Reintensification of the Anomalous Western North Pacific Anticyclone during the El Niño Modoki Decaying Summer: Relative Importance of Tropical Atlantic and Pacific SST Anomalies

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ABSTRACT

The El Niño Modoki–induced anomalous western North Pacific anticyclone (WNPAC) undergoes an interesting reintensification process in the El Niño Modoki decaying summer, the period when El Niño Modoki decays but warm sea surface temperature (SST) anomalies over the tropical North Atlantic (TNA) and cold SST anomalies over the central-eastern Pacific (CEP) dominate. In this study, the region (TNA or CEP) in which the SST anomalies exert a relatively important influence on reintensification of the WNPAC is investigated. Observational analysis demonstrates that when only anomalous CEP SST cooling occurs, the WNPAC experiences a weak reintensification. In contrast, when only anomalous TNA SST warming emerges, the WNPAC experiences a remarkable reintensification. Numerical simulation analysis demonstrates that even though the same magnitude of CEP SST cooling and TNA warming is respectively set to force the atmospheric general circulation model, the response of the WNPAC is still much stronger in the TNA warming experiment than in the CEP cooling experiment. Further analysis demonstrates that this difference is caused by the distinct location of the effective tropical forcing between the CEP SST cooling and TNA SST warming for producing a WNPAC. The CEP cooling–induced effective anomalous diabatic cooling is located in the central Pacific, by which the forced anticyclone becomes gradually weak from the central Pacific to the western North Pacific. Thus, a weak WNPAC is produced. In contrast, as the TNA SST warming–induced effective anomalous diabatic cooling is just located in the western North Pacific via a Kelvin wave–induced Ekman divergence process, the forced anticyclone is significant and powerful in the western North Pacific.

1. Introduction

The anomalous western North Pacific anticyclone (WNPAC), produced by El Niño during its mature and decaying seasons, is a crucial atmospheric system in linking the impacts of El Niño to the East Asian climate (e.g., Zhang et al. 1996; Wang et al. 2003; Wu et al. 2003). This WNPAC cannot only prevent the East Asian

winter monsoon from intruding southward but also brings above-normal moisture to mainland China, causing a warmer and wetter winter over East Asia during El Niño mature winters (Chen et al. 2000; Huang et al. 2004; Tomita and Yasunari 1996; Wang et al. 2008). More importantly, the long-lasting WNPAC exerts a delayed influence of El Niño on the East Asian summer monsoon (EASM) during El Niño decaying summer, which often yields extreme weather events, such as heavy rainfall or severe droughts (e.g., Chang et al. 2000a,b; Huang et al. 2004; Feng et al. 2014; among others), and further causes serious natural disasters and economic losses. El Niño is an important air–sea coupling phenomenon in the tropics and is regarded as an effective forecast factor for the EASM.

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Therefore, in-depth understanding of the relationship between El Niño and the WNPAC is of importance to improve the prediction skill of EASM interannual variability.

It is widely recognized that the formation mechanism of the WNPAC during El Niño mature winter and decaying spring is distinct from that during the decaying summer (Wang et al. 2000; Xie et al. 2009; Rong et al. 2010; Ham et al. 2013a; Xie et al. 2016; Wu et al. 2010b, 2017a,b). During mature winter and decaying spring when the anomalous SST warming and cooling in the tropical Pacific can be significantly observed, the formation of the WNPAC is closely related to the El Niño SST anomalies (Wang et al. 2000). These SST anomalies tend to drive an anomalous Walker circulation that rises in the eastern Pacific and sinks in the western Pacific. Thus, the resultant suppressed convection over the western Pacific induces the WNPAC through the Matsuno–Gill response (e.g., Wang et al. 2000; Wu et al. 2010a; Feng et al. 2010). In addition, the WNPAC is coupled with the cold SST anomalies over the western Pacific. On the eastern side of this WNPAC, the anomalous northeasterly winds are in accord with the climatological winds. Thus, the total wind speeds are increased and evaporation is enhanced, which further cools the SST in the western North Pacific. The cooling SST anomalies in turn yield a WNPAC by inducing Rossby waves. This positive feedback between atmospheric circulation and local SST anomalies maintains the WNPAC during the El Niño mature winter and decaying spring (Wang et al. 2000). During the decaying summer when El Niño further decays, as the El Niño–induced anomalous Walker circulation disappears and the local air–sea interaction in the western North Pacific gradually weakens, the mechanisms aforementioned cannot effectively work. It is known that El Niño can cause the remote ocean SST to increase from its mature to decaying stages through both ocean processes and atmospheric dynamics (Chikamoto and Tanimoto 2006; Enfield and Mayer 1997; Klein et al. 1999; Du et al. 2009; Schott et al. 2009). This process has been described as being like a battery charging a capacitor in other studies (Yang et al. 2007). The Indian Ocean SST warming in the El Niño decaying summer can in turn induce Kelvin waves propagating eastward (Xie et al. 2009). In the western North Pacific, surface friction causes the anomalous northeasterly surface winds in Kelvin waves to flow onto the low pressure region over the Indian Ocean and further induces surface divergence, which suppresses convective activity in the western North Pacific and drives a WNPAC (Terao and Kubota 2005; Xie et al. 2009). The process of the Indian Ocean SST warming producing a WNPAC has been described as being like a battery discharging a capacitor in the

study by Xie et al. (2009). Therefore, the process of El Niño inducing Indian Ocean SST warming and the anomalous SST warming in turn affecting the atmospheric circulation is often referred to as the Indian Ocean capacitor effect (Xie et al. 2009). In addition to the Indian Ocean capacitor effect, the anomalous SST warming over the tropical North Atlantic (TNA) has a similar capacitor effect on the WNPAC (Lu and Dong 2005; Rong et al. 2010; Ham et al. 2013a,b). The TNA SST is increased by El Niño–induced ocean and atmospheric teleconnections (Chikamoto and Tanimoto 2006; Enfield and Mayer 1997). The anomalous TNA SST warming stimulates Kelvin waves to propagate eastward into the western Pacific and further produces a WNPAC (Rong et al. 2010; Ham et al. 2013a).

