Interdecadal enhancement in the relationship between western North Pacific summer monsoon and sea surface temperature in the tropical central-western Pacific after the early 1990s

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ABSTRACT

This study reveals the interdecadal strengthening in the relationship between the western North Pacific summer monsoon (WNPSM) and tropical central-western Pacific sea surface temperature anomaly (SSTA) in summer after the early 1990s. In the first period (1979–1991, P1), the WNPSM-related precipitation anomaly and horizontal wind anomaly are presented as a analogous Pacific-Japan (PJ)-like pattern, generally considered as to be related to the Niño-3 index in the preceding winter. During a subsequent period (1994–2019, P2), the WNPSM-related precipitation anomaly presents a zonal dipole pattern, correlated significantly with the concurrent SSTA in Niño 4 and tropical western Pacific. The negative (positive) SSTA in tropical western Pacific and positive (negative) SSTA in Niño 4 area, could work together to influence the WNPSM. And the two types of anomalous SSTA configuration enhance/weaken the WNPSM by the positive/ negative phase PJ-like wave and Gill response, respectively, with an anomalous cyclone/anticyclone located in WNPSM, which shows obvious symmetry about the anomalous circulation. Specifically, the SSTA in Niño 4 exerts impacts on WNPSM by atmospheric Gill response, with stronger (weaker) WNPSM along with positive (negative) SSTA in Niño 4. And the SSTA in tropical western Pacific exerts influence on the WNPSM by PJ-like wave, with stronger (weaker) WNPSM along with negative (positive) SSTA in the tropical western Pacific. In general, SSTA in the tropical western Pacific and Niño 4 could work together to exert influence on the WNPSM, mainly concentrated in the El Niño (La Niña) developing year in P2. However, SSTA in the tropical western Pacific/ Niño 4 works alone to exert influence on WNPSM mainly in 2013,2014,2016,2017/CP La Niña developing years. The sensitive experiments also can reproduce the PJ-like wave/Gill response associated with SSTA in the tropical western Pacific/Niño 4. Therefore, the respective and synergistic impacts from Niño 4 and the tropical western Pacific on WNPSM have been revealed, which helps to acquire a better understanding about the interdecadal variation of WNPSM and associated climate influences.

Key words: western North Pacific summer monsoon, tropical central-western Pacific, SST, interdecadal change https://doi.org/10.1007/s00376-023-2200-0

Article Highlights:

The interdecadal enhancement in the relationship between the WNPSM and tropical central-western Pacific SSTA after the early 1990s has been revealed.

The SSTA in tropical western Pacific exerts influence on WNPSM by PJ-like wave, and SSTA in Niño 4 exerts impact on WNPSM by Gill response.

The respective and synergistic impacts of the Niño 4 and tropical western Pacific on WNPSM have been confirmed by numerical experiments.

1. Introduction

Asia summer monsoons is composed of the Indian summer monsoon (ISM), East Asian summer monsoon (EASM), and western North Pacific summer monsoon (WNPSM), considered as one of the most important climate systems for earth (Wang et al. 2000; Wang et al. 2001; Kwon et al. 2005; Lee et al. 2014). Compared to ISM and EASM, the WNPSM obtained less attentions, mainly located at 5°–15°N, 100°–130°E and 20°–30°N, 110°–140°E (Wang et al. 2001). However, a large proportion of the rainfall in Indochina Peninsula, Philippines, and south China is related with the WNPSM (Vega et al. 2020), and has large variations, which can affect agriculture and lives of millions of people (Wu and Wang 2000; Wu 2002; Chou et al. 2003). Therefore, to understand the variability of WNPSM has great socioeconomic significance.

The WNPSM features complex spatiotemporal variations, mainly in terms of the burst, withdrawal, and the breaks along with its northward progress. The onset date displays a high interannual variability (Vega et al. 2020), and during the period the rainfall is mainly located in the South China Sea (Wu and Wang 2000; Wang and Lin 2002). In contrast, the WNPSM withdrawal presents a lower interannual variation (Vega et al. 2020), spanning from September to November (Wang and Lin 2002; Janowiak and Xie 2003; Zeng and Lu 2004). In addition, during the period of northeastward movement, WNPSM has a distinct monsoon break phenomenon. When the WNPSM passes through the Philippines and the Mariana Islands (Wu and Wang 2000; Wang and Lin 2002;Zhou and Chan 2007), it presents a prominent interannual variation in either intensity or duration (Wang and Xu, 1997; Xu and Lu, 2015).

The diverse variations of WNPSM have different climate impact, mainly in the associated circulation, precipitation, and tropical cyclone (TC) events. The strong (weak) WNPSM connects with the enhanced (reduced) precipitation over the subtropical WNP (Chou et al. 2003), and the negative (positive) rainfall anomalies along the mei-yu/baiu front (Wang et al. 2001). Even, a suppressed WNPSM has a remote influence on reduced summer rainfall over the Great Plains of the United States (Wang et al. 2001). During the break of WNPSM, striking convection suppression and remarkable decrease of precipitation over the Northeast of WNP (10°–20°N, 140°–160°E) happens (Xu and Lu, 2016). The WNPSM is also related to the extreme precipitation, by exerting influence on TC. The WNPSM break and WNPSM trough can influence the formation location, genesis frequency, and strength of TC (Gray 1968; Wu et al. 2012; Molinari and Vollaro 2013; Zong and Wu 2015; Choi et al. 2016), by the means of supplying the associated dynamic and thermodynamic conditions (Gray 1968; Briegel and Frank 1997; Wu et al. 2012; Cao et al. 2014; Zong and Wu 2015; Zhao et al. 2019), further leading to some extreme rainfall events in associated regions.

The influences from WNPSM on associated weather and climate are documented, and in addition, the impacts from other factors on WNPSM are also investigated, such as from intraseasonal oscillations (ISO), the atmospheric heat source, and tropical SST, etc. ISO has a significant impact on the interannual variability of onset, break of WNPSM and atmosphere-ocean interaction associated with the western Pacific subtropical high (WPSH) (Li and Wang et al. 2005; Zhou and Chan 2005; Xu and Lu, 2015; He et al. 2017; Wang and Yu, 2018; Huang et al. 2018; Wu and Wang, 2019), as well as its seasonal cycle (Wu and Wang 2000; Guan and Chan 2006). Atmospheric heat sources over the WNP (Wang et al. 2001) and the tropical Indian Ocean (Xie et al. 2009), are important in the formation of the circulation pattern associated with WNPSM. Besides, Hu and Long (2020) further considered that the combined action of an atmospheric heating (cooling) over the subtropical WNP and a cooling (heating) in the tropical Indian Ocean and the midlatitudes from China to the southern Japan, plays a most important role in enhancing (weakening) WNPSM. In addition, a significant connection between WNPSM and El Niño–Southern Oscillation (ENSO) has also been investigated (Wang et al. 2001). A weak (strong) WNPSM prefers to happen during the La Niña (El Niño) developing year and a strong (weak) WNPSM tends to appear in the La Niña (El Niño) decaying year (Wang et al. 2001; Chou et al. 2003). From the 1980s on, the WNPSM obviously tends to begin later (earlier) and finish earlier (later) in a eastern Pacific (EP) El Niño (La Niña) background, and the withdrawal of WNPSM is postponed (advanced) during CP La Niña (El Niño) (Vega et al. 2020). The interdecadal variation mode of the WNPSM trough is mainly related with the Pacific decadal oscillation (PDO) and the interdecadal Pacific oscillation (IPO) in different periods in the past decades, respectively (Feng and Wu, 2021). Besides, the decadal change of WNPSM break after 2002/2003 is attributed to the differences in the evolution of SST in the warm pool region of western Pacific after 2003 (Xu and Lu, 2018). Yim et al. (2008) considered that WNPSM in the period 1979–1993 is mainly linked to the warming of SST in the Niño 3 region (5°S–5°N, 150°W–90°W); but in the period

1994–2006 is associated with the SST warming in the Niño 4 region (5°S–5°N, 160°E–150°W).

In general, the previous studies mainly focus on the synoptic and interannual variability of WNPSM, and its association with different key sea region in the different situation, respectively. However, different key SST areas may work together to exert influence on the WNPSM, which has obtained few attention. The present study will conduct further exploration about this issue. We have further confirmed the result shown in Yim et al. (2008) before carrying out the research in this study. But besides the enhancement of the influence from Niño 4 region after 1994, we also find that the influence of the tropical western Pacific on WNPSM is also enhanced. Namely, the interdecadal strengthening in the relationship between WNPSM and tropical central-western Pacific after the early 1990s has been found in the study. Moreover, we also further explore when Niño 4 and tropical western Pacific work in accordance to impact on WNPSM, and when they work alone to exert influences on WNPSM.

In this paper, the characteristics and associated physical processes of the interdecadal change in the relationship between SSTA in the tropical central-western Pacific and WNPSM are investigated. The data and methods used in the study are described in section 2. Section 3 confirms the enhancement of the interdecadal relationship between WNPSM and SSTA in the tropical central-western Pacific after the early 1990s. Section 4 outlines how the tropical central and western SSTA influences WNPSM after the interdecadal shift of the early 1990s, respectively. Section 5 discusses when tropical western Pacific, and Niño 4 area work in coherence to influence the WNPSM, and when they work alone to exert an impact on WNPSM, respectively. Finally, conclusions and a discussion are presented in the section 6.

2. Data and Methods

In this paper, JRA-55 monthly reanalysis data are applied, with 1.25° × 1.25° horizontal resolution (Kobayashi et al. 2015). Monthly precipitation data from the Global Precipitation Project (GPCP) are adopted, with 2.5° × 2.5° horizontal resolution (Adler et al. 2003). Monthly average SST data (HadISST version 1.1) are obtained from the Hadley Centre, with 1° × 1° horizontal resolution (Rayner et al. 2003). This study focuses on the period from 1979 to 2019. The 15-year sliding correlation is applied in this study, which can extract the active time ranges of two factors acting mutually and resist the disturbance of noises (Xie et al. 2016). Here, the width of the moving window (15 years) was determined considering the sample size.

The WNPSM index (hereafter WNPSMI) was defined as the normalized difference of 850-hPa zonal wind between the southern region (5°–15°N, 100°–130°E) average and northern region (20°–30°N, 110°–140°E) average, following Wang and Fan (1999) and Wang et al. (2001). Namely, the bigger WNPSMI value is, the stronger the WNPSM is. The Niño-3 index is defined as the average of SSTAs in the eastern equatorial Pacific (5°S–5°N, 90°–150°W). Here, JJA (June, July and August) refers to the summer. In the figures, “A” and “C” indicate the anomalous anticyclone and cyclone, respectively, which are marked in Figures 5-11. We also define the tropical western Pacific index (TWPI) using SSTA averaged over 5°S–5°N, 120°–140°E, and the Niño 4 index using SSTA in 5°S–5°N, 160°E–150°W. And the normalized sequence of the subtraction between Niño 4 and TWPI is defined as the tropical central-western Pacific thermal contrast index (TCWI).

