Influence of tropical Atlantic sea surface temperature anomalies on the East Asian summer monsoon

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This study investigates the relationship between tropical Atlantic (TA) sea surface temperature (SST) anomalies and the East Asian summer monsoon (EASM), as well as the possible mechanism by which TA SST anomalies affect the EASM. We demonstrate a robust positive simultaneous correlation between the boreal summer TA SST anomalies and the EASM. Observational and model-based studies identify an atmospheric teleconnection in which the summer TA warming can enhance convection and induce low-level convergence in the Atlantic basin, which alters the Walker circulation and produces a sinking motion and divergence in the central Pacific. As a Rossby response to the anomalous divergence, an anomalous anticyclonic pair is generated over the western Pacific. As a result, the EASM is strengthened. Additionally, a significant lag correlation of the EASM with TA SST anomalies from the previous boreal spring is demonstrated, which implies potential applicability of the TA SST factor to the EASM prediction at seasonal time-scales.

KEYWORDS
East Asian summer monsoon, sea surface temperature anomalies, tropical Atlantic

1 | INTRODUCTION

The East Asian summer monsoon (EASM) has significant interannual variability (Ding and Chan, 2005; Wu et al., 2009; Huang et al., 2012; Feng et al., 2014) and has a remarkable impact on the summer climate in the East Asian region (e.g., Tao and Chen, 1987; Wang et al., 2000; Feng et al., 2014). Investigating the relationship between the EASM and the factors that affect it, and determining the mechanisms by which this occurs, can facilitate improvements in EASM seasonal prediction.

It has been found that the El Niño–Southern Oscillation (ENSO), a dominant climate mode of interannual variability in the tropical Pacific, has a remarkable influence on the EASM (Wang et al., 2000; Wu and Wang, 2002; Wu et al., 2009; Xie et al., 2009; Xie et al., 2016). In El Niño decay years, the cooling over the western tropical Pacific can induce an anticyclonic circulation anomaly over the western North Pacific (WNP) through the Matsuno–Gill response (Matsuno, 1966; Gill, 1980) and thus enable this anomaly to persist into the summer via local air–sea interactions. The south-easterly wind anomaly on the west side of this anomalous anticyclonic circulation can strengthen the EASM (Wang et al., 2000; Wu et al., 2003). Moreover, several studies have suggested that the ENSO can affect the EASM by inducing Indian Ocean warming (e.g., Du et al., 2009; Xie et al., 2009; 2016). An El Niño event can lead to Indian Ocean basin-scale warming (Alexander et al., 2002; Xie et al., 2009; 2016). A positive tropical Indian Ocean SST anomaly triggers an eastward-propagating warm Kelvin wave, which gives rise to a low-level anticyclonic circulation anomaly in the lower troposphere over the off-equatorial WNP that can strengthen the EASM (Du et al., 2009; Xie et al., 2009; 2016).
Recently, the remote impact of tropical Atlantic (TA) SST anomalies on climate variability over the tropical Pacific and Indian Ocean basins has gained increased attention (e.g., Srivastava et al., 2002; Lu and Dong, 2005; Chang et al., 2006; Wang, 2006; Keenlyside and Latif, 2007; Kucharski et al., 2008; Rajeevan and Sridhar, 2008; Rodriguez-Fonseca et al., 2009; Rong et al., 2010; Ham et al., 2013; Chen et al., 2014; Hong et al., 2014a; 2014b; Huo et al., 2015; Polo et al., 2015). On an interannual time-scale, the relationship between the Indian monsoon and TA SST variability has been found to be stronger after the mid-1970s, when the Indian monsoon–ENSO relationship weakened significantly (Kucharski et al., 2007; Kucharski et al., 2008; Rajeevan and Sridhar, 2008). The positive (negative) TA SST anomalies force a Matsuno–Gill-type quadrupole response with a low-level anticyclone (cyclone) anomaly located over India that weakens (enhances) the Indian monsoon circulation and reduces (increases) the Indian monsoon rainfall (Kucharski et al., 2009).

A significant correlation between the Atlantic equatorial mode (or Atlantic Niño) and the Pacific Niño was found by Keenlyside and Latif (2007), who demonstrated that the Atlantic SST anomalies precede the Pacific anomalies by 6 months. Rodriguez-Fonseca et al. (2009) argued that the Atlantic Niño during the boreal summer can favour ENSO development in the following winter due to a modulation in the Walker circulation since the late 1960s. The warm SST anomalies associated with the Atlantic Niño strengthen the Walker circulation, inducing anomalous surface divergence over the central Pacific. This surface divergence contributes to a shallowing of the Pacific thermocline. The Bjerknes positive feedback has the effect of amplifying these anomalies which favours the development of a cold ENSO event in the following winter, and vice versa (Losada et al., 2010; Ding et al., 2012; Polo et al., 2015). These findings have the potential to enhance ENSO prediction skills (Keenlyside et al., 2013). The aforementioned remote effect of TA variability on the tropical Pacific takes place on an interannual time-scale. It has also been detected on decadal and multidecadal time-scales (Martín-Rey et al., 2012; Chikamoto et al., 2016; Kucharski et al., 2016).

Since the Atlantic Niño can affect ENSO development via the atmospheric bridge, Ham et al. (2013) present the idea that the north TA SST with strong variability may modulate variability of the Pacific climate. They suggest that the north tropical SST during the boreal spring can trigger a warm-pool ENSO event (Ashok et al., 2007; Kao and Yu, 2009; Kug et al., 2009) in the following winter through a subtropical tele-connection. Noting the sustained remote impacts of north TA SST anomalies on tropical Pacific climate variability, Huo et al. (2015) reveal a strong relation between the WNP tropical cyclone genesis and the north TA SST anomalies. Additionally, summer TA SST anomalies are found to be related to the intensification of the western Pacific subtropical high since the early 1980s (Chen et al., 2014; Hong et al., 2014a; 2014b). A zonally overturning circulation anomaly is forced by the positive TA SST anomalies, and the sinking branch over the central Pacific enhances the western Pacific subtropical high (Hong et al., 2014a; 2014b).

Because the western Pacific subtropical high is such an important component of the EASM system (Tao and Chen, 1987), it is quite possible that the TA SST anomalies have an impact on EASM activity. However, few studies have focused on this. If such a connection exists, how do the TA SST anomalies influence the EASM? Can the preceding TA SST anomalies contribute to seasonal prediction of the EASM? This study aims to investigate these issues and clarify the physical mechanism by which TA SST anomalies affect the EASM. Additionally, this study aims to assess the impact on EASM seasonal prediction by taking a well-known empirical model of the EASM (Wu et al., 2009) and modifying it to include the spring TA SST anomalies as an additional predictor.

This article is structured as follows. Section 1 describes the research motives of this study. A brief description of the data and the numerical model are given in section 2. An analysis of the relationship between summer TA SST anomalies and the EASM is presented in section 3. Section 4 investigates the possible physical mechanism by which TA SST anomalies affect the EASM, and section 5 develops a statistical EASM prediction model based on spring TA SST anomalies and other predictors. A discussion and conclusions follow in section 6.

2 | DATA AND THE MODEL

This study uses the monthly reanalysis data for 1979–2015 produced by the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) (Kalnay et al., 1996) and the Global Precipitation Climatology Project (GPCP)’s monthly precipitation data for the same period, which have a horizontal resolution of 2.5\degree × 2.5\degree (Adler et al., 2003). Monthly SST data for 1978–2015 (horizontal resolution: 1\degree × 1\degree) produced by the UK Met Office’s Hadley Centre (Rayner et al., 2003) are also used. In order to focus on the interannual time-scale, long-term linear trends and interdecadal variations of periods of more than 11 years are filtered out from all of the data. This high-pass filtering technique has been widely applied in climate analysis to obtain the interannual components of variables (Wu et al., 2012; Hong et al., 2014a; Huo et al., 2015; Jin et al., 2013; Xie et al., 2009). Unless otherwise stated, the variables used in the following sections are the components of their interannual variations. The spring and summer referred to in this study are the boreal spring (March, April and May; MAM) and boreal summer (June, July and August; JJA).

The latest version of the Community Atmosphere Model (CAM5.3) (Neale et al., 2012), which was released as part of the Community Earth System Model (CESM), is used for
FIGURE 1  JJA (June, July and August) tropical Atlantic (TA) sea surface temperature (SST) anomalies regressed onto \( I_{\text{EASM}} \). The dotted areas indicate the regression coefficients exceeding the 95% confidence level, and the red rectangle is the range of the selected \( I_{\text{TA}} \) [Colour figure can be viewed at wileyonlinelibrary.com]

this study. The finite-volume dynamic core (Lin, 2004) has a horizontal resolution of 1.9° latitude and 2.5° longitude, and 30 vertical levels with hybrid pressure–sigma vertical coordinates (Simmons and Burridge, 1981). The physical parameterization in CAM5.3 includes a two-moment cloud micro-physics scheme (Morrison and Gettelman, 2008), a deep convection scheme (Zhang and McFarlane, 1995; Richter and Rasch, 2008), a shallow convection scheme (Bretherton and Park, 2008), a moist turbulence scheme (Bretherton and Park, 2009), and the Rapid Radiative Transfer Model for GCMs (RRTMG) package for radiation (Mlawer et al., 1997). The time step is 30 min. More detailed information about this model can be found in Neale et al. (2012). The specific experimental designs are discussed in section 4.2.

3 | RELATIONSHIP BETWEEN THE TA AND THE EASM

The difference between the averaged zonal wind over 22.5°–32.5°N 110°–140°E and 5°–15°N 90°–130°E at 850 hPa is defined as the East Asian summer monsoon index (\( I_{\text{EASM}} \)) (Wang and Fan, 1999; Wang et al., 2008; Wu et al., 2009). It is noted that the \( I_{\text{EASM}} \) used here has the opposite sign relative to the original EASM index defined by Wang and Fan (1999). Positive (negative) \( I_{\text{EASM}} \) represents a strong (weak) East Asian summer monsoon year. The JJA TA SST anomalies regressed onto the \( I_{\text{EASM}} \) (Figure 1) show that the regression coefficients over the entire TA region are consistently positive. Values exceeding the 95% confidence level are located between approximately 20°S and 20°N. Therefore, the averaged SST anomaly over 20°S–20°N 80°W–10°E is defined as the TA SST anomaly index (\( I_{\text{TA}} \)).

The unfiltered time series of \( I_{\text{TA}} \) and \( I_{\text{EASM}} \) (Figure 2a) indicate that there is a significant positive correlation between them, with a correlation coefficient of 0.54 (above the 99% confidence level). Both the TA SST anomalies and the EASM exhibit significant long-term and interdecadal variation (Figure 2a). Previous studies have demonstrated that preceding ENSO events can influence the following EASM (Wang et al., 2000; Wu et al., 2003; Xie et al., 2009). The correlation coefficient between the \( I_{\text{EASM}} \) and the Niño 3.4 index (averaged SST anomaly over 5°S–5°N 170°–120°W) of the previous winter (December–February) is 0.53 (significant at the 99% confidence level). Moreover, it is generally agreed that an ENSO event occurring the previous winter can influence Atlantic SST variability (e.g., Alexander and Scott, 2002; Chiang and Sobel, 2002). However, the simultaneous effect of ENSO on Atlantic variability is not statistically significant, because the atmospheric response to the ENSO signal is offset by the opposing influence of oceanic processes.

FIGURE 2  Standardized time series for the JJA \( I_{\text{TA}} \) (wide red bars) and \( I_{\text{EASM}} \) (narrow blue bars). (a) The unfiltered field and (b) the interannual components excluding precursory El Niño–Southern Oscillation (ENSO) signals [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 3 (a) JJA 850 hPa vorticity (coloured areas; unit: $10^{-6}$ s$^{-1}$) and wind (arrows; unit: m/s) regressed onto the \( I_{EASM} \), and (b) precipitation regressed onto the \( I_{EASM} \) (coloured areas; unit: mm/day). The dotted areas represent the regression coefficients exceeding the 95% confidence level, the wind fields below the 95% confidence level are not shown, and the red and green rectangles in (a) represent the ranges of the selected \( I_{EASM} \) in the two regions. (c) and (d) are similar to (a) and (b) but for the variables regressed onto the JJA \( I_{TA} \). The orange streamlines in (c) are the JJA mean flow at the lower level, while the blue shading in (d) is the JJA mean precipitation [Colour figure can be viewed at wileyonlinelibrary.com]

(Chang et al., 2006). Therefore, using the linear regression with respect to the Niño 3.4 index during the previous winter, the lagged effect of ENSO is removed from all the meteorological variables used in the following analysis. In addition, the decadal and lower frequencies are also filtered out from all observational data. If \( V \) and \( V_R \) denote the time series of the meteorological variable and its residual value of \( V \) after the precursory winter ENSO signals have been removed, then \( V \) can be written as

\[
V = a \cdot I_{\text{Nino}3.4} + V_R, \tag{1}
\]

where \( a \) is the coefficient obtained by the least squares procedure. This method has been widely utilized in climate research to remove the linear component of a specific signal (e.g., Kucharski et al., 2008; Huo et al., 2015).

The time series of \( I_{TA} \) and \( I_{EASM} \) (Figure 2b) show that there is still a robust positive correlation between \( I_{TA} \) and \( I_{EASM} \) even after the preceding ENSO effect has been removed (with a correlation coefficient of 0.62 that is above the 99% confidence level).

Wind and vorticity in the lower troposphere regressed onto \( I_{EASM} \) (Figure 3a) show that there is a zonally elongated anomalous anticyclonic circulation over the WNP and that the anomalous easterlies to its south extend westward to the Bay of Bengal. In addition, a negative vorticity anomaly is located over the region between the Bay of Bengal and the WNP (Figure 3a), and the precipitation in this region is below normal (Figure 3b). There is an anomalous positive vorticity and a rain belt with above-average precipitation (Figure 3b) located in the Yangtze river basin, the Korean Peninsula and the Japanese archipelago. It is also noted that a positive vorticity anomaly from the tropical eastern Indian Ocean to the western central Pacific (Figure 3a) exists in conjunction with excessive precipitation (Figure 3b).

The meteorological variable fields related to the JJA \( I_{TA} \) (Figure 3c,d) show that anomalous easterlies prevail from the tropical western Pacific to the Bay of Bengal in the warm TA years (Figure 3c). Moreover, the anomalous easterlies enhance the anomalous anticyclone over the WNP. The mean flow over East Asia in the lower troposphere is southwesterly winds, and the anomalous southwesterlies on the west side of this anomalous anticyclonic circulation overlaid onto the mean flow have the effect of strengthening the EASM (Figure 3c). The anticyclonic circulation also transports water vapour from the western Pacific to the Yangtze river basin, the Korean Peninsula and the Japanese archipelago, which helps
to maintain the rain belt (Figure 3d) (Sampe and Xie, 2010; Wu and Hsu, 2016). These anomalous circulations (Figure 3a) are consistent with the spatial distribution of the circulation related to $I_{EASM}$ (Figure 3c), which further demonstrates the robust positive correlation between TA SST anomalies and the EASM.

4 | POSSIBLE MECHANISMS AFFECTING THE EASM

4.1 | Observations

The stream function and rotational wind fields regressed onto $I_{TA}$ (Figure 4) show a pair of anomalous cyclonic circulations in the lower troposphere originating in the subtropical eastern Pacific and extending into the North and South Atlantic. Meanwhile, an anomalous anticyclonic pair is generated over the western Pacific (Figure 4a). The circulation pattern in the upper troposphere is for the most part opposite to that in the lower troposphere, with a pair of zonally elongated anomalous anticyclonic circulations located over the region from the eastern tropical Pacific to the Atlantic, and a pair of zonally elongated anomalous cyclonic circulations over the western Pacific (Figure 4b). Further analysis shows that in warm TA (or positive $I_{TA}$) years, the anomalous convergence occurs in the lower troposphere (Figure 5a) and the anomalous divergence occurs in the upper troposphere (Figure 5b) over the Atlantic region. The anomalous convergence and divergence centres are located between approximately 5 and 15°N. This configuration consists of an anomalous ascending motion over the TA (Figure 5c), and can be interpreted as follows. The TA warming can enhance the convection activity in the equatorial Atlantic and thus give rise to a pair of low-level cyclonic circulation flows (Figure 4a) over the Atlantic and the eastern Pacific in the form of a Gill-type response (Gill, 1980; Ham et al., 2013; Hong et al., 2014a). The accompanying anomalous convergence and ascent over the Atlantic basin alter the Walker circulation, and thus induce the anomalous divergence and descent in the central Pacific region in the lower troposphere (Figure 5a,c) (Rodriguez-Fonseca et al., 2009). A Rossby wave response to this surface wind divergence is produced in the form of two low-level anticyclonic anomalies over the western Pacific on both sides of the Equator (Polo et al., 2015). The anomalous circulation pattern is reversed in the upper troposphere due to baroclinicity. As a result, the EASM is strengthened.

The above analysis shows that the TA SST warming during the boreal summer can enhance the EASM by altering the Walker circulation over the Pacific. However, the remote effect of the Atlantic Ocean on the Pacific is not confined to the atmosphere. As demonstrated by Rodriguez-Fonseca et al. (2009) and Polo et al. (2015), the anomalous divergence over the central Pacific induced by the altered Walker circulation causes shallowing of the equatorial thermocline triggering air–sea coupled processes in the following few months. In addition, a cold ENSO event would develop in the Pacific during the following winter.

4.2 | Model results

The observational analysis above shows that the TA SST anomalies may well influence the EASM via an “atmospheric bridge” mechanism. In warm TA years, a strengthening Walker circulation is produced with low-level convergence

![FIGURE 4](a) 850 hPa PSI & Rot. V reg onto $I_{TA}$
(b) 200 hPa PSI & Rot. V reg onto $I_{TA}$

The dotted areas indicate the regression coefficients exceeding the 95% confidence level, and the dark arrows represent the rotational wind exceeding the 95% confidence level [Colour figure can be viewed at wileyonlinelibrary.com]
FIGURE 5  (a) and (b) are the same as in Figure 4 except for the velocity potential (coloured areas; unit: 10^6 m^2/s) and the divergent wind (arrows; unit: m/s). Shown in (c) is the regressed JJA zonal vertical circulation averaged between 5° and 15°N onto $I_{TA}$. The horizontal component is the zonal component of the divergent wind. The dotted areas indicate the regression coefficients exceeding the 95% confidence level [Colour figure can be viewed at wileyonlinelibrary.com]

and an upward branch over the Atlantic and low-level divergence and a downward branch over the central Pacific. The enhanced surface divergence leads to a low-level pair of anomalous anticyclonic circulations over the western Pacific. The EASM is therefore enhanced.

To verify this mechanism, a control and two sensitivity experiments are conducted. In the control (CTL) experiment, the observed climatological SST and sea ice data are used to process the CAM5.3 model for 20 continuous years, and the results of the last 19 years are used for the next simulations. Two groups of sensitivity experiments, namely the positive (POS) and negative (NEG) anomaly sensitivity experiments, are then performed with identical lower boundary SST conditions to the CTL except for the TA region. The SST prescribed in the TA region for the POS (NEG) experiment is the observed anomalous SST regressed onto the EASM for the period 1979–2015 (as shown in Figure 1) adding to (subtracting from) the climatological SST. That is, the observed SST is prescribed in the TA, whereas the climatological SST is prescribed elsewhere. For both POS and NEG experiments, there are 19 ensemble members respectively, with each simulation integrating from June 1 to September 30. These 19 ensemble members differ only in their atmospheric initial conditions, taken from June 1 in the last 19 years of the simulation derived from the CTL experiment.

The differences in the wind fields between the POS and NEG experiments at 850 hPa (Figure 6a) show that anomalous easterlies prevail from the tropical western Pacific to the Bay of Bengal. In addition, the WNP region is controlled by an anomalous anticyclonic circulation, and the EASM is strengthened. These features are consistent with the observational results. A comparison of the differences in rainfall between the results derived from the POS and NEG experiments (Figure 6b) and the observations (Figure 3d) shows that the model reproduces well the below-normal precipitation from the WNP to the Bay of Bengal and the above-normal rainfall belt over East Asia.

The differences between the 850 hPa rotational winds for the POS and NEG simulations (Figure 7a) are shown as two
cyclones straddling the Equator at the lower level, ranging from the eastern Pacific to the Atlantic and accompanied by enhanced ascending motion and surface wind convergence over the Atlantic (Figure 7b), and an anomalous low-level anticyclonic pair located over the western Pacific as a Rossby wave response to the enhanced surface wind divergence in the central Pacific (Figure 7b). The EASM circulation and rainfall are strengthened (Figure 6). Thus, it can be seen that the results derived from model simulations are consistent with the observational results.

5 | SEASONAL PREDICTION

5.1 | Connection between the precursory TA and the EASM

In the above analysis, it is found that the EASM has a remarkable positive relationship with simultaneous SST anomalies in the TA. However, it remains unclear whether a lagged relationship exists between the spring TA SST anomalies and the EASM, which is critical for seasonal prediction of the EASM. To address this, the correlation coefficient between the MAM \( I_{TA} \) and the JJA \( I_{TA} \) is calculated, and is found to reach up to 0.83. This result indicates that the TA SST anomalies have relatively good persistence from spring to summer. The correlation coefficient between the MAM \( I_{TA} \) and \( I_{EASM} \) is 0.62 (significant at the 99% confidence level), which implies that MAM TA SST anomalies can persist into JJA and exert influence on the EASM. Figure 8 displays the low-level wind and SST fields regressed on to the MAM \( I_{TA} \). During the MAM season, TA heating enhances the convection and induces anomalous low-level convergence over the equatorial Atlantic, giving rise to two cyclonic circulation anomalies over the eastern Pacific and the Atlantic. The compensatory sinking motion and surface wind divergence are generated in the central Pacific, causing SST cooling in the equatorial central Pacific and equatorial easterly anomalies from the central to the western Pacific through air–sea coupled processes (Ham et al., 2013; Huo et al., 2015). The equatorial easterly anomalies deepen the water in the western Pacific and shallow the thermocline in the equatorial central Pacific. This perturbation in the thermocline propagates eastward as a Kelvin wave and westward as an off-equatorial Rossby wave in the following few months (Rodriguez-Fonseca et al., 2009; Polo et al., 2015). The responses to TA warming in the atmosphere and in the Pacific Ocean are thus amplified gradually. In JJA, the SST cooling extends eastward to the eastern equatorial Pacific and is intensified via air–sea interaction, which will lead to a La Niña event the following winter (Rodriguez-Fonseca et al., 2009; Polo et al., 2015). An anomalous anticyclonic pair are generated over the western Pacific, which enhances the EASM.

5.2 | Seasonal prediction

The analysis described above shows that the MAM TA SST anomalies can have a lagged effect on the EASM through subtropical atmospheric teleconnection. Can a seasonal prediction model including the MAM TA SST anomalies as a predictor improve the accuracy of EASM seasonal prediction? The statistical model developed by Wu et al. (2009), which uses the precursory North Atlantic Oscillation (NAO; Hurrell, 1995) and ENSO as its predictors, can predict the EASM with high accuracy. The correlation coefficient between the hindcast and the observed EASM index for 1979–2006 was 0.79. This study attempts to modify this existing seasonal prediction model using the MAM \( I_{TA} \), the \( I_{NAO} \) for April–May (AM) used by Wu et al. (2009) (Li and Wang, 2003), the Niño 3.4 index of the precursory winter (December, January and February [DJF]) and the ENSO decay index (\( ENSO_{\text{decay}} \)) that is the difference between the Niño 3.4 index for April–May and the Niño 3.4 index for February–March. With the exception of the MAM \( I_{TA} \), the other predictors are the same as those in the seasonal prediction model developed by Wu et al. (2009). Note that the following prediction model is based on unfiltered original data. Table 1 shows that there
is a significant correlation between the EASM and the above predictors:

\[
I_{\text{EASM}} = -0.25 \cdot I_{\text{NAO}} - 0.07 \cdot \text{ENSO}_{\text{decay}} + 0.35 \cdot \text{ENSO}_{\text{DIF}} + 0.44 \cdot I_{\text{TA}}. \tag{2}
\]

Equation (2) shows the modified seasonal prediction model based on the predictors described above. The correlation coefficient between the hindcast and the observed \(I_{\text{EASM}}\) is 0.78. The time series of the hindcast \(I_{\text{EASM}}\) is consistent with the observed data (Figure 9). Equation (3) shows the prediction model excluding the \(I_{\text{TA}}\). The correlation coefficient between its hindcast and the observed \(I_{\text{EASM}}\) is 0.67, which implies
TABLE 1 Correlation coefficients between $I_{EASM}$ and precursory predictors from 1979 to 2015. The critical value at the 99% confidence level is 0.42.

| $I_{TA}$ (MAM) | $I_{NAO}$ (AM) | ENSO (DJF) | ENSO_decter |
|----------------|----------------|-------------|--------------|
| $I_{EASM}$ (JJA) | 0.63 | -0.42 | 0.53 | -0.54 |

![Reconstructed EASM](image)

**FIGURE 9** Time series of the observed EASM (black solid line) and hindcast EASM with $I_{TA}$ (red solid line with open squares) and no $I_{TA}$ (dashed blue line) from 1979 to 2015 [Colour figure can be viewed at wileyonlinelibrary.com]

that the accuracy of the seasonal prediction model hindcast is improved when the preceding TA SST anomalies are included.

6 | CONCLUSIONS AND DISCUSSION

This study investigates the relationship between TA SST anomalies and the EASM, as well as the possible mechanism by which these anomalies affect the EASM using reanalysis data produced by NCEP/NCAR and simulations by CAM5.3. The main conclusions of this study are as follows.

1. There is a robust positive correlation between the JJA TA SST anomalies and the EASM. In warm TA years, anomalous easterlies prevail from the western tropical Pacific to the Bay of Bengal in the Northern Hemisphere. Additionally, an anomalous anticyclone occurs in the WNP. The EASM is thus enhanced.

2. The TA SST anomalies and EASM are connected via an atmospheric bridge. The TA warming (cooling) can enhance (weaken) the convection activity in the equatorial Atlantic, giving rise to a pair of low-level cyclonic (anticyclonic) circulation flows over the Atlantic and eastern Pacific in the form of a Gill-type response. The accompanied anomalous convergence (divergence) and upward (downward) motion over the Atlantic basin alter the Walker circulation, and thus induce the anomalous divergence (convergence) and downward (upward) motion in the lower troposphere in the central Pacific region. As a Rossby wave response to this surface wind divergence (convergence), two low-level anticyclonic (cyclonic) anomalies over the western Pacific are produced on both sides of the Equator. The EASM is therefore strengthened (weakened).

3. The MAM TA SST anomalies can persist into JJA due to ocean memory effects and affect the EASM. An anomalous cyclonic (anticyclonic) circulation is produced over the eastern Pacific and the Atlantic on each side of the Equator due to the Gill response during positive (negative) TA SST anomaly years. The compensatory sinking (ascending) motion and surface wind divergence (convergence) in the central Pacific cause the SST cooling (warming) and easterly (westerly) anomalies in the equatorial central Pacific. The responses in the Pacific Ocean are amplified gradually via air–sea coupled processes in the following few months. In JJA, an anomalous anticyclonic (cyclonic) pair are generated over the western Pacific, which strengthens (weakens) the EASM.

4. MAM TA SST anomalies can serve as an additional predictor of the EASM. The seasonal prediction model developed based on the MAM TA SST anomalies, the $I_{NAO}$ and the precursory winter ENSO indices show the improvements in hindcast prediction skill. The model including the MAM TA SST anomalies as an additional predictor can improve the accuracy of hindcast prediction.

Wu et al. (2009) developed a model including the preceding NAO and ENSO indices for 1979–2006 as predictors. The correlation coefficient between its hindcast and the observation is 0.79. This study extends the period to 1979–2015, which results in a correlation coefficient of 0.67 between the hindcast and the observed $I_{EASM}$. It indicates that the relationship between the NAO and the EASM has weakened over the last decade. The relationship between the TA SST anomalies and the NAO has been clarified to take into account interdecadal variation (Chen et al., 2015). Is the weakening of the relationship between the NAO and the EASM over the last decade related to TA SST anomalies? Note that the hindcast derived from the model with $I_{TA}$ does not improve with every year, and is in fact worse in some years (such as 2005 and 2010) relative to the hindcast of the model without $I_{TA}$ (see Figure 9). What is the cause of this? Additionally, Indian Ocean SST anomalies can also affect the EASM (Du et al., 2009; Xie et al., 2009; 2016). Can Indian Ocean SST anomalies and TA SST anomalies have a combined influence on the EASM? Additional studies are needed to clarify these questions.

The present study shows how the TA can influence the EASM via a westward atmospheric teleconnection associated with the Walker circulation in the Atlantic. Other recent studies have suggested an eastward propagating teleconnection from the TA to the Indian Ocean and adjacent regions (Kucharski et al., 2007; 2008; 2009). The physical mechanism by which this occurs has been investigated by Kucharski et al. (2009) with idealized atmospheric general circulation model (AGCM) experiments. In addition, a Gill–Matsuno-type quadrupole has been proposed to explain the eastward response between the TA and the Indian Ocean basin. Despite the fact that eastward propagating signals triggered by the TA were not detected in the current study, the coexistence of eastward and westward teleconnection is still possible. To clarify this issue, further investigation is needed.
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