In recent years, it has been widely accepted that there are two types of El Niño. One is conventional El Niño (also referred to as the eastern Pacific El Niño or cold-tongue El Niño), during which warm SST anomalies dominate the tropical eastern Pacific (Ashok et al. 2007; Kug et al. 2009; Larkin and Harrison 2005). The other is El Niño Modoki (also referred to as the central Pacific El Niño, warm pool El Niño, or date line El Niño), which is characterized by warm SST anomalies over the tropical central Pacific (Ashok et al. 2007; Kao and Yu 2009; Yeh et al. 2009). Different types of El Niño induce distinct WNPAC evolution (Feng et al. 2011; Yuan et al. 2012). Conventional El Niño SST anomalies can persist into spring, which produces a WNPAC via anomalous Walker circulation and local air–sea interaction (Wang et al. 2000; Feng et al. 2011). Conventional El Niño almost disappears in summer (Feng et al. 2011). Nevertheless, due to the close relationship between conventional El Niño and Indian Ocean SST (Yuan et al. 2012), the Indian Ocean has remarkable SST warming in conventional El Niño decaying summer and exerts a capacitor effect on the WNPAC (Feng et al. 2011; Wu et al. 2009). Thus, the WNPAC maintains from the mature winter to the decaying summer for conventional El Niño (Feng et al. 2011; Yuan et al. 2012). However, for El Niño Modoki, a WNPAC is observed in winter, but quickly weakens in the following spring due to fast weakening of El Niño Modoki (Figs. 1a,b). Interestingly, WNPAC obviously reintensifies in the following summer when El Niño Modoki completely decays (Fig. 1c). Owing to the poor relationship between El Niño Modoki and Indian Ocean SST, there is no SST warming over the Indian Ocean in the decaying summer (Fig. 1c), and thereby the reintensification of the WNPAC cannot be attributed to the Indian Ocean warming effect. Feng et al. (2011) noted that El Niño Modoki decays into a La Niña in summer with cold SST anomalies over the tropical central-eastern Pacific

FIG. 1. Composite evolution of SST anomalies ($^{\circ}\text{C}$) and 850-hPa wind anomalies (m s^{-1}) from (a) the mature winter of El Niño Modoki to (b) its decaying spring and (c) summer. The stippled regions are above the 95% confidence level based on a two-tailed Student's t test. Only wind vectors exceeding the 95% confidence level based on a two-tailed Student's t test are plotted.

(CEP) and warm SST anomalies over the western Pacific (Fig. 1c). Therefore, they discussed that La Niña cold SST anomalies might produce reintensification of the WNPAC through suppressing convection over the central Pacific and inducing Rossby waves. However, note that the cold SST anomalies over the CEP are quite weak (Fig. 1c), whereas the WNPAC response is much stronger (Fig. 1c). Whether weak anomalous SST cooling over the CEP can induce such a strong WNPAC is unclear and deserves further study, which is one of the aims of this study. Based on the composite El Niño Modoki conditions in Fig. 1c, it is found that there is anomalous TNA SST warming in addition to the anomalous CEP SST cooling. The warm SST anomalies over the TNA (Fig. 1c) can also produce a WNPAC through the capacitor effect, the role of which however is not discussed in Feng et al. (2011).

What is the contribution of the TNA SST warming to the WNPAC reintensification compared with the CEP SST cooling? Which plays the dominant role in forcing the WNPAC? These questions will be resolved in this study.

The rest of this paper is organized as follows. Section 2 gives an introduction to the data, methods, and models used in this study. In section 3, we first separate the El Niño Modoki events into two groups based on the anomalous SST distribution: one group with only CEP SST cooling and the other group with only TNA SST warming. Then the relative importance of CEP SST cooling and TNA SST warming in producing a WNPAC is investigated using observational data and numerical experiments. Section 4 uses the El Niño Modoki case that occurred in 2009/10 to further explore the region in which the SST anomalies have a

more important influence on the reintensification of the WNPAC during El Niño Modoki decaying summer. Finally, a summary and discussion are given in [section 5](#).

2. Data, methods, and model introduction

The monthly mean data produced by the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) are used in this study, including wind, sea level pressure, and temperature fields ([Kalnay et al. 1996](#)). This dataset has a horizontal resolution of 2.5° latitude $\times$ 2.5° longitude and has 17 levels in the vertical direction. The Hadley Centre Global Sea Ice and Sea Surface Temperature dataset (HadISST) with a resolution of 1° latitude $\times$ 1° longitude is used to diagnose the SST anomalies in El Niño Modoki cases ([Rayner et al. 2003](#)). The period from 1961 to 2011 is used for all the data in this study. In addition, to avoid the impacts of long-term trends on the results, the data are detrended before use.

There are two steps to select El Niño Modoki events. First, all the El Niño events are selected according to the Climate Prediction Center (CPC) definition, that is, when the 3-month running-mean Niño-3.4 index is greater than a threshold of 0.5 and persists for at least five consecutive overlapping seasons. Second, from the El Niño events, El Niño Modoki cases are selected using the definition that the winter mean (December–February) Niño-4 index is greater than the Niño-3 index, which is widely used in the other studies ([Kug et al. 2009](#); [Yeh et al. 2009](#); [Ham and Kug 2012](#)). Seven El Niño Modoki events (1968/69, 1977/78, 1994/95, 2002/03, 2004/05, 2006/07, 2009/10) are selected. In addition, note that Niño-3 and Niño-4 indices have a comparable magnitude for the El Niño event in 1963/64. Nevertheless, another index, the El Niño Modoki index (EMI), which is widely used to measure El Niño Modoki ([Ashok et al. 2007](#); [Feng et al. 2011](#); [Weng et al. 2007](#)), has an evidently high value in 1963/64. Furthermore, the anomalous SST warming during the 1963/64 El Niño is dominantly located in the tropical central Pacific. Therefore, the 1963/64 El Niño is defined as an El Niño Modoki. Eventually, we selected eight El Niño Modoki events.

An atmospheric general circulation model (AGCM) is employed to explore the relative importance of CEP SST cooling and TNA SST warming in producing the WNPAC by a series of sensitivity experiments. We use a Spectral Atmospheric Model developed at the Institute of Atmospheric Physics (IAP)/State Key Laboratory of Numerical Modeling for Atmospheric

Sciences and Geophysical Fluid Dynamics (LASG) (SAMIL). The dynamical framework of SAMIL is a hybrid-coordinate system with 26 vertical layers, rhomboidally truncated at wavenumber 42 in the horizontal (R42), that contains a nominal Gaussian grid resolution of 2.81° longitude $\times$ 1.66° latitude. For moisture transport, a flux-form semi-Lagrangian transport scheme (FFSL) was used ([Wang et al. 2013](#)). For details of this model refer to the studies of [Bao et al. \(2013\)](#) and [Wang et al. \(2013\)](#). The experiments designed in this study are introduced in [section 3](#).

To analyze the role of anomalous diabatic heating/cooling in forcing a WNPAC, a baroclinic dry model is utilized in this study, which was developed by the University of Hawai'i International Pacific Research Center (IPRC) ([Jiang and Li 2005](#); [Li 2006](#)). The primitive equations of this model are linearized by a realistic three-dimensional basic state, which retains full nonlinearity in the second-order perturbation terms of the prediction equations. In the horizontal, the resolution of this model is Triangle 42, corresponding to roughly 2.8° latitude $\times$ 2.8° longitude. In the vertical it has five levels. An ideal anomalous heating/cooling and climatological state are prescribed when running this model. The climatological state is calculated using the summer (June–August) mean NCEP/NCAR reanalysis data for 1960–2011.

3. Relative importance of TNA SST warming and CEP SST cooling

a. Evolution of SST anomalies and WNPAC

Since the composite SST anomalies for all the El Niño Modoki events in the decaying summer show that there is anomalous CEP SST cooling together with TNA SST warming ([Fig. 1c](#)), it is difficult to distinguish in which region the SST anomalies play a more important role in building the WNPAC. We inspected the anomalous SST distribution in the decaying summer for each El Niño Modoki event, and found that there are three El Niño Modoki events (1963/64, 1977/78, 2006/07) with only CEP SST cooling (ELM-CEP group) and another three El Niño Modoki events (1968/69, 1994/95, 2004/05) with only TNA SST warming (ELM-TNA group). Thus, we next compare the atmospheric responses over the western North Pacific to these two El Niño Modoki groups.

[Figure 2](#) shows the evolution of the SST anomalies for the two El Niño Modoki groups. For the ELM-CEP group, warm SST anomalies over the central Pacific are seen in winter ([Fig. 2a](#)), which subsequently quickly decay ([Fig. 2b](#)) and convert into cold SST anomalies ([Fig. 2b](#)) in the following spring.

FIG. 2. Composite SST anomalies ($^{\circ}\text{C}$) in (top) winter and the following (middle) spring and (bottom) summer for the (a)–(c) ELM-CEP group and (d)–(f) ELM-TNA group. The black contours indicate the SST anomalies that exceed the 95% confidence level based on a two-tailed Student's t test.

The negative SST anomalies further develop in the following summer and extend to the central Pacific (Fig. 2c). Note that there are no significant warm SST anomalies over the TNA and Indian Ocean, which means that the cold SST anomalies over the CEP can be regarded as the main tropical driving factor for the atmospheric circulation anomalies in the decaying summer of El Niño Modoki (Fig. 2c). In contrast, for the ELM-TNA group (Figs. 2d–f), the warm SST anomalies in the central Pacific decay much more slowly compared with the ELM-CEP group. Obviously positive SST anomalies in the central Pacific can be still observed in the following spring (Fig. 2e). In summer, only extremely weak anomalous SSTs are left in the central Pacific (Fig. 2f), whereas remarkable anomalous TNA SST warming emerges in spring and persists into summer (Figs. 2e,f). Therefore, for the ELM-TNA group, the TNA SST warming is the dominant signal in the El Niño Modoki decaying summer, which acts as the main tropical forcing factor for the atmospheric circulation anomalies.

To determine in which El Niño Modoki group the WNPAC experiences a more evident reintensification process in summer, Fig. 3 shows the evolution of the anomalous 850-hPa wind and the associated stream-function responses to the two El Niño Modoki groups from winter to the following summer. For the ELM-CEP group, the anticyclonic anomalies over the western

North Pacific are seen in winter (Fig. 3a). Subsequently, this anomalous anticyclone over the western North Pacific becomes weakened in the following spring (Fig. 3b). Instead, we observe an anomalous anticyclone located in the central Pacific (Fig. 3b), however, which is not the WNPAC we focus on. The WNPAC at this time weakens. In summer, anticyclonic wind anomalies reintensify over the western North Pacific, indicating that the WNPAC reintensifies. However, the WNPAC intensity in Fig. 3c is much weaker than the composite result for all the El Niño Modoki events shown in Fig. 1c. The evolution of the WNPAC for the ELM-CEP group demonstrates that although there is indeed a WNPAC reintensification process, the WNPAC in summer is extremely weak. For the ELM-TNA group, the anticyclonic anomalies are seen from winter to the following summer (Figs. 3d–f), suggesting that the WNPAC always exists for three seasons. It is worth noting that the WNPAC intensity declines in spring (Fig. 3e) but substantially reintensifies in summer (Fig. 3f). The intensity of the WNPAC in summer for the ELM-TNA group is comparable to that shown in Fig. 1c. Therefore, the ELM-TNA cases have a more evident WNPAC reintensification process compared with the ELM-CEP cases, implying that the TNA SST warming plays a much more important role in reintensifying the WNPAC than the CEP SST cooling during the El Niño Modoki decaying summer.

FIG. 3. Composite 850-hPa wind anomalies (vectors; m s^{-1}) and 850-hPa streamfunction (shading; $10^6 \text{ m}^2 \text{ s}^{-1}$) for the (a)–(c) ELM-CEP group and (d)–(f) ELM-TNA group. Only wind vectors exceeding the 95% confidence level based on a two-tailed Student's t test are plotted. The symbol “A” denotes the anomalous western North Pacific anticyclone.

In addition, the WNPAC in winter and following spring shows distinct features between the ELM-CEP and ELM-TNA groups, which is caused by the different intensity and evolution of the El Niño

Modoki SST anomalies. This difference is however not the main focus of this study. In the following sections, we focus on the physical process of the WNPAC generation forced by CEP SST cooling and

FIG. 4. Composite free-tropospheric temperature anomalies (shading; $^{\circ}\text{C}$) and 200-hPa velocity potential (contours) during the El Niño Modoki decaying summer for the (a) ELM-CEP group and (b) ELM-TNA group. The contour interval is $5 \times 10^5 \text{ m}^2 \text{ s}^{-1}$. The stippled regions indicate where the free-tropospheric temperature anomalies are above the 95% confidence level based on a two-tailed Student's *t* test.

TNA SST warming during the El Niño Modoki decaying summer.

b. WNPAC generation process during El Niño Modoki decaying summer

Figure 4 shows the composite of 200-hPa velocity potential anomalies and free-tropospheric temperature anomalies for the ELM-CEP and ELM-TNA groups. For the ELM-CEP group (Fig. 4a), the anomalous CEP SST cooling produces upper-level anomalous convergence over the CEP and divergence over the Indian Ocean, and thereby anomalous Walker circulation is formed with upward motion over the CEP and downward motion over the Indian Ocean. Hence, the convection over the tropical central Pacific is suppressed in such a case. Convection can adjust the free-tropospheric temperature (Hurrell and Trenberth 1998; Sobel et al. 2002). Therefore, the cold SST anomalies over the tropical central Pacific convective region act to cool the tropospheric column. The cold free-tropospheric temperature anomalies over the tropical region are observed for the ELM-CEP group (Fig. 4a), which further confirms the close relationship between tropical SST anomalies and free-tropospheric temperature anomalies that is widely known (Hurrell and Trenberth 1998; Sobel et al. 2002). The free-tropospheric temperature

anomalies spread over most of the tropics via the atmospheric waves (Fig. 4a), although the cold SST anomalies are concentrated in the tropical central Pacific (Fig. 2c). The negative free-tropospheric temperature anomalies have a Matsuno–Gill spatial pattern (Gill 1980; Matsuno 1966). A Rossby wave pattern with a pair of maximum anomalies off the equator over the central-eastern Pacific propagates westward and a Kelvin wave propagates eastward into Africa (Fig. 4a). Accordingly, as a Rossby wave response to cold SST anomalies over the central Pacific, the atmospheric anomaly is characterized by a pair of anticyclones over the central-western Pacific (Fig. 5a). Note that the wind anomaly over the central Pacific is much more significant than that over the western North Pacific. Therefore, a weak WNPAC is formed for the ELM-CEP group (Figs. 3c and 5a).

In contrast, for the ELM-TNA group, the anomalous TNA SST warming induces upper-level divergence over the TNA (Fig. 4b). Hence, the TNA convection is enhanced and then warms the free-tropospheric temperature. The warm free-tropospheric temperature anomalies have a Rossby wave spatial pattern with a pair of maximum anomalies off the equator over the west side of the TNA SST warming and a Kelvin wave pattern over the east side of the TNA. This Kelvin

FIG. 5. Composite 1000-hPa wind anomalies (vectors) and associated streamfunction anomalies (shading; $10^6 \text{ m}^2 \text{ s}^{-1}$) for the (a) ELM-CEP group and (b) ELM-TNA group. Only wind vectors exceeding the 95% confidence level based on a two-tailed Student's t test are plotted. The symbol "A" denotes the anomalous western North Pacific anticyclone.

wave signal extends to the western Pacific due to its fast propagation speed (Fig. 4b). In terms of low-level wind and streamfunction anomalies (Fig. 5b), over the western side of the TNA, a pair of anomalous cyclones symmetric about the equator is observed, which is a Rossby wave response emanating from the TNA and propagating westward. This wind anomaly is consistent with the Rossby wave spatial pattern of the warm free-tropospheric temperature anomalies (Fig. 4b). More importantly, note that over the western North Pacific, there is a robust WNPAC (Fig. 5b), which is much stronger and larger than that for the ELM-CEP group. This WNPAC formation has a close relationship with the Kelvin wave emanating from the TNA SST warming region. The TNA warming-induced Kelvin wave is only related to the anomalous easterly winds over the western North Pacific (Xie et al. 2009). However, how this Kelvin wave (i.e., anomalous easterly winds) links to the WNPAC formation can be explained by the Kelvin wave-induced divergence over the western North Pacific. This process is well investigated in the study of Xie et al. (2009). They proposed that surface

friction drives the anomalous surface easterly winds into northeasterly winds over the western North Pacific, causing surface divergence and suppressing the western North Pacific deep convection. Then such suppressed convection induces the formation of the WNPAC via the Matsuno–Gill response (Xie et al. 2009). The process of the Kelvin wave-induced Ekman divergence over the western North Pacific is also evident for the ELM-TNA cases. In Fig. 5b, surface wind anomalies over the western Pacific are characterized by anomalous northeasterly winds, which cross the anomalous streamfunction line, indicating an obvious divergence feature. Moreover, Fig. 6 gives the composite anomalous low-level divergent winds, potential velocity, and 500-hPa vertical p velocity for the ELM-TNA cases. It can be seen that there are obvious low-level divergent anomalies over the western North Pacific, and the anomalous vertical motion is downward (Fig. 6). Thus, the convection is suppressed over the western North Pacific. Subsequently, the WNPAC is generated by the suppressed convection over the subtropical western Pacific via inducing a Rossby wave response. In fact, the

FIG. 6. Composite 500-hPa vertical p -velocity anomalies (shading; $10^{-2} \text{ Pa s}^{-1}$), 850-hPa velocity potential (contours), and the related divergent wind anomalies (vectors) during the El Niño Modoki decaying summer for the ELM-TNA group. The contour interval is $1.5 \times 10^5 \text{ m}^2 \text{ s}^{-1}$.

physical process that the anomalous TNA SST warming induces a WNPAC is similar to that of the anomalous north Indian Ocean SST warming induces a WNPAC (Rong et al. 2010; Ham et al. 2013a,b; Xie et al. 2009; Yang et al. 2007).

On the basis of the above analysis, we find that the anomalous CEP SST cooling and the TNA SST warming produce a WNPAC via distinct physical processes. The CEP SST cooling forces a WNPAC through a Rossby wave emanating from the central Pacific, while the TNA SST warming forces a WNPAC via a Kelvin wave emanating from the TNA and a Kelvin wave-induced Ekman divergence process over the western North Pacific. This raises the question why the WNPAC forced by the TNA warming is much stronger than that forced by the CEP cooling. In terms of the SST anomalies, the SST cooling over the central Pacific where the SST

anomalies are actually valid to drive the atmospheric anomalies is much weaker than the SST warming over the TNA (Figs. 2c,f). Thus, the weak CEP SST cooling is not in favor of producing a strong WNPAC. Is this the only reason for the different response of the WNPAC intensity to the CEP SST cooling and TNA SST warming? What happens if we set the SST anomalies over the CEP and TNA with equal magnitude? Therefore, in the next section, a numerical simulation is explored to try to answer the above questions. In addition, the observational analysis has the limitation of an insufficient number of samples. Furthermore, we cannot completely exclude the impacts of SST anomalies in other oceans using observational data. A numerical simulation can avoid these limitations of the observational analysis.

c. Numerical simulation results

A series of experiments is set, including one control run and several sensitivity runs forced by different SST boundary conditions. The detailed experiment design is shown in Table 1. We integrate each experiment for 20 years. To avoid the initial influence, the first 5 years of integration are discarded and the remaining 15 years are retained. The ensemble-mean results are shown here, which can largely remove the internal variability. The atmospheric responses to prescribed SST anomalies are obtained by the difference between the sensitivity run and control run.

First, we specify the model SST anomalies according to the observed anomalous SST distribution over the CEP and TNA, respectively (Table 1). Figure 7 shows anomalous 850-hPa wind responses to the forcing of CEP SST cooling (CEP_run minus CLIM_run) and TNA SST warming (TNA_run minus CLIM_run), respectively. The anomalous CEP SST cooling induces negative rainfall anomalies over the central Pacific, which are located on both sides of the equator (Fig. 7a). This negative rainfall anomaly further forces a low-level

TABLE 1. Experiment details.

Experiment name	Introduction of imposed SST boundary
CLIM_run	Monthly climatological SST
CEP_run	SST anomalies in the central-eastern Pacific (10°S – 10°N , 170°E – 80°W) for ELM-CEP group from January to December imposed on monthly climatological SST
TNA_run	As in CEP_run, but with SST anomalies in the TNA (0° – 25°N , 80° – 15°W) for ELM-TNA group
CEP_run_0.8	As in CEP_run, but with SST anomalies in the central-eastern Pacific with the equal magnitude of -0.8°C
TNA_run_0.8	As in TNA_run, but with SST anomalies in the TNA with the equal magnitude of 0.8°C
2009/2010_global	Global SST anomalies in the 2009/10 El Niño Modoki case imposed on climatological SST
2009/2010_global_without CEP	As in 2009/2010_global experiment, but with the imposed SST anomalies over the CEP region (20°S – 20°N , 120°E – 80°W) removed
2009/2010_global_without TNA	As in 2009/2010_global experiment, but with the imposed SST anomalies over the TNA region (15°S – 30°N , 80° – 10°W) removed

FIG. 7. Ensemble-mean anomalies of 850-hPa wind (vectors) and rainfall (contours) response to the (a) anomalous CEP SST cooling in CEP_run experiment and (b) anomalous TNA SST warming in TNA_run experiment. The shading denotes SST anomalies that are imposed on climatological SST. The contour interval is 1.2 mm day^{-1} . Red (blue) lines indicate negative (positive) rainfall anomalies. The symbol “A” denotes the anomalous anticyclone.

anticyclone over the central Pacific as a Rossby wave response (Fig. 7a). Note that this anticyclonic response is strong and robust over the central Pacific, but is extremely weak over the western North Pacific due to the effective forcing being located over the central Pacific (Fig. 7a). The simulated result is similar to the observed one, although there is a slight bias in that the low-level anticyclone induced by the CEP cooling is extended farther westward in the observations than in the simulations (Figs. 5a and 7a). Hence, the simulated results demonstrate that the role of CEP cooling in forcing a WNPAC generation is weak.

In contrast, the positive TNA SST anomalies produce positive rainfall anomalies over the TNA, which stimulates a Rossby wave over the western side of TNA and a Kelvin wave over the eastern side of TNA propagating eastward into western Pacific (Fig. 7b). These wave responses bear close resemblance to those simulated in Gill-Matsuno model (Matsuno 1966; Gill 1980), despite the fact that diabatic heating in this study is not artificially specified, but is generated via a full physical

process in response to warming SST anomalies. The Kelvin wave-induced divergence further leads to negative rainfall anomalies over the western North Pacific, which forces a remarkable WNPAC as a Rossby wave response (Fig. 7b). Its location is roughly consistent with the observed WNPAC in Fig. 5b, although its intensity is slightly weak. In general, the simulated results basically capture the observed difference between the CEP cooling-induced anticyclone and the TNA warming-induced anticyclone. This result confirms that the observed findings are robust, even though the number of observational samples is not sufficient.

To exclude the impacts of different anomalous SST intensity on the atmospheric response, we design another two sensitivity experiments with ideal equal magnitude of SST anomalies in the CEP and TNA regions, respectively. Here, we set the TNA and CEP SST anomalies with the equal and opposite values of 0.8° and -0.8°C , respectively—values that are stronger than the observed SST anomalies to obtain a much stronger atmospheric response. The detailed experiment

FIG. 8. Ensemble-mean anomalies of 850-hPa wind (vectors) and rainfall (contours) response to the (a) anomalous CEP SST cooling in CEP_run_0.8 experiment and (b) anomalous TNA SST warming in TNA_run_0.8 experiment. The blue (orange) shading denotes negative (positive) SST anomalies that are imposed on climatological SST. The contour interval is 2 mm day^{-1} . Red (blue) lines indicate negative (positive) rainfall anomalies. The symbol “A” denotes the anomalous anticyclone.

description is given in Table 1. In the CEP_run_0.8 experiment (Fig. 8a), the CEP cooling-induced negative rainfall anomaly is much stronger but its location is still in the central Pacific compared with that in the CEP_run experiment (Fig. 7a). Therefore, as a Rossby wave response, the forced anomalous anticyclone is still mainly located in the central Pacific (Fig. 8a). Instead, the anomalous cyclone covers the western North Pacific as a Rossby wave train emanating from the central Pacific (Fig. 8a). Therefore, the CEP SST cooling is not in favor of building an obvious and powerful WNPAC, even though the SST anomalies are strengthened. In the TNA_run_0.8 experiment (Fig. 8b), there is a pair of cyclonic responses over the western TNA and an anticyclonic response over the western North Pacific, which is much more significant and systematic compared with that in the TNA_run (Fig. 7b). This is because the TNA warming-induced positive rainfall anomalies and the associated Kelvin wave-induced negative rainfall anomalies over the western North Pacific are much more enhanced (Fig. 8b). Under the condition of equal magnitude of SST anomalies between CEP cooling and TNA warming, the TNA warming still induces a more robust WNPAC than the CEP cooling. This result implies that the distinct

physical mechanisms of the effects of the TNA warming and CEP cooling on WNPAC generation are the main reason for the different reintensification process of the WNPAC.

It is widely known that the impacts of tropical SST anomalies on the atmospheric anomalies are actually via inducing anomalous diabatic heating/cooling, which further disturbs the atmosphere by generating Rossby and Kelvin waves. In view of the crucial role of the anomalous diabatic heating/cooling in generating a WNPAC, we use a dry baroclinic model to investigate the role of the anomalous diabatic heating/cooling associated with TNA warming and CEP cooling in generating a WNPAC.

Anomalous ideal diabatic cooling/heating is set as an external forcing in the dry baroclinic model. In the horizontal, the anomalous diabatic heating/cooling has a rectangle profile (Fig. 9). In the vertical, the heating/cooling reaches its peak at $\sigma = 0.5$ with a value of 1.5 K day^{-1} , and its magnitude decreases upward and downward. According to the anomalous CEP SST cooling, the anomalous ideal diabatic cooling is placed in the central Pacific (15°S – 15°N , 160°E – 150°W) where the cold SST anomalies tend to suppress the deep

FIG. 9. The 850-hPa wind response to anomalous diabatic heating/cooling in (a) the ELM_CEP experiment, (b) ELM_TNA experiment, and (c) ELM_TNA_WNP experiment. The shading is the anomalous diabatic heating/cooling at $\sigma = 0.5$ with an interval of 0.3 K day^{-1} .

convection, which is called the ELM_CEP experiment. This anomalous diabatic cooling region is slightly different from that in Fig. 8a. To simplify the external forcing design, the anomalous diabatic cooling is set to an ideal shape symmetric about the equator (Fig. 9a). Based on the previous analyses, it is known that the TNA warming produces the WNPAC through two processes: One is the TNA warming-induced anomalous diabatic heating over the TNA, which emanates a Kelvin wave. The other is the Kelvin wave-induced suppressed convection (i.e., the anomalous diabatic cooling) over the western North Pacific, which induces the WNPAC as a Rossby wave

response. Here, in order to see the respective role of the anomalous diabatic heating over the TNA and anomalous diabatic cooling over the western North Pacific, two experiments are designed. In one experiment, which is called the ELM_TNA experiment (Fig. 9b), the ideal anomalous diabatic heating is placed in the TNA (0° – 25°N , 90° – 10°W) based on the TNA warming-induced positive rainfall anomalies. To further examine the role of the western North Pacific anomalous diabatic cooling in building a WNPAC, another experiment is designed, where the external forcing is confined not only over the TNA (0° – 25°N , 90° – 10°W)

region but also over the western North Pacific (10° – 20° N, 110° – 160° E) region (Fig. 9c). This experiment is referred to as the ELM_TNA_WNP experiment.

The low-level atmospheric responses to different anomalous diabatic heating/cooling are shown in Fig. 9. In the ELM_CEP experiment (Fig. 9a), the anomalous anticyclone forced by the anomalous CEP diabatic cooling is dominantly located over the central Pacific and extends westward into the western North Pacific. However, the anomalies over the western North Pacific are much weaker than those over the central Pacific (Fig. 9a). This is because the CEP diabatic cooling is far from the western North Pacific—the anticyclonic response gradually weakens from the central Pacific to the western Pacific. This result shows a large similarity to the observational result. In the ELM_TNA experiment, the anomalous TNA diabatic heating produces a pair of anomalous cyclones over the western side of the TNA as a Rossby wave response and anomalous easterly winds over the eastern side of the TNA as a Kelvin wave response (Fig. 9b). It is found that there is no anomalous anticyclone over the western North Pacific when there is a lack of anomalous western North Pacific diabatic cooling. In contrast, when the anomalous western North Pacific diabatic cooling is added and combines with the anomalous TNA diabatic heating, atmospheric responses over the western North Pacific are completely different. A conspicuous anticyclonic response appears over the western North Pacific (Fig. 9c). Such a result illustrates that the anomalous diabatic cooling over the western North Pacific is a key and indispensable process for the prominent impacts of TNA SST warming on the WNPAC formation. More importantly, it is only because of the existence of the anomalous diabatic cooling over the western North Pacific (i.e., the process of Kelvin wave–induced divergence over the western North Pacific) that the TNA SST warming can induce a much more powerful and significant WNPAC compared with CEP SST cooling.

4. A case study

The El Niño Modoki event that occurred in 2009/10 is characterized by robust cold SST anomalies over the CEP and warm anomalies over the TNA during the El Niño Modoki decaying summer (Fig. 10a). This means that there are two dominant tropical driving factors for the atmospheric anomalies for the 2009/10 El Niño Modoki case. In this section, we use a numerical simulation to further examine in which ocean the SST anomalies play a more important role in generating a WNPAC through designing different sensitivity experiments.

We first give the observational results, which are shown in Fig. 10. The SST anomalies in the decaying summer of the 2009/10 El Niño Modoki have a roughly

equal intensity over the CEP and TNA regions, with a maximum absolute value of 1°C (Fig. 10a). The wind anomalies are characterized by a pair of cyclones over the western side of the TNA due to the TNA warming forcing and a larger, strong anticyclone over the western North Pacific (Fig. 10b). The free-tropospheric temperature response shows an obvious warming that roughly surrounds the equator (Fig. 10c). On the basis of the abovementioned analysis, this free-tropospheric temperature warming is dominantly a response to the TNA SST warming not the CEP SST cooling, indicating that the TNA SST warming possibly plays a more prominent role in forcing atmospheric circulation anomalies.

The roughly equal intensity of the SST anomalies over the TNA and CEP provides a good opportunity to testify the relative importance of the TNA and CEP SST anomalies in forcing a WNPAC via setting different numerical sensitivity experiments (Table 1). Here, the SST anomalies over the global region according to the 2009/10 El Niño Modoki case are set as an external forcing and are imposed on the climatological SST in the AGCM, which is referred to as the 2009–2010_global experiment. Subsequently, in the experiment named 2009/2010_global_without CEP, the SST anomalies outside the Pacific region (20°S – 20°N , 120°E – 80°W) are imposed on the climatological SST. Over the Pacific region, the climatological SST is used to force the AGCM. Similarly, in the experiment named 2009/2010_global_withoutTNA, the SST anomalies outside the Atlantic region (15°S – 30°N , 80° – 10°W) are imposed on the climatological SST. The low-level wind responses to different SST anomaly forcings are shown in Fig. 11. In the 2009–2010_global experiment (Fig. 11a), a pair of anomalous cyclones over the western side of the TNA and a strong, large WNPAC can be observed, which has a good agreement with the observational results (Fig. 10a). When the anomalous cold SST forcing over the Pacific is removed, the wind responses over the equatorial CEP are slightly weakened (Fig. 10b). However, the response of the anomalous anticyclone over the western North Pacific is still significant and robust. This result indicates that when the role of the anomalous CEP SST cooling is removed, the TNA SST warming can still force a powerful and remarkable WNPAC. In contrast, when the role of TNA SST warming is removed in the 2009/2010_global_without TNA experiment (Fig. 11c), the WNPAC response is extremely weakened compared with the 2009/2010_global without CEP experiment. The results from Fig. 11 further verify the main finding of this study that the TNA SST warming exerts a much more important influence on the WNPAC than the CEP SST cooling.

FIG. 10. (a) SST anomalies ($^{\circ}\text{C}$), (b) 850-hPa wind anomalies (vectors) and the associated streamfunction anomalies (shading; $10^6 \text{ m}^2 \text{ s}^{-1}$), and (c) free-tropospheric temperature (850–200 hPa) anomalies for the decaying summer of the 2009/10 El Niño Modoki event.

5. Summary and discussion

The El Niño Modoki-induced WNPAC experiences an interesting evolution, which appears in El Niño Modoki mature winter, quickly decays in the following spring but interestingly reintensifies in the following summer. In this study, we focus on such a reintensification of an El Niño Modoki-induced WNPAC, and further investigate the relative roles of TNA SST warming and CEP SST cooling in reintensifying a WNPAC during the El Niño Modoki decaying summer.

The El Niño Modoki events are first divided into an El Niño Modoki with CEP SST cooling group and an El Niño Modoki with TNA warming group. In the ELM-CEP group, the WNPAC experiences a weak reintensification during the decaying summer, while it experiences an apparent reintensification in the ELM-TNA group. This difference is caused by the distinct

location of the effective tropical forcing between the CEP SST cooling and TNA SST warming. The anomalous CEP SST cooling produces anomalous downward motion over the central Pacific. Therefore, the convection is suppressed over the central Pacific, which further stimulates an anticyclone over the central-western Pacific. This anticyclonic response is strong over the central Pacific, but it gradually weakens over the western Pacific due to the effective forcing far from the western Pacific. Therefore, the WNPAC induced by the CEP SST cooling is much weaker, indicating a weak reintensification of the WNPAC. In contrast, in the ELM-TNA group, the TNA SST warming leads to upward motion over the TNA region. The resultant enhanced convection over the TNA stimulates a Kelvin wave over the east side of TNA that propagates into the western Pacific. Surface friction drives the anomalous western North Pacific surface winds into northeasterly

FIG. 11. Ensemble-mean anomalies of 850-hPa wind response (vectors; m s^{-1}) to the SST anomalies in (a) the 2009/2010_global experiment, (b) the 2009/2010_global_without CEP experiment, and (c) 2009/2010_global_without TNA. The shading is the forcing of SST anomalies ($^{\circ}\text{C}$).

winds in a Kelvin wave, which cross the anomalous streamfunction line, causing an obvious divergence over the western North Pacific. Thus, a powerful WNPAC is generated by the western North Pacific suppressed convection. Therefore, the effective forcing for producing a WNPAC is located in the western North Pacific for TNA SST warming, whereas it is located in the central Pacific for CEP SST cooling. Therefore, the TNA SST warming can produce a much more significant and powerful WNPAC.

An AGCM and a dry baroclinic model are used on the one hand to test the observed results and on the other

hand to further explore which physical process is responsible for the TNA warming forcing a more powerful WNPAC than CEP cooling. First, the observed SST anomalies over the CEP and TNA are respectively set as the external forcing in an AGCM. The simulation results confirm the observational findings that the TNA warming can induce a much stronger WNPAC compared with the CEP cooling. Second, to remove the impacts of SST anomalies with different intensities on the WNPAC formation, the AGCM is forced respectively by an equal magnitude of SST anomalies over the CEP and TNA regions. In such a situation,

FIG. 12. Composite summer (JJA) SST anomalies (shading; $^{\circ}\text{C}$) and 850-hPa wind anomalies (vectors) for (a) all the CEP SST cooling cases and (b) all the TNA SST warming cases. Only wind vectors exceeding the 95% confidence level based on the Student's t test are plotted.

the TNA warming still forces a much more powerful and larger WNPAC than CEP cooling, indicating that the difference in the anomalous SST intensity between the TNA and CEP regions is not the main reason for the TNA warming inducing a more powerful WNPAC than CEP cooling. An El Niño Modoki case study also demonstrates the above results.

In addition, in the sensitivity experiments where the anomalous TNA SST warming is set as a forcing, we found that the suppressed convection (negative rainfall anomaly) is observed only in the western Pacific–Bay of Bengal–Indian island belt but not in the Indian Ocean (Figs. 7b and 8b). It is possibly because over the Asian region, the largest climatological rainfall belt in summer is located in western Pacific–Bay of Bengal–Indian island region, where hence the convection is more easily suppressed.

Furthermore, we utilize a dry baroclinic model to illustrate the roles of diabatic cooling/heating associated with CEP SST cooling and TNA warming in producing a WNPAC. It is found that the anomalous TNA diabatic heating induced directly by the TNA SST warming can generate a Kelvin wave that spreads into the western Pacific, but fails to force a WNPAC. When the anomalous TNA diabatic heating is combined with the anomalous western North Pacific diabatic cooling that is associated with the Kelvin wave–induced divergence process, a powerful anticyclone is formed over the

western North Pacific. Therefore, the western North Pacific diabatic cooling (i.e., Kelvin wave–induced divergence) plays a key and indispensable role in WNPAC formation. In contrast, the anomalous CEP diabatic cooling generates an anticyclone over the central-western Pacific via emanating a Rossby wave. However, this anticyclone becomes gradually weaker from the central Pacific to the western Pacific, which is consistent with the observational results. Since the CEP diabatic forcing is located far from the western North Pacific compared with the TNA warming–induced western North Pacific diabatic cooling, the forced WNPAC is much weaker for CEP SST cooling situation.

It is widely known that an El Niño event can cause abnormal summer rainfall and temperatures over East Asia via an anomalous WNPAC (e.g., Wang et al. 2003; Wu et al. 2003). However, many factors can force a WNPAC, such as Indian Ocean warming, TNA warming and CEP cooling, which are discussed in this study. Plus, due to the complex relationship between El Niño and remote ocean SST anomalies, the El Niño–WNPAC relationship correspondingly becomes complicated. For El Niño Modoki events during its decaying summer, some cases are accompanied by anomalous TNA SST warming, some decay into cold SST anomalies over the CEP, and some cases are accompanied by TNA

warming and CEP cooling simultaneously. Therefore, the different anomalous SST distributions make the El Niño Modoki–WNPAC relationship difficult to predict. This study provides a reminder that we should note the features and combinations of SST anomalies over different tropical regions when we use El Niño Modoki to predict the EASM condition.

To see whether the difference in producing the WNPAC by the TNA SST warming and CEP SST cooling is universal, we select all the cases respectively with TNA warming and CEP cooling in summer without considering the existence of El Niño Modoki events in the previous winter. Here, the TNA warming and CEP cooling indices are defined by the area-averaged SST anomalies over the TNA (0° – 25° N, 80° – 10° W) and over the CEP (5° S– 5° N, 180° – 120° W), respectively. TNA warming (CEP cooling) cases are selected based on the TNA warming (CEP cooling) index. The results are shown in Fig. 12, which gives the composite SST anomalies and 850-hPa wind anomalies for the all the CEP cooling and TNA warming cases, respectively. It can be seen that the WNPAC induced by the CEP SST cooling is much weaker than that induced by the TNA SST warming (Figs. 12a,b). In addition, the features of WNPAC, including its intensity and domain, are similar to Fig. 5. This result indicates that the different impacts of CEP SST cooling and TNA SST warming on the WNPAC formation are a universal phenomenon regardless of whether there is an El Niño Modoki in the previous winter.

Note that the difference between the CEP cooling-induced WNPAC and the TNA warming-induced WNPAC lies not only in WNPAC intensity but also in its location. The CEP cooling-induced WNPAC is often located more equatorward, while the TNA warming-induced WNPAC is located more northward. This difference would have potentially distinct impacts on the western North Pacific monsoon trough, tropical cyclone activity in western Pacific and East Asian summer monsoon, which deserves further investigation.

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