To confirm the relative influence of the Niño 4 and tropical western Pacific on WNPSM, we perform the numerical experiments using the Community Atmospheric Model of version 5.0, which is widely used for a variety of atmosphere- and climate-related studies and offers an ability to be configured with a variety of physical parameterization suites of varying complexity. The model is developed by the National Center for Atmospheric Research with an approximately 1.9° × 2.5° latitude-longitude spatial resolution and 31 vertical levels (Neale et al., 2010). We perform one control experiment and three sensitivity experiments. In all experiments, the model is integrated for 20 years. The control experiment serves as a reference for the sensitivity experiment, with climatological monthly SST for the period 1981–2010 specified in the global oceans. In the sensitivity experiments, the SST forcing is composed of climatological monthly SST and monthly idealized SST anomalies added in Niño 4 (5°S–5°N, 160°E–150°W), marked in the right box in Fig.1, in the tropical western Pacific (5°S–5°N, 120°E–140°E), marked in the left box in Fig.1, as well as these both as shown, determined based on the statistical analyses. The specified monthly SST forcing repeats from year to year, and the largest SST anomalies are 0.6℃ and –0.6℃, respectively. In the first sensitivity experiment, positive SST anomalies are added in the central Pacific to climatological monthly SST, and the results are displayed in Fig. 6(f). In the second sensitivity experiment, negative SST anomalies are added in the western Pacific to climatological monthly SST, and the results are shown in Fig. 7(f). In the third sensitivity experiment, positive and negative SST anomalies are added in the above two regions, respectively, to climatological monthly SST, shown in Fig. 9. The differences of last 16 years horizontal wind anomalies between sensitivity experiments and control experiment represent the atmospheric circulation response to the JJA SST anomalies.

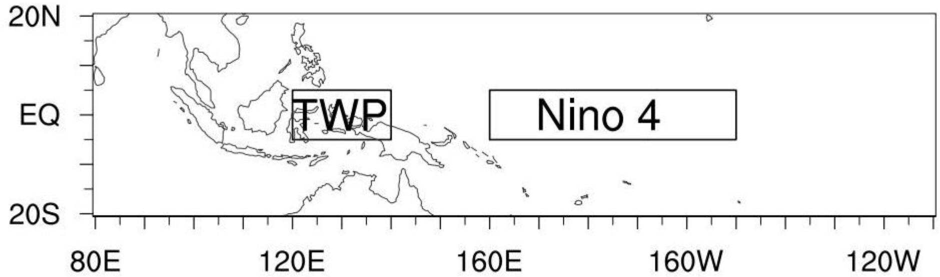

FIG. 1.The locations to add SSTA in sensitive experiments.

3. Interdecadal change in the relationship between WNPSM and the tropical central-west Pacific SST

As displayed in Fig. 2a, the significant domains of correlation between WNPSM and the tropical SST, mainly concentrate in the tropical Indian Ocean prior to the 1990s, but after the 1990s, the significant areas mainly appear in the tropical central-west Pacific. It means that a strong (weak) WNPSM is accompanied by a cold (warm) SSTA in the tropical Indian Ocean before the early 1990s. Whereas, when the positive (negative) SSTA appears in the Niño 4 (5°S–5°N, 160°E–150°W) area and negative (positive) SSTA appears in the tropical west Pacific (5°S–5°N, 120°E–140°E), a strong (weak) WNPSM easily generates after the early 1990s. The key SSTA areas associated with strength of WNPSM differ greatly before and after 1990, therefore, we divide the research period into two subsection 1979–1991 (Period 1, referred to as P1) and 1994–2019 (Period 2, P2).

As shown in Figs. 2b, 2c, there is an obvious interdecadal change in the relationship between Niño 4 and WNPSMI, with an insignificant correlation during P1, and a significant correlation up to 0.41 ($p > 95\%$) during P2. Similarly, as shown in Figs. 2d, 2e, there is an obvious interdecadal change in the relationship between TWPI and WNPSMI, also with an insignificant correlation during P1, and a significant correlation up to –0.56 ($p > 99\%$) during P2. As shown in Figs. 2(f), (g), we define TCWI, and calculate its correlation with WNPSMI, with the correlation coefficient up to 0.54 (p >

99%) during P2.

The correlation between TWPI and WNPSMI (-0.56) during P2 is more significant than that between Niño 4 and WNPSMI (0.41), and that between TCWI and WNPSMI (0.54), which implies that the SSTA in Niño 4 and TWPI do not always work in coherence, and tropical western Pacific SST may play a more important role in influencing WNPSM during P2.

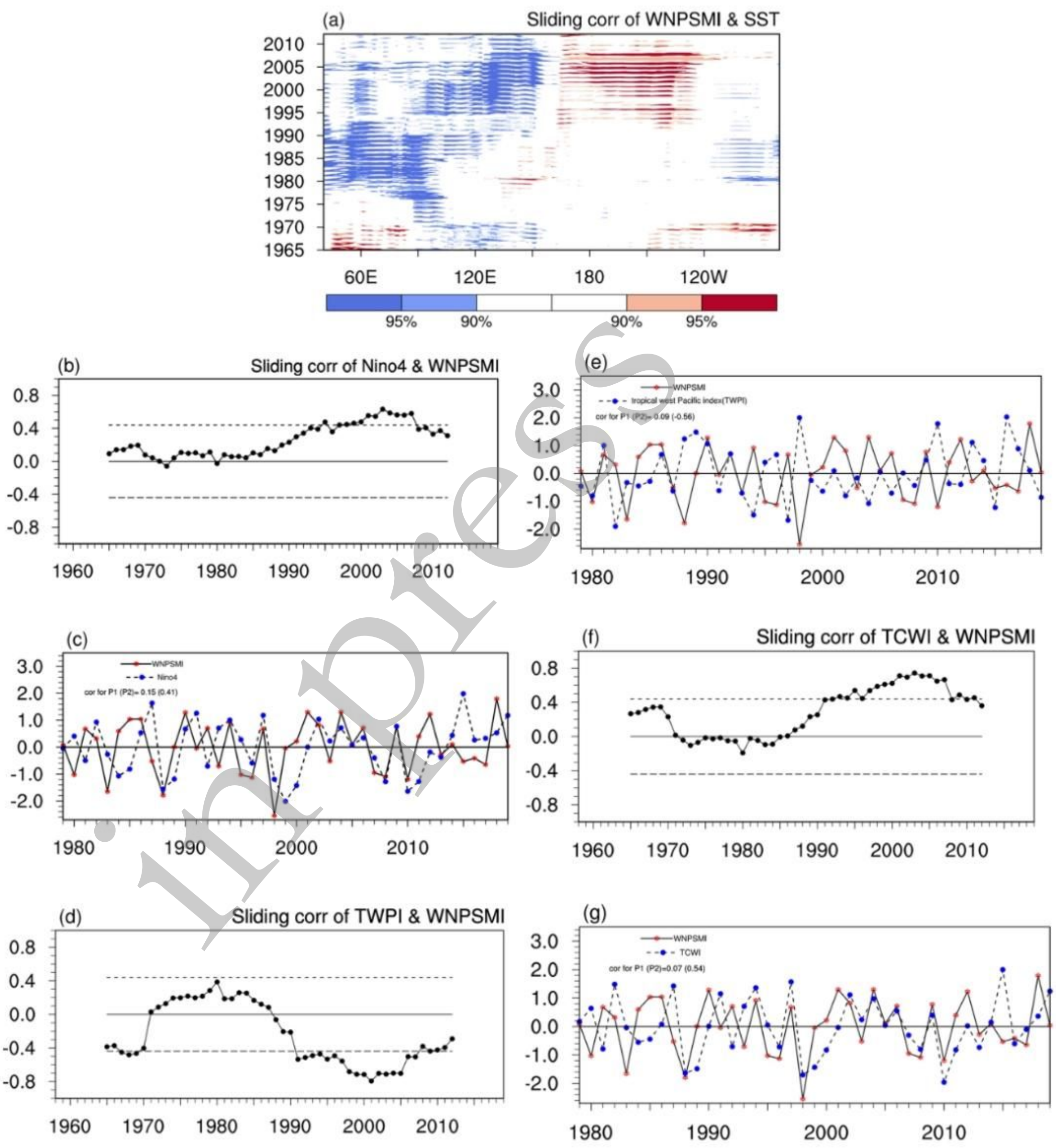

FIG. 2. (a) The 15-year moving correlation between WNPSMI and simultaneous JJA SST (9.5°S–9.5°N); light/dark areas on behalf of 90%/95% confidence level. (b) The 15-year moving correlation between WNPSMI and concurrent Niño-4, and dashed lines indicate 90% confidence level. (c) The WNPSMI index and JJA Niño-4 index, as well as their correlation between 1979–1991 (P1) and 1994–2019 (P2). (d), (e) same as (b), (c), but for TWPI. (f), (g) same as (b), (c), but for TCWI.

As displayed in Fig. 3a, the significant area of correlation mainly concentrates in the tropical Indian ocean in JJA. However, when the impact of Niño 3 in the preceding winter is detached, the correlation decreases dramatically, as presented in Fig.3b. Hence, the WNPSM is mainly related to SSTA of Niño 3 in the preceding winter during P1, consistent with the result obtained by Yim et al. (2008).

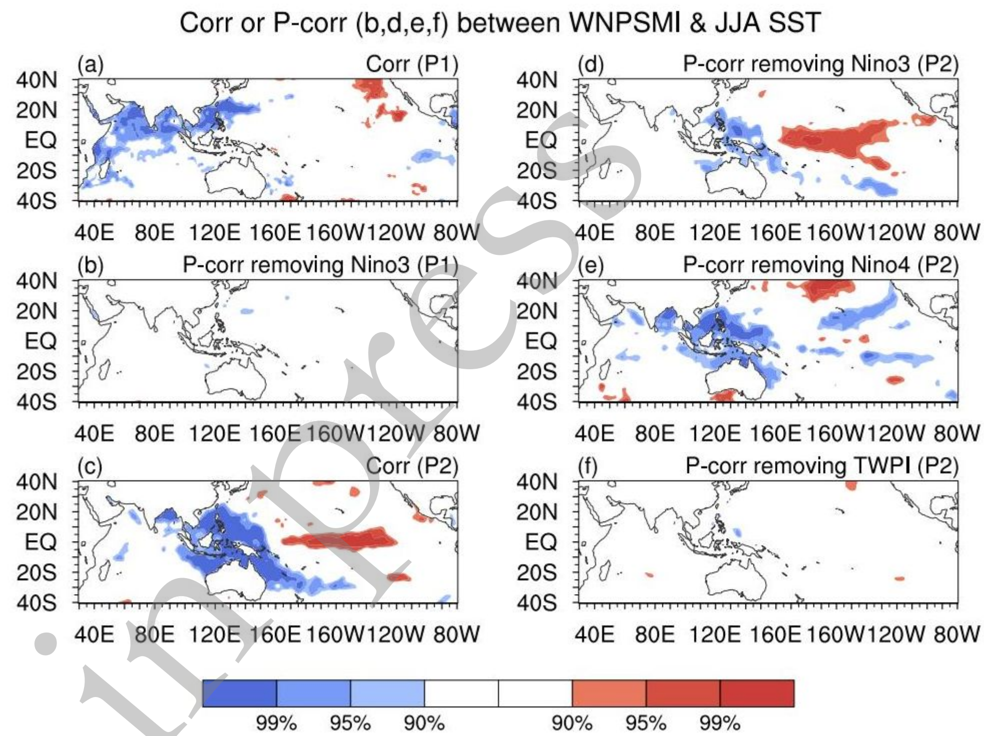

FIG. 3. Correlation (a) and (b) partial correlation of WNPSMI and synchronous JJA SST, detaching impact of Niño 3 in preceding winter during P1. (c)–(d) same as (a)–(b), but for P2, and (e), (f) same as (d), but removing the synchronous impact of Niño 4 and TWPI, respectively. Light to dark shading indicates 90%, 95%, and 99% confidence levels.

As shown in Fig. 3c, the significant region of correlation is mainly located in the tropical west Pacific and central Pacific. However, when the influence from Niño 3 in the preceding winter is removed (Fig. 3d), the significant correlation in the tropical western and central Pacific still remains there, which suggests that SSTA associated with WNPSMI during P2 is not governed by Niño 3 in the preceding winter, which differs greatly to that in P1. When the concurrent influence of Niño4 (Fig. 3e) is removed, the SSTA in the tropical western Pacific still remains and only the SSTA in central Pacific disappears. However, when the influence of TWPI is removed, the significance over the tropical central-west Pacific decrease dramatically (Fig. 3f), which implies that compared to Niño 4, maybe TWPI plays a more important and independent role in exerting influences on WNPSMI during P2.

As displayed in Fig. 4a, the most visible precipitation anomaly is a Pacific-Japan (PJ)-like pattern in JJA during P1. Nevertheless, when the impact from Niño 3 in preceding winter is removed, the areas through above 90% confidence level almost disappear (Fig. 4b), which further indicates that the relationship between WNPSMI and precipitation over western Pacific and East Asia is mainly dominated by Niño 3 during P1.

As displayed in Fig. 4c, the significant precipitation anomaly demonstrates a dipole pattern during P2, with negative correlation to the west of 140°E and positive correlation to the east of 140°E, which means that a strong WNPSM is accompanied by a positive rainfall anomaly in the tropical western Pacific and a negative rainfall anomaly in Marine continent. When the influence from Niño 3 in the preceding winter and concurrent Niño 4 is removed respectively, the significance dipole pattern still remains (Figs. 4d, e), which bears a similarity to the pattern shown in SSTA in Fig. 3(c), except within a smaller scope and shifting westward. Whereas, the dipole pattern weakens obviously, with the removing of the influence from TWPI (Fig. 4f), which means that the precipitation linked with WNPSM during P2, is mainly connected with both Niño 4 and TWPI, both of which obtain less modulations of Niño 3 in the preceding winter. Moreover, maybe the tropical western Pacific plays a more important role, same as the results obtained in Fig. 3.

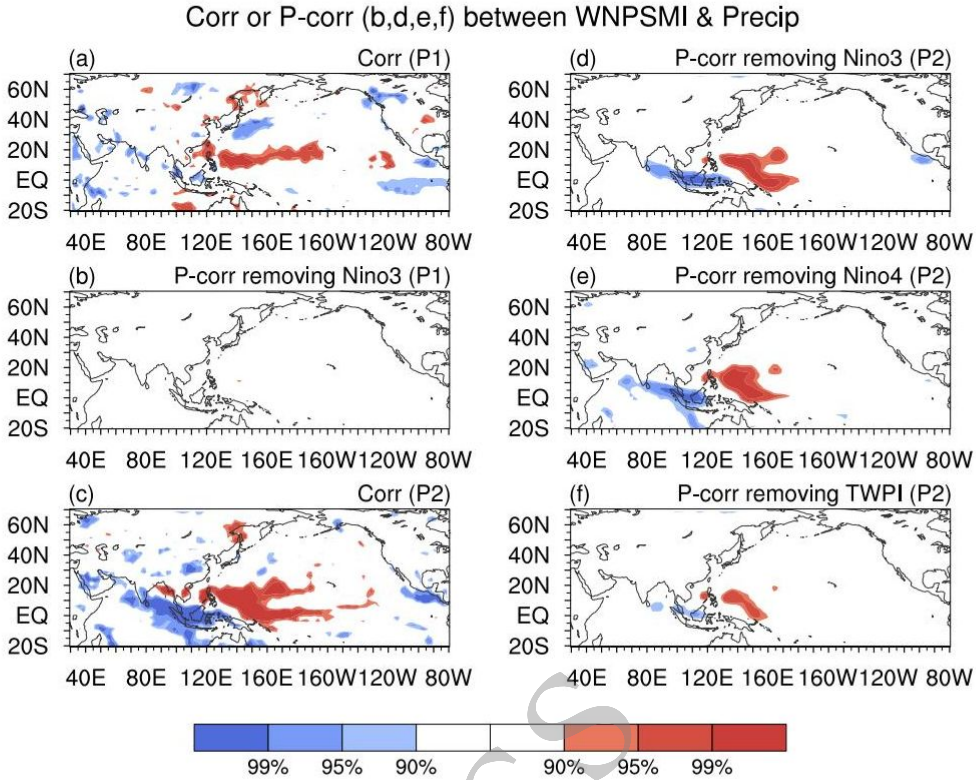

FIG. 4. Same as Fig. 3 but for WNPSMI and grid GPCP precipitation.

The circulations related to WNPSMI also have different features during P1 and P2. During P1, when WNPSM is strong, the anomaly of horizontal wind related to WNPSM exhibits a positive-phase PJ-like pattern, with anomalous cyclones existing in 0°–30°N and mid–high latitudes (45°–60°N) and an anomalous anticyclone in between (30°–45°N) at 850-hPa level (Fig. 5a), which parallels the pattern displayed in Fig. 4(a). A similar tripolar pattern also exists in the horizontal wind of 200-hPa, albeit with anomalous cyclone near the equator tilting northward, a stronger middle polarity and a weaker cyclone in northernmost polarity (Fig. 5b). During P1, the PJ-like pattern features an equivalent barotropic structure in the lower and upper troposphere. Furthermore, the PJ-like pattern could also be distinguished in the 500-hPa geopotential height, with the significant area only centered in the polarity near the equator, and the significant area in 2-m air temperature passing through the 95% confidence level, only concentrated in the middle polarity (Fig. 5c).

During P1, the correlation is 0.88 between WNPSMI and PJ index, which is defined as the first principal component of the EOF (Empirical orthogonal function decomposition) analysis of 850-hPa vorticity field over (0°–60°N, 100°–160°E) based on Kosaka and Nakamura (2010). When the impact of Niño 3 in the preceding winter is detached (Fig. omitted), the PJ pattern would vanish, similar to Fig. 4b. Therefore, during P1, the anomalous circulation related to WNPSMI, mainly present a tripole pattern, which is governed by Niño 3 in the preceding winter.

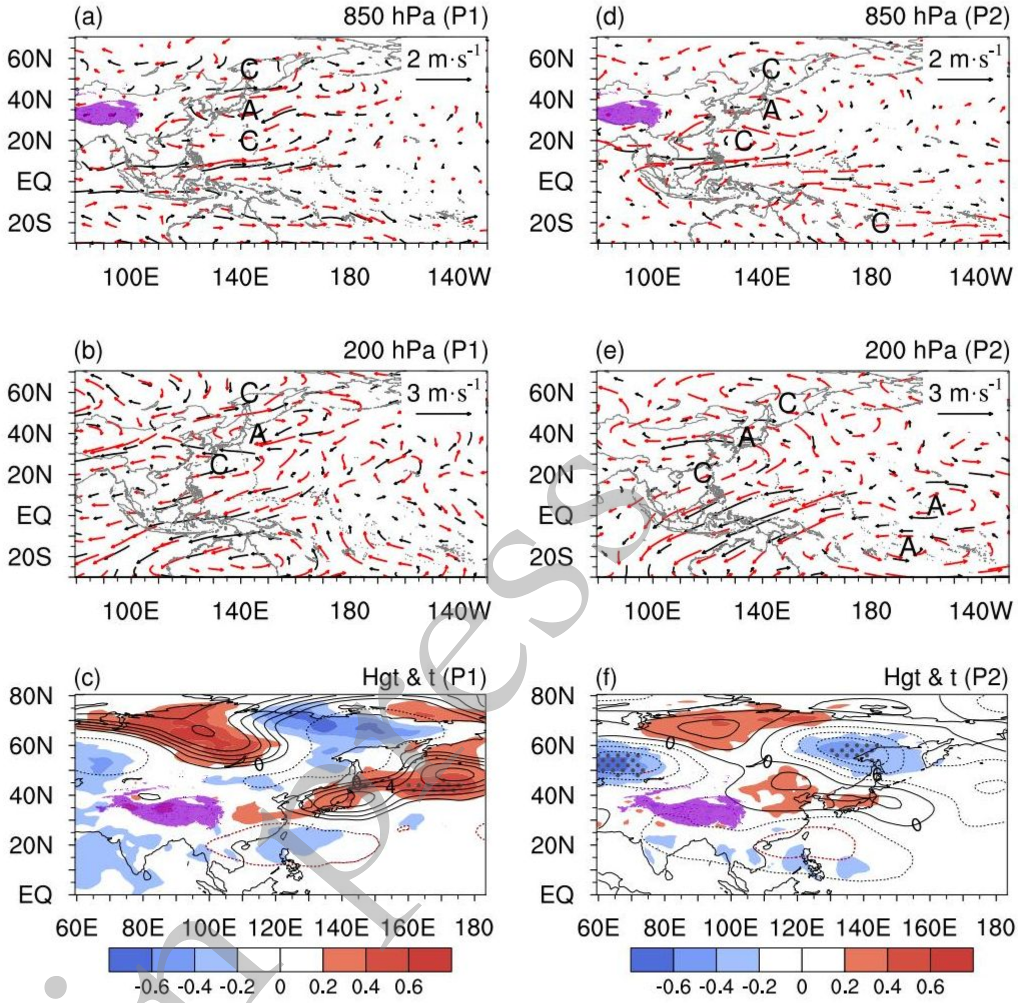

FIG. 5. Regression map of (a) 850 hPa horizontal wind (unit: m s^{-1}), (b) 200 hPa horizontal wind (unit: m s^{-1}), and (c) 500 hPa geopotential height (unit: gpm) and 2 m temperature (unit: °C) on WNPSMI during P1. (d)–(f) same as (a)–(c), but for P2. Red vectors, dots, and red contours indicate the 95% confidence level, respectively. Violet shading represents the Tibetan Plateau.

In contrast, the circulation anomalies associated with WNPSMI differ to some extent during P2. The anomalous wind presents a positive PJ-like pattern in 850-hPa, with an anomalous cyclone to the south of equator (Fig. 5d), but in 200-hPa, the positive PJ-like pattern also appears, with two centers in the northernmost polarity and more narrow middle polarity, also with an anomalous anticyclone to the both sides of equator (Fig. 5e). The circulation anomalies to the both sides of equator presents a Gill response-like pattern (Figs. 5d, 5e). However, during P2, the tripole pattern also can be discerned in terms of the 500-hPa geopotential height anomaly, while the northernmost polarity in the 2-m temperature anomaly is more significant (Fig. 5f), which is different to that in P1. In addition, as shown in Fig. 5f, the anomalous circulation in 500-hPa geopotential height between 40°–80°N seem to be a British-Baikal Corridor-like (BBC-like) wave, with a polarity in 60°–80°E, 90°–120°E, 130°–150°E, respectively (Xu et al., 2019).

Based on the above analyses, it could be found that the correlation between WNPSM and tropical Pacific SST underwent an conspicuous interdecadal shift around the early 1990s, with WNPSM significantly linked to tropical Indian Ocean, governed by the influence of Niño 3 in the preceding winter during P1, and significantly connected with the tropical western Pacific and Niño 4 SSTA, both of which obtain less influence of Niño 3 in the preceding winter during P2. Maybe, the SSTA in the tropical western Pacific plays a more important role during P2, compared with Niño 4, identical to the results obtained in rainfall and circulation associated with WNPSM.

4. The respective influence of SST in Niño 4 and tropical west Pacific on WNPSM during P2

Many studies have revealed that the WNPSM is closely linked to El Niño–Southern Oscillation (ENSO) (Fu and Ye 1988; Zhang et al. 1996; Wu and Wang 2000). Therefore, the relationship between WNPSM and Niño 3 in the the previous winter have not been further study in this paper. This paper mainly focus on the investigation of the relationship between WNPSM and SSTA in the tropical central-western Pacific on WNPSM during P2.

From the analyses in section 3, we can find that both Niño 4 and tropical western Pacific have impacts on WNPSM during P2. When the influence of Niño 4 is removed, the anomalies associated with tropical western Pacific still exist, and in addition, the correlation coefficient between Niño 4 and TWPI is only –0.42 during P2, which both implies that maybe SSTA over Niño 4 and tropical western Pacific do not always work in coherence on WNPSM. Although the previous studies mainly focus the impact from Niño 4 on WNPSM after 1994 year (i.e.,Yim et al. 2008). Now, it is necessary to explore the respective influence from Niño 4 and tropical Western Pacific on WNPSM during P2.

4.1 The influence of Niño 4 on WNPSM

As shown in Fig. 6b, when positive SSTA is located in Niño 4 area and the signals associated with TWPI are removed, an anomalous cyclone is excited in western North Pacific (WNP), accompanied by a strong WNPSM. But the tripole pattern circulation anomaly associated with WNPSM cannot be reappeared well (Figs. 6b, c), compared to Figs. 5d, 5e, respectively. In terms of the 500-hPa geopotential height anomaly and 2-m temperature anomaly in Fig. 6d, the PJ-like wave also do not appear, but the BBC-like wave still exist along 60°–80°N, similar to that in Fig. 5f.

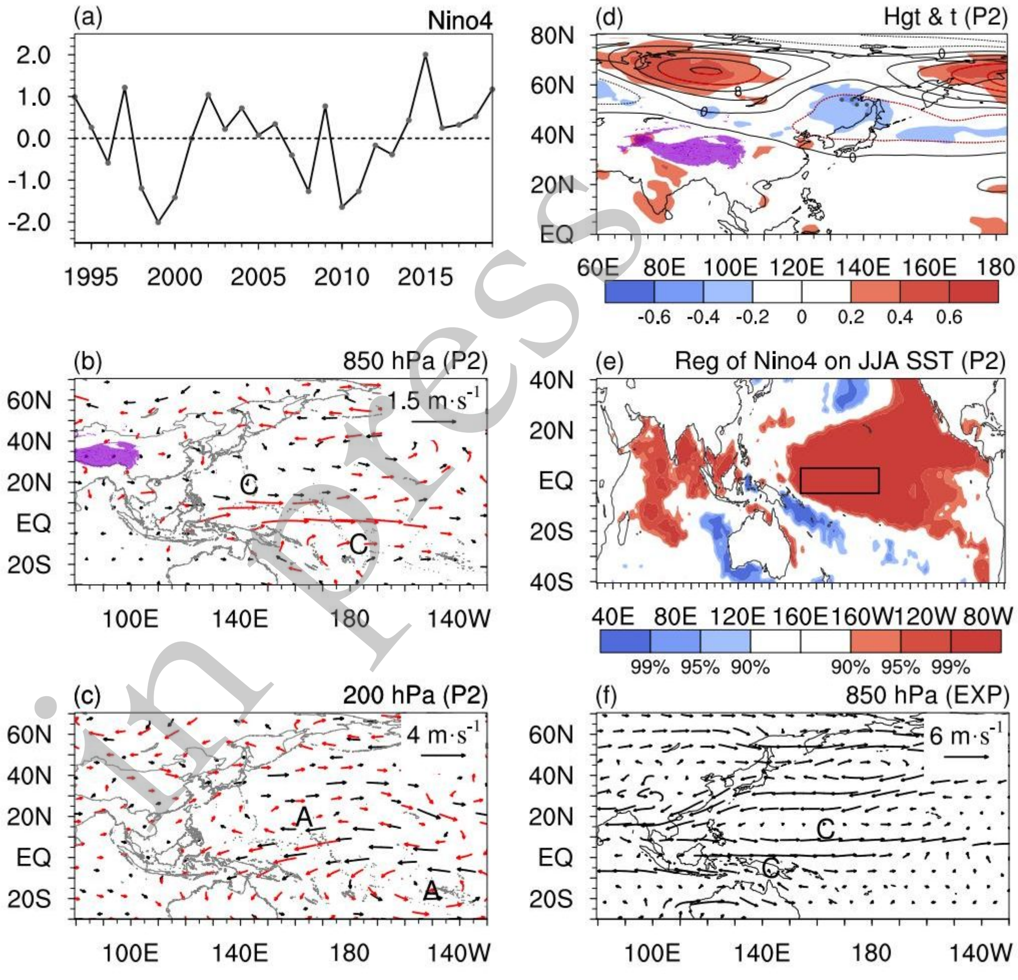

FIG. 6. (a) Normalized Niño 4 index during P2. Its regression on (b) 850-hPa horizontal wind (unit: m s^{-1}), (c) 200-hPa horizontal wind (unit: m s^{-1}), (d) 500-hPa geopotential height (unit: gpm) and 2-m temperature (unit: °C), (e) JJA SST during P2, after removing the signals of TWPI. (f) The sensitive experiment minus the control experiment, the SST anomaly is added in the rectangle in (e), detailed description shown in section 2. Red vectors, red contours, and dots represent the 95% confidence level in Figs. (b)-(d). Light to dark shadings represent 90%, 95%, and 99% confidence level. Violet shading highlights the Tibetan Plateau.

As shown in Figs. 6b and 6c, an anomalous cyclone generates in the south and north sides to the equator at the level of 850 hPa, which transforms into anomalous anticyclonic circulation at 200 hPa (Fig. 6c). The configurations of the anomalous circulation in lower and higher layers show that positive SSTA induces the response of the atmosphere Gill type and the anomalous cyclone at the north side to the equator in 850 hPa can enhance the WNPSM, which is consistent with circulation anomalies in 20°S–20°N displayed in Figs. 5d, 5e. When the positive SSTA is added in the Niño 4 area, marked by rectangle in Fig. 6e, the sensitive experiment also can reproduce the Gill response (Fig. 6f), same as the statistical results in Fig. 6b. So, the anomalous cyclone in WNP associated with Gill response may be an important factor of Niño 4 exerting influences on WNPSM.

4.2 The influence of tropical west Pacific SST on WNPSM

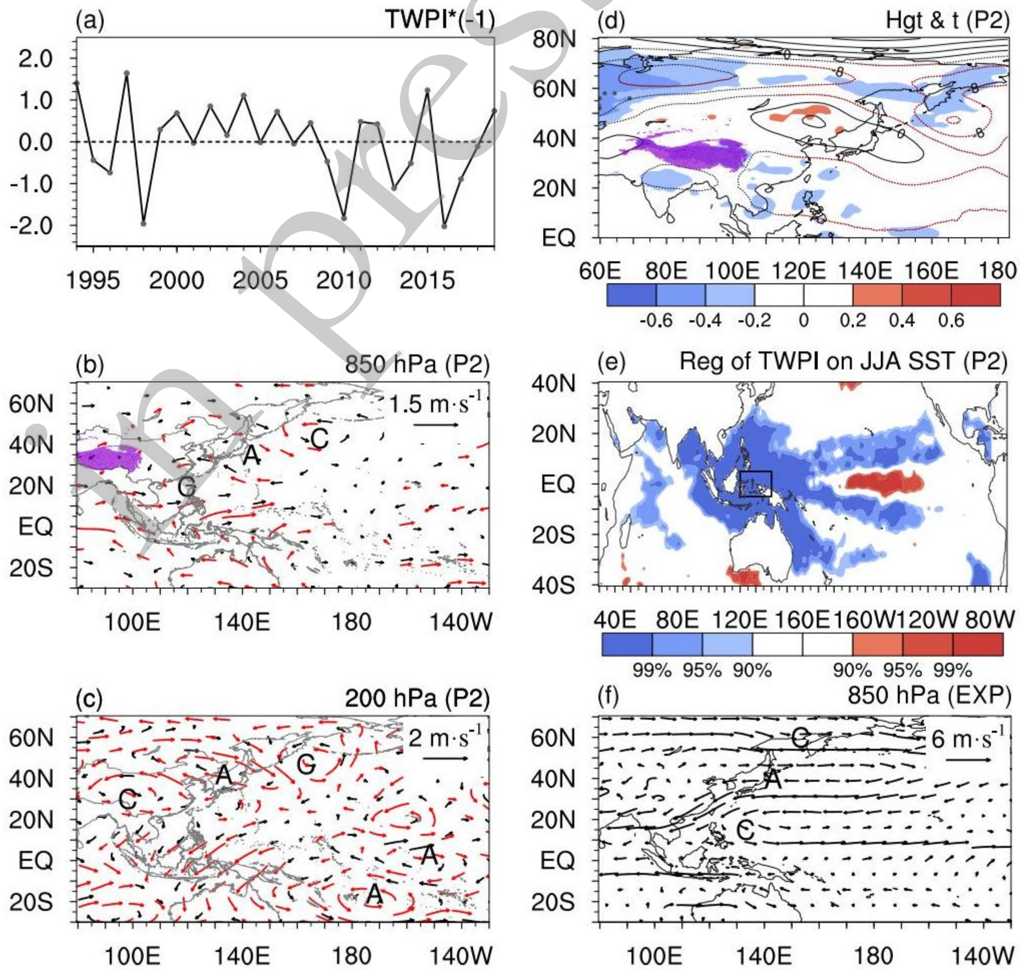

FIG. 7. Same as Fig. 6, but for TWPI.

As shown in Fig. 7b, when the negative SSTA appears in tropical western Pacific and the signals related to Niño 4 are removed, an anomalous positive-phase PJ-like pattern can be reproduced, very similar to that in Fig. 5d, and the polarity over WNP helps to enhance the WNPSM. The anomalous circulation displayed in Fig.7c also can reproduce that shown in Fig. 5e. In terms of the 500-hPa geopotential height anomaly and 2-m temperature anomaly, the circulation anomaly in Fig. 5f can also be reproduced well, only with a weaker temperature anomaly and stronger geopotential height anomaly (Fig. 7d). The negative SSTA in the tropical western Pacific excites influence on WNPSM by the positive PJ-like circulation anomaly, which can be verified in 7f, because the different between the sensitive and control experiment can also reproduce the statistical results, also displaying a PJ-like pattern. Although the Gill response-like pattern also exists in 20°S–20°N displayed in Fig. 7c, maybe this is a signal associated with Niño 4 related to TWPI, displayed in Fig. 7e.

Therefore, we initially believe that the SSTA in Niño 4 (tropical western Pacific) generate influences on WNPSM by Gill response (PJ-like wave).

5. The different influences of Niño 4 and TWPI working in coherence and out of coherence

In section 4, the impacts from both Niño 4 and tropical western Pacific SSTA on WNPSM have been analyzed. Through the comparison among Figs. 2c, 2e, 2g, and Figs. 3c, 3e, 3f, it can be found that the SSTA related-to WNPSM, located in Niño 4 and tropical western Pacific do not always work in accordance, namely not always with a significant negative (positive) SSTA in the tropical Western Pacific and positive (negative) SSTA in Niño 4 area. Now, it is necessary to further analyze when both work in coherence, and when the tropical western Pacific SSTA and Niño 4 area work alone to exert influence on WNPSM, respectively.

Table 1. The six combinations of years with different anomalies of TWPI and Niño 4, positive (negative) anomalies means beyond (below) the (minus) 0.5 standard deviation.

Types	Years

Negative&Positive	1994, 1997, 2002, 2004, 2015, 2019
Positive&Negative	1996, 1998, 2010
Negative&Normal	No
Positve&Normal	2013, 2014, 2016, 2017
Normal&Negative	1999, 2008, 2011
Normal&Positve	2009, 2018

As shown in Table 1, we define the year with a value (below) beyond (minus) 0.5 standard deviation as (negative) positive anomaly year for TWPI and Niño 4 series, respectively. Because the SSTAs in Niño 4 and tropical western Pacific always present a dipole pattern in climatologically mean, so have no need to study“Negative & Negative”,“Positive & Positive”and“Normal & Normal”types of SSTA of TWPI and Niño 4. The necessary combinations are displayed in Table 1. During the years of 1994, 1997, 2002, 2004, 2015 and 2019, the negative SSTA in the tropical Western Pacific and positive SSTA in Niño 4 area, could work in accordance to influence WNPSM; during the years of 1996, 1998 and 2010, the positive SSTA in the tropical Western Pacific and negative SSTