; Chung et al. 2011) have also identified SST forcing on the WNPSH from adjacent oceans, such as the Indian Ocean, Maritime Continent, WNP, and equatorial eastern Pacific.
Wang et al. (2013) provided an integrated perspective by proposing an atmosphere–ocean interaction mode in the WNP and northern Indian Ocean (hereafter denoted as the WNP–NIO coupling pattern) in boreal summer. When the NIO SST is sufficiently warm to sustain the WNPSH, the anomalous northeasterly in the southeastern flank of the WNPSH reinforces the WES feedback in the WNP and continuously enhances the WNPSH. The enhanced WNPSH also induces anomalous easterlies in the NIO, weakens the South Asian monsoonal southwesterly, and warms the NIO. A positive feedback system between the NIO and WNP is therefore established. Xiang et al. (2013) further indicated that in addition to the easterly anomalies, the anomalously strong convection occurring in the climatologically convection-active region is a key process for WES feedback. Accordingly, they proposed a local convection–wind–evaporation–SST feedback system and emphasized that the influence of the WNP is more efficient in maintaining the WNPSH than the remote forcing from the El Niño–like SST anomaly.

Hong et al. (2014) reported a relatively unknown remote forcing: anomalous SST in the northern tropical Atlantic (TA). Similar influences of the TA SST on the summer WNP climate and TC activity have also been reported (e.g., Chen et al. 2015; Huo et al. 2015; Yu et al. 2015). Hong et al. (2014) also observed that the TA SST has had a significantly stronger influence on the WNPSH since the early 1980s. This TA SST variation, which was noted by Ham et al. (2013a) to have influenced El Niño since the early 1980s. This TA SST variation, which was also reported (e.g., Chen et al. 2015; Huo et al. 2015; Yu et al. 2015). Hong et al. (2014) also observed that the TA SST has had a significantly stronger influence on the WNPSH since the early 1980s. This TA SST variation, which was also noted by Ham et al. (2013a) to have influenced El Niño–Southern Oscillation (ENSO), is different from the Atlantic equatorial zonal mode (also called the Atlantic Niño) located in the tropical southern Atlantic. The Atlantic Niño mode sustains itself through an air–sea interaction similar to that in the Pacific during the peak phase in boreal summer (Keenlyside and Latif 2007). In its warm phase, this mode triggers a La Niña–like SST distribution in the eastern Pacific via an anomalous Walker circulation (Rodríguez-Fonseca et al. 2009; Ding et al. 2012; Ham et al. 2013b; Polo et al. 2015) and also affects the Indian monsoon rainfall through the Gill–Matsuno mechanism (Kucharski et al. 2009).

The influence of the TA SST on the WNP and NIO is poorly understood. Therefore, the current study explored the mechanism inducing the influence of the TA SST anomaly on the atmosphere–ocean coupling in the WNP and NIO. The major aims of this study are two-fold: 1) to provide more evidence of the influences of the TA SST on the WNPSH, and 2) to explore the responsible mechanisms on the basis of empirical diagnostics and numerical simulations by using an AGCM coupled to a slab ocean model (SOM). The rest of this paper is organized as follows. Section 2 introduces the data, methodology, and model used in this study. In section 3, the potential effect of the TA SST on the NIO SST and the WNPSH is explored on the basis of data analysis. The characteristics and temporal evolution of an atmosphere–ocean coupled pattern linking the variation of the TA SST, NIO SST, and WNPSH are explored in section 4. The mechanism explaining the effect of the TA SST on both the NIO SST and WNPSH is proposed and verified in section 5 on the basis of three sets of numerical experiments. Section 6 presents the conclusions and discussion.

2. Data, methodology, and model
   a. Data

Datasets used in this study are outlined as follows: 1) monthly atmospheric data from the National Centers for Environmental Prediction–National Center for Atmospheric Research Reanalysis I (Kalnay et al. 1996), 2) monthly SST data from NOAA Extended Reconstruction SST v3b (Smith et al. 2008), 3) monthly rainfall data from the Global Precipitation Climatology Project version 2.2 (Adler et al. 2003), and 4) TC tracks from the International Best Track Archive for Climate Stewardship v03r05 (Schreck et al. 2014).

Hong et al. (2014) identified that in boreal summer [defined herein as July and August (JA)], both the variance of the WNPSH and its correlation with the TA SST on interannual time scales increased significantly after the early 1980s. To investigate this change in interannual characteristics, data were separated into an earlier epoch (1948–80) and a later epoch (1981–2012). Nine-year running means and long-term trends were removed to isolate the interannual variation.

b. Methodology

Climate indices were defined to represent relevant phenomena investigated in this study. The TA index representing the interannual variation of the tropical North Atlantic SST was defined as the standardized SST averaged over the region 0°–20°N, 25°–80°W. Other indices were defined in the same manner: 1) The NIO index (0°–20°N, 50°–100°E) and the eastern-central Pacific (ECP) index (5°S–5°N, 170°–240°E) for SST were defined to represent the interannual SST variation in the NIO and eastern-central Pacific, respectively; and 2) the WNPSH index (15°–25°N, 130°–150°E) for 850-hPa streamfunction was defined to represent the interannual fluctuation of the WNPSH.

Partial correlation and singular value decomposition (SVD) were applied to extract climatic signals. Partial correlation is a method of calculating correlations on a plane that is orthogonal to one or more specified vectors
Specifically, this method pinpoints what would have happened if the influence of one or several particular variables had been removed. We evaluated the relative influence of various factors on a particular parameter by comparing the regular and partial correlations. SVD is a method of identifying a series of paired variability modes between variables. Such modes possess the tightest relationship between paired components. The pairs are designated numerically, such as SVD1 and SVD2, in descending order (i.e., from the highest to the lowest squared covariance fraction) that represents the degree of importance (Bretherton et al. 1992). Student's $t$ test was applied to evaluate the significance of derived statistics. The level of significance was set at 5%, unless mentioned otherwise.

c. Model

The model used in this study is the atmospheric general circulation model version 41 developed at the Abdus Salam International Centre for Theoretical Physics (ICTP AGCM); this model is also called “SPEEDY” (for “simplified parameterizations, primitive equation dynamics”; Kucharski et al. 2013). This model is an intermediate-complexity AGCM that can be forced with prescribed monthly SST anomaly (SSTA) or coupled with a SOM. The AGCM contains eight vertical levels with a horizontal resolution of T30. In the SOM, the depth of the mixed layer that is held constant throughout the whole simulation period varies from 60 m in the extratropics to 40 m in the tropics. The variation of the mixed-layer temperature anomaly is derived from the net heat flux into the ocean (i.e., the sum of shortwave and longwave radiation, and sensible and latent heat flux). The SPEEDY model is used to evaluate the effect of the TA SST on the forcing of the NIO SST and the WNPSH and to reveal how the TA SST enhances the WNP–NIO atmosphere–ocean coupling.

3. Influence of the TA SST

a. Atmosphere–ocean perturbations in the Indian Ocean and WNP

According to Hong et al. (2014), the interannual fluctuation of the WNPSH and the associated large-scale circulation has amplified and become more significantly correlated with TA SST after the early 1980s. The amplification is also observed in the TA index as shown in Fig. 1a, which demonstrates an enhanced amplitude envelope function (i.e., low-pass filtered squared amplitude) after 1980. This synchronization implies that the amplification of the TA SST exerts an enhanced effect on the WNPSH, leading to the strengthened variability of the WNPSH.

Figures 1b and 1c illustrate the regression of SST and 850-hPa streamfunction and rotational winds on the TA index in JA during the early and later epoch, respectively. In the later epoch, when the TA SST was anomalously warm, an anomalous anticyclonic circulation over South Asia and the WNP as well as an anomalously warm SST in the NIO and the western Pacific west of 150°E were evident. By contrast, in the earlier epoch, although warmer SST was observed in the eastern Indian Ocean, no statistically significant coherent atmospheric circulation was evident. Another notable disparity was the observation of warmer and cooler SSTs in the central-eastern
Pacific in the earlier and later epochs, respectively. The cooler SST in the later epoch may be related to the recent findings regarding the effects of the TA SST on the La Niña–like distribution in the equatorial eastern Pacific, as described in the introduction. The observed SST and circulation anomalies in the later epoch resemble the WNP–NIO coupling pattern suggested by Wang et al. (2013). This prevailing circulation features Rossby waves with strong off-equator rotational winds, rather than equatorial Kelvin waves that have maximum wind speed at the equator and decay exponentially with increasing latitudes. Comparing the geopotential height, streamfunction, and wind anomalies (not shown) also indicated the characteristics of Rossby waves, rather than those of Kelvin waves. The considerable contrast before and after the early 1980s reported herein was not identified by Wang et al. (2013) because they analyzed only data obtained after 1980.

Considering the stronger influence in the later epoch, we further investigated the relationships among circulation, precipitation, and TC tracks in the anomalously warm and cool TA SST summer periods during this epoch. The results (Fig. 2) revealed the following perturbations: an anticyclonic (cyclonic) anomaly over South Asia and the WNP, and less (more) precipitation and weaker (stronger) TC activity in the tropical WNP during the anomalously warm (cool) TA SST years. These results are consistent with recent findings of TA SST influences on the WNP TC activity (Yu et al. 2015; Huo et al. 2015). Our findings further suggest that the TA SST may have contributed to this enhanced control of the WNPSH on TCs since the early 1980s.

b. Net influence of the TA SST

Several studies have described the notable effects of the NIO and ECP SST on the enhancement of the WNPSH. To isolate the effect of the TA SST, Hong et al. (2014) calculated partial correlations by removing the NIO and ECP indices from the regular correlation with the TA index; they found that the NIO and ECP SST did not notably influence the correlation pattern. To more clearly delineate the relative influences of various SSTs, we isolated the influence of the SST in a region-wise manner. The regular correlation of the 850-hPa stream-function with the TA index in JA (Fig. 3a) was characterized by a quadrupole structure: a cyclonic anomaly pair in the eastern Pacific–TA region and an anticyclonic anomaly pair in the WNP–NIO region when the TA SST was anomalously warmer. This quadrupole structure did not change greatly when the ECP SST was removed (i.e., partial correlation in Fig. 3b), indicating that the ECP SST exerted little influence on the correlation. When the NIO SST was removed, a similar structure was observed, but with a weaker correlation in the WNP–NIO region when the TA SST was anomalously warmer. This quadrupole structure did not change greatly when the ECP SST was removed (i.e., partial correlation in Fig. 3b), indicating that the ECP SST exerted little influence on the correlation. When the NIO SST was removed, a similar structure was observed, but with a weaker correlation in the WNP–NIO region. When both the ECP and NIO SSTs were removed, the quadrupole structure was still evident, whereas the correlations in the WNP–NIO region were considerably
weaker (Fig. 3d). The cyclonic anomaly in the eastern Pacific–TA region, which was the most robust feature in all four calculations, is possibly the direct atmospheric response to the warm TA SST through the Gill–Matsuno mechanism (Gill 1980). The significantly weakened correlation in the WNP–NIO region when only the TA SST was considered revealed that although the TA SST exerted a notable influence on the WNP–Indian Ocean circulation, it could not solely account for the interannual variation of this circulation. A joint effect with SSTs in other basins (e.g., NIO) seemed necessary to produce the observed statistical relationship.

c. Variability modes

To further delineate the statistical relationship between the low-level atmospheric circulation and the SST, we applied SVD analysis to the tropical SST (40°S–40°N) and the 850-hPa streamfunction over the Pacific and the Indian Ocean (60°S–60°N, 60°E–60°W) during JA to determine whether the quadrupole structure emerged as a leading pattern and how it was related to the SST. The data of the entire 1948–2012 period were used to evaluate the robustness of the reported pattern and the interdecadal shift.

In the first SVD (SVD1; Fig. 4a), the SST pattern characterized by negative and positive anomalies in the central-eastern Pacific and western Pacific, respectively, was similar to a mature La Niña pattern. The corresponding streamfunction pattern exhibited two large-scale anticyclonic cells over the Pacific and South Asia regions straddling the equator. Although the northern anticyclonic cell exhibited the strongest signal over the equatorial central Pacific, the signals over the tropical WNP were also strong. This pattern has a weak correlation with the SST in the equatorial Atlantic, which is south of the TA SST region considered in this study.

The second SVD mode (SVD2; Fig. 4b) exhibited a pattern similar to that shown in Figs. 1c and 3a: warm SSTs in the TA and NIO, and a quadrupole circulation structure over the Pacific and Indian Ocean. The SVD2 time series also demonstrated a high correlation (0.66) with the TA index (Fig. 4c). The correlation was higher in the later epoch than in the earlier epoch (0.71 vs 0.59). To further confirm the statistical relationships between various indices, correlation coefficients between various indices and the SVD2 time series in both epochs were calculated (Table 1). A decadal shift around 1980 was again evident in the correlation coefficients with the WNPSH, TA, and NIO indices: The correlations in the later epoch were significantly stronger than those in the earlier epoch. SVD2 was barely correlated with the ECP index during the summer. Instead, it demonstrated a stronger correlation with the ECP index during the winter, reflecting the known delayed ENSO effect on the SST in the TA and the WNPSH. In contrast to the other indices, we observed no significant changes in the correlations between the earlier and later epochs for the ECP index. SVD2 confirms that the relationship between the TA SST and the quadrupole circulation structure, as identified in the one-point correlation approach, is indeed a critical interannual pattern that contributes significant variability to the atmospheric circulation and SST in the Pacific–NIO region and the TA. This relationship may also exert a strong effect on the subtropical high and TC activity in the WNP. The relationships among the SST, circulation, and convection in addition to the mechanisms connecting the SST and streamfunction anomalies were further explored, as described in the following sections.

FIG. 3. (a) Correlation coefficients between the 850-hPa streamfunction and the TA index in the later epoch. (b),(c) Partial correlation coefficients derived when the ECP and NIO indices, respectively, were removed. (d) As in (b), but with both NIO and ECP indices removed. Dotted shading marks represent the correlation coefficients exceeding the 5% level of significance.
4. WNP–NIO coupling pattern and TA SST

In this section, we focused on the temporal evolution of SVD2 in the second epoch when the enhancement of the TA SST and the WNP–NIO coupling was observed. Regular and partial lag correlations of SVD2 with the SST, velocity potential, and streamfunction were computed. As shown in Fig. 5a, the warm SST in the TA and NIO during JA was preceded by a warm TA during March–April (MA; note that weaker correlations were also observed in the previous winter). A warm SST persisted from previous winter to spring was also observed in the ECP. The warming in the TA and NIO became more significant from spring to summer, whereas the warm SST in ECP decayed. This lead–lag relationship is consistent with previous findings that an El Niño event is often followed by a warm TA in the following spring (e.g., Enfield and Mayer 1997; Alexander et al. 2002). We repeated the lag correlation calculation by removing the DJF ECP SST and found that the SST pattern in the Atlantic, Indian Ocean, and WNP (not shown) during May–August was essentially the same as that shown in Fig. 5a. This indicated that although the winter ECP SST may influence the TA SST in the following spring, this influence may not be directly associated with the warm TA and NIO SST in the summer. Figure 5b illustrates partial lag correlation maps with the TA SST removed, indicating the development of positive and negative SST anomalies in the Arabian Sea and the equatorial western Pacific, respectively. However, the correlations in the TA, Bay of Bengal, and South China Sea disappeared. The contrast between Figs. 5a and 5b suggests the potential effect of the TA SST in inducing the SST in the eastern NIO.

The warm TA and cool western Pacific SST structure during MA (Fig. 5a) was accompanied by an east–west Walker circulation-like anomaly, with a low-level convergence anomaly occurring over the TA and a corresponding divergence anomaly occurring in the western

<table>
<thead>
<tr>
<th>WNPSH</th>
<th>TA</th>
<th>NIO</th>
<th>ECP (JA)</th>
<th>ECP (DJF)</th>
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<tbody>
<tr>
<td>Earlier</td>
<td>0.44</td>
<td>0.59</td>
<td>0.20</td>
<td>0.12</td>
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<tr>
<td>Later</td>
<td>0.75</td>
<td>0.71</td>
<td>0.62</td>
<td>−0.12</td>
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Fig. 4. (left) SST and (right) streamfunction patterns of (a) SVD1 and (b) SVD2. (c) Time series of the TA index (red) and SVD2 (streamfunction; black). Correlation coefficients between time series in different epochs are shown below the curves.

TABLE 1. Correlation coefficients between the time series of the streamfunction part of SVD2 and various indices in two epochs. Numbers in bold indicate significant differences between the epochs.
Pacific (Fig. 6a). This convergence–divergence dipole was associated with a cyclonic circulation pair over the TA and the eastern Pacific (Fig. 6b). By May–June (MJ), when the convergence–divergence dipole and cyclonic anomaly pair weakened slightly, the anticyclonic pair in the WNP and Indian Ocean started developing. Two months later (in JA), both the quadrupole circulation structure and convergence–divergence dipole adequately developed and coupled in a similar manner to the Gill–Matsuno mechanism. A similar evolution, but with weaker correlations, was observed when the lag correlation was computed by removing the TA SST (Figs. 6c,d). Removing only the ECP SST did not affect the evolution observed in Figs. 6c and 6d (not shown), suggesting the dominant effect of the NIO SST on SVD2. When both the ECP and NIO SSTs were removed, the evolution from March to June (Figs. 6a–d) was not discernible (Figs. 6e,f). Notably, the coupled convergence–divergence dipole and quadrupole circulation pattern with a strength equivalent to that observed in the regular correlation calculation emerged in JA. The contrasts among the three lag correlation calculations suggested that although the TA SST has little direct effect on the quadrupole structure during the developing phase, it has a significant amplification effect on the structure in the summer. By contrast, the NIO SST plays a key role in inducing both the convergence–divergence dipole and quadrupole structure during the evolution from spring to summer.

To further understand the role of the NIO SST, we examined the lag correlation maps (Fig. 5). A warming in the NIO was evident in MJ before the full onset of SVD2 in the summer (Fig. 5a). This warming was not observed in the calculation when the TA SST was removed (Fig. 5b), suggesting the key role of the TA SST in inducing the warming in the NIO. The influence of the TA SST on the NIO SST was further explored by calculating lag correlations with 10-m winds and net surface heat fluxes in the WNP and Indian Ocean. The same calculations conducted for all flux terms indicate the dominant effect of the latent heat flux. The results (Fig. 7a) indicated easterly anomalies and positive (downward) net heat fluxes in the NIO during MJ. The easterly anomaly is a reflection of a weaker southwesterly in the NIO that prevails in this season. A weaker southwesterly extracts less heat (red shading indicating a downward heat flux anomaly) from the ocean surface and therefore tends to warm the NIO. When the anticyclonic anomaly is fully developed in summer, the ocean warming in the NIO and WNP is further enhanced because of the considerable reduction in heat loss (Fig. 7b). The mutual enhancement between the anomalous low-level circulation and the SST was evident. When the TA SST was removed, the anomalous easterlies, net downward heat fluxes, and SST warming in the NIO was significantly reduced (Figs. 7c,d). Regarding our observations after the TA SST was removed from the calculation, comparing the results in Fig. 5b with those in Figs. 6c and 6d shows that the convergence–divergence dipole and anticyclonic anomaly in the WNP and NIO during JA are closely associated with the negative SST anomaly in the WNP and the positive SST anomaly in the Arabian Sea. This spatial relationship resembles the WNP–NIO coupling pattern identified by Wang et al. (2013) and suggests the existence of a self-sustained atmosphere–ocean coupling in the region. Although the system is not necessarily directly associated with the TA SST, a considerably stronger anticyclonic anomaly and more widely spread warm SST anomaly were observed in the regular correlation when the TA SST was included (i.e., Figs. 5a and 6a,b). Previous studies (e.g., Hong et al. 2014; Xie et al. 2009) have demonstrated that a warmer NIO can enhance the anticyclonic anomaly that includes the WNPSH. Hence, the TA SST plays a role in enhancing the WNP–NIO coupling pattern. On the basis of the described results, we hypothesized that the amplified TA SST after the early 1980s enhanced its forcing on the WNP–NIO coupling pattern and indirectly exerted a greater impact on the
NIO SST, Asian monsoon trough, and subtropical high and TC activity in the WNP. This hypothesis was validated by numerical simulations, as described in the next section.

5. Numerical experiments

We conducted three numerical experiments to evaluate our hypothesis. Each experiment contained five members of 100-yr (1911 to 2010) simulation involving different initial conditions. The results of the five simulation members were averaged and analyzed. The climatological monthly SST was prescribed globally in all three experiments, except in the specified regions in which the AGCM either interacted with SOM or was forced by observed SST anomalies. In the experiment designed for evaluating the forcing effect of the TA SST (Exp_TA), the observed monthly SST of each year was superimposed on the climatological monthly SST in the TA region ($30^\circ S$–$30^\circ N$) to simulate the influences of the TA SST on the interannual variability of the global atmospheric circulation. The second experiment entailed evaluating coupled patterns (Exp_cup) in which the atmosphere–ocean interaction was considered only in the tropical Pacific and Indian Ocean ($30^\circ S$–$30^\circ N$), whereas the climatological monthly SST was prescribed in other ocean basins. Specifically, the atmosphere–ocean interaction in this region was the only major mechanism inducing interannual variability. The third experiment (Exp_cupTA) involved combining the Exp_TA and Exp_cup experiments by considering both the TA SST forcing and atmosphere–ocean coupling in the tropical Pacific and Indian Ocean. We determined the relative and combined effects of tropical SST forcing.
and the atmosphere–ocean interaction on the WNP–NIO interannual variability by comparing the results of the three experiments.

a. SVD patterns

SVD analysis was applied to the outputs of the ensemble-averaged simulations from 1948 to 2010 in three experiments to extract the leading coupled structure. In the Exp_cupTA experiment (Fig. 8a), SVD1 closely reflected the observed SVD2 and it featured a quadrupole circulation structure over the Pacific–Indian Ocean region and SST anomalies in the TA and NIO. The forcing exerted by the TA SSTA and the atmosphere–ocean coupling were effectively combined to reproduce the major interannual variability in the region as well as that of the WNP. The perturbations in the tropical eastern Pacific were not properly simulated because the SPEEDY model does not consider ocean circulation and therefore does not simulate ENSO-like variability. The high similarity between the observed SVD2 and SVD1 in this simulation (except the SST in the eastern Pacific) also confirmed that the phenomena explored in this study were essentially independent of ENSO variability.

The atmosphere–ocean interaction and the TA SST can be regarded as an internal process and an external forcing, respectively, in the model. In the Exp_TA experiment (Fig. 8b), SVD1 exhibited a Pacific cyclonic (anticyclonic) circulation pair associated with a warm (cool) TA SST. A comparison with those in the observation and Exp_cupTA experiment indicates that the anomalous TA SST engendered the observed anomalous circulation pair over the eastern Pacific, but forced circulation anomalies in the western Pacific and Indian

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**Fig. 7.** Correlation patterns of net heat fluxes into the ocean (shading) and 10-m winds on the observed SVD2 during (a) MJ and (b) JA. Net heat flux is defined as the sum of the net longwave radiation, net shortwave radiation, latent heat flux, and sensible heat flux. Only wind vectors with at least one component exceeding the 5% level of significance are plotted. Dotted shading marks represent net heat fluxes exceeding the 5% level of significance. (c),(d) As in (a),(b), but for partial correlations derived when the TA SST in MJ was removed.
Ocean that are in an opposite phase to the observation. SVD1 of the Exp_cup experiment (Fig. 8c) exhibited a circumglobal anticyclonic circulation pair in the tropics and a warm SST in the NIO and a cool SST in the tropical eastern and southeastern Pacific. The easterly anomalies inferred from the streamfunction anomaly countered the prevailing climatological southwesterly in the NIO and enhanced the prevailing climatological easterly in the eastern Pacific. These anomalous winds would extract less and more heat from the ocean surface and lead to warmer and cooler SSTs in the respective ocean basins. Notably, a certain combination of the characteristics of SVD1 associated with the Exp_TA and Exp_cup experiments may yield a circulation–SST pattern similar to that of SVD1 of the Exp_cupTA experiment and the observed SVD2. To achieve such a combination, the TA SST forcing and the atmosphere–ocean interaction must be the essential factors inducing the circulation pair over the eastern Pacific and over the western Pacific and Indian Ocean, respectively. Clearly, the atmosphere–ocean interaction is not the sole factor engendering the circulation–SST pattern in the western Pacific and Indian Ocean, as suggested by the observations and the Exp_cupTA experiment. In addition, the indirect influence of the TA SST, which is further explored subsequently in this paper, must be considered.

b. Mechanism verification

1) CONVERGENCE–DIVERGENCE DIPOLE AND QUADRUPOLE CIRCULATION STRUCTURE

Figure 9 shows the temporal evolutions of the velocity potential and streamfunction associated with SVD1s extracted from the three experiments. In the Exp_cupTA experiment (Figs. 9a,b), a growing convergence–divergence dipole and a quadrupole circulation structure, similar to those in the observation (Figs. 6a,b), were identified. When the observed TA SST was considered as the only forcing in the Exp_TA experiment, a convergence–divergence dipole and an anticyclonic pair over South Asia and the Indian Ocean were formed as early as in MA (Figs. 9c,d), followed by the emergence of a quadrupole circulation structure similar to those in the observation (Figs. 6a,b), were identified. When the observed TA SST was considered as the only forcing in the Exp_TA experiment, a convergence–divergence dipole and an anticyclonic pair over South Asia and the Indian Ocean were formed as early as in MA (Figs. 9c,d), followed by the emergence of a quadrupole circulation structure in MJ. The phase relationship between the convergence–divergence dipole and quadrupole circulation structure in MJ is consistent with the Gill–Matsuno mechanism, suggesting that a warm TA SST can induce an ascending branch over the TA and a descending branch in the tropical western Pacific in addition to inducing corresponding rotational circulations. Although the simulated divergent–rotational flow pattern was similar to the observed pattern and to the...
pattern in the Exp_cupTA experiment before the summer, unrealistic features developed in the summer: 1) an extra descending branch over the Indian Ocean and strong cyclonic anomalies over the western Pacific, and 2) an anticyclonic pair that was unrealistically restricted over Africa and the western Indian Ocean during the warm phase of the TA SST. This indicated that the TA SST was not the proper driving force for the observed divergent and rotational circulation in the summer. As presented subsequently, an atmosphere–ocean interaction may correct this unrealistic development in the summer.

In the Exp_cup experiment (Figs. 9e,f), major divergent and rotational circulation perturbations did not appear until JA. The anticyclonic circulation prevailing over the Pacific and Indian Ocean was associated with an anomalous convergence over the western Indian Ocean and the western central Pacific, and an anomalous divergence over Central America.

Although the atmosphere–ocean interaction induced unrealistic circulation in the eastern Pacific, it induced a realistic anticyclonic circulation pair over the western Pacific and Indian Ocean. Therefore, the atmosphere–ocean coupling in the western Pacific and the Indian Ocean tended to counterbalance the unrealistic atmospheric responses to the TA SST forcing. This counterbalancing effect seemed to be amplified in the Exp_cupTA experiment, possibly because of the mutual enhancement between the atmosphere and the ocean, and resulted in the realistic circulation when both the TA SST forcing and atmosphere–ocean coupling were considered.

2) SURFACE WIND AND HEAT FLUX

The surface heat fluxes illustrated in Fig. 7 indicate that the NIO warming in late spring is a possible precondition of a favorable circumstance for amplifying
the WNP–NIO atmosphere–ocean coupling pattern. Comparing the three experiments clearly revealed this preconditioning effect. Figure 10 shows the correlated surface wind and net heat flux into the ocean during MJ and JA with the SVD1 of the three experiments. In the Exp_cupTA experiment (Fig. 10a), the heat fluxes into the NIO increased from MJ to JA, and they were accompanied by the development of northeasterly anomalies. This feature was consistent with the observation (Fig. 7).

When the atmosphere–ocean coupling was not considered (Exp_TA; Fig. 10b), the TA SSTA forced northeasterly and downward surface heat flux anomalies over the NIO. Although similar to those in the Exp_cupTA experiment, these heat fluxes did not warm the ocean temperature because the observed climatological SST was assigned to this region in the Exp_TA experiment. Therefore, no oceanic feedback to the atmosphere existed. This was why a low-level convergence anomaly, which typically occurs in the event of a positive SST anomaly, did not develop over the NIO; instead, a low-level divergence anomaly remotely forced by a positive TA SSTA developed. Notably, this divergence anomaly contributed to maintaining the northeasterly anomaly and downward surface fluxes in the NIO during JA.

Similar northeasterly and surface heat flux anomalies but with considerably weaker amplitudes were also simulated in the Exp_cup experiment (Fig. 10c). As mentioned, these features were markedly stronger in the Exp_cupTA experiment that entailed considering TA SSTA forcing. Clearly, the downward heat flux anomalies engendered by the TA SSTA warmed the NIO when the coupling was allowed to function and triggered a positive feedback between the atmosphere and the ocean. Comparing the three experiments indicated that the TA SST forcing induced anomalies mainly in the Arabian Sea and Bay of Bengal, whereas the atmosphere–ocean interaction was most active in the Bay of Bengal and South China Sea. A combination of both effects resulted in a more widespread response (i.e., from the Arabian Sea to the South China Sea) in the Exp_cupTA experiment. A similar contrast could also be inferred by comparing partial correlation maps with and without TA SSTA shown in Fig. 7. These results suggested that the TA SST forcing enhanced the intrinsic atmosphere–ocean interaction in the NIO, thus facilitating the intensification of the WNP–NIO coupling pattern, which would be unrealistically weak without an external forcing such as the TA SSTA.

3) LINKAGE BETWEEN THE TA SSTA AND DIVERGENCE ANOMALY IN THE TROPICAL WESTERN PACIFIC

As discussed above, the divergence anomaly in the tropical western Pacific plays the key role in inducing Rossby wave–like perturbation in the NIO–WNP region. We propose that the warm SSTA in the tropical Atlantic induces a zonally overturning circulation with ascending over the tropical Atlantic and descending over the tropical western Pacific. The latter results in low-level divergence in the western Pacific and induces
the anticyclonic perturbations. To illustrate this mechanism more clearly, an extra experiment by prescribing diabatic heating in the Exp_cup experiment was conducted. Instead of prescribing SST forcing, a deep heating with a profile peaking near 400 hPa is prescribed over the tropical North Atlantic (0°–25°N, 80°–10°W) during March–August in the heating experiment. The model setup of the heating experiment is the same as in the Exp_cup experiment except the prescribed heating. The simulation was conducted for 100 years and the results of last 50 years were analyzed. Differences between 50-yr means of the heating and Exp_cup experiments are shown in Fig. 11. The results indicate that the prescribed diabatic heating over the tropical North Atlantic is able to trigger upper-level convergence and low-level divergence anomalies over the western Pacific (Fig. 11a) and the associated quadrupole streamfunction anomalies (Fig. 11b). Similar responses were also simulated in our previous study on the record-breaking WNPSH in 2010 summer (Hong et al. 2015). Although subsidence may be induced in any direction in response to the anomalous heating over the tropical Atlantic, the tropical western Pacific is the most active region of tropical convection and is likely to respond most vigorously. The anomalous low-level convergence can therefore force and maintain a Rossby wave–like response in the western Pacific and Indian Ocean. Atmosphere–ocean interaction further enhances the NIO–WNP coupling pattern.

6. Summary and discussion

Several studies have reported the remote influences of the Atlantic SST on the climate variability in South Asia, the tropical eastern Pacific, and the monsoon and TC activity in East Asia and the WNP. In this paper, we report a new finding and related mechanism: the forcing effect of the TA SST on the atmosphere–ocean coupling in the WNP and NIO. Since the early 1980s, the interannual covariability between the TA SST and the atmospheric circulation–SST in the WNP and NIO regions in summer has been significantly enhanced. The amplitudes of related interannual variations have also increased since then. This study explored this change through empirical diagnostics and numerical simulations. Statistical analyses showed that in JA, during which the TA SST is warmer (cooler), there are higher (lower) SSTs in the NIO as well as a stronger (weaker) subtropical anticyclone, less (more) precipitation, and weaker (stronger) TC activity in the WNP.

This covariability of the TA SST and the atmospheric circulation–SST system in the NIO and WNP was
identified in a regular and partial correlation analysis; it was also identified as the second SVD of the 850-hPa streamfunction over the tropical Indian Ocean and Pacific and the SST in the entire tropics. The pattern exhibits the following features: 1) a cyclonic (anticyclonic) circulation pair straddling the equator over the eastern Pacific, 2) an anticyclonic (cyclonic) circulation pair straddling the equator in the WNP and Indian Ocean, 3) overturning circulation with ascending (descending) and descending (ascending) anomalies over the TA and tropical western Pacific, respectively, and 4) positive (negative) SSTA in the TA and the NIO. The spatial distribution of the divergent–rotational circulation and SST anomalies are consistent with those predicted by the Gill–Matsuno mechanism. The spatial relationship between the atmospheric circulation and SST anomalies in the western Pacific and Indian Ocean demonstrates the same characteristics as those of the WNP–NIO coupling pattern simulated in the Exp_cup experiment, which involved considering only the atmosphere–ocean interaction in the tropical Pacific and Indian Ocean and the observed TA SST as forcing, revealed that the observed circulation–SST pattern is effectively simulated as the first SVD. The observed enhancement of the coupling system after 1980 was also effectively simulated. The Exp_TA experiment, which entailed considering only the TA SST forcing, demonstrated the effect of the warm TA SST forcing on engendering northeasterly and downward surface heat flux anomalies in the NIO. The Exp_cup experiment, which involved considering only the atmosphere–ocean interaction in the tropical Pacific and Indian Ocean, showed that an atmospheric circulation–SST pattern similar to the observed WNP–NIO coupling pattern is an intrinsic pattern in the region.

According to the lag correlation analysis, the WNP–NIO coupling pattern simulated in the Exp_cup experiment does not appear until summer and the amplitude is too weak. In the Exp_TA experiment, the anomalously warm TA SST induces an ascending anomaly over the TA and a descending anomaly over the tropical western Pacific as early as in MJ. The associated divergence–convergence dipole triggers an anticyclonic circulation pair over the Indian Ocean and western Pacific. The northeasterly anomaly between the anticyclonic circulation pair weakens the prevailing climatological southwesterly and reduces the net surface heat flux, thus contributing to the warming of the NIO. This response to the TA SST forcing persists through the subsequent summer. When both the atmosphere–ocean coupling and TA SST forcing are considered, a coupled atmospheric circulation–SST pattern developing in late spring and persisting through the following summer as observed is successfully simulated. An extra experiment indicates that the deep heating anomaly associated with the positive TA SSTA can trigger a zonally overturning circulation with anomalous ascending over the tropical Atlantic and descending over the tropical western Pacific. The anomalous low-level convergence can therefore force and maintain a Rossby wave–like response in the western Pacific and Indian Ocean. Atmosphere–ocean interaction further enhances the NIO–WNP coupling system. Our findings suggest that the TA SST forcing enhances the intrinsic atmosphere–ocean interaction in the NIO and WNP, thus facilitating the intensification of the WNP–NIO coupling pattern, which would be unrealistically weak without an external forcing such as the TA SSTA. A schematic diagram depicting this mechanism is shown in Fig. 12.

Wang et al. (2013) demonstrated that adopting the ENSO development and the SSTA difference between the NIO and WNP as predictors enables improving the prediction of the summer WNPSh index. Hong et al. (2014) indicated that including the TA SST in regression equations for reconstructing the WNPSh index facilitates removing the spring predictability barrier. In this study, we further demonstrate that the TA SST forcing on the low-level circulation and surface heat flux triggers the capacitor effect of the NIO that starts storing the heat in late spring and enhances the atmosphere–ocean coupling in the following summer. This heating memory possibly helps break the spring predictability barrier.

The results of the numerical experiments indicate that the TA SST forcing on the WNP–NIO atmosphere–ocean coupling is also simulated even before the 1980s, although less significant. For example, correlation coefficients between time series of streamfunction vector in observed SVD2 (Fig. 4b) and simulated streamfunction vector in SVD1 of the Exp_cupTA (Fig. 9a) are 0.30 and 0.66 in 1948–80 and 1981–2010, respectively. The atmosphere–ocean coupling in the NIO and WNP was evidently enhanced after the early 1980s. To further confirm this enhancement, five more simulations were conducted and signal-to-noise ratio was calculated. We computed regression coefficients between prescribed tropical Atlantic SSTA with the model responses (e.g., SST, streamfunction, and velocity potential) in the Indian Ocean and the Pacific for 10 individual members and ensemble mean. The ratio between the regression
coefficients for ensemble mean and the standard deviation of regression of 10 members at each grid point is defined as the signal-to-noise ratio. This analysis was conducted for 1948–2010, 1948–80, and 1981–2010. The results (e.g., 850-hPa velocity potential shown in Fig. 13) indicate the robustness of the results (e.g., large ratio in key regions) presented above and a much larger signal-to-noise ratio in the later period, indicating a significantly enhanced predictability after 1980. Similar features were also observed in other variables such as streamfunction.

Fig. 12. Schematic diagram illustrating the remote forcing effect of positive TA SST anomaly on enhancing the WNP–NIO atmosphere–ocean coupling. The schematic over the NIO and WNP is modified based on Wang et al. (2013). Hollows arrows indicated the prevailing climatological low-level flow in the NIO and WNP. Blue solid arrows indicate the anomalous flows. The blue solid arrows marking the cross-basin overturning circulation are intended to show the anomalous vertical circulation in the tropics with ascending over the tropical Atlantic, cross-basin easterly, and descending over the tropical western Pacific.

Fig. 13. Signal-to-noise ratio (see text for definition) for the 850-hPa velocity potential between the ensemble mean and 10 individual members.
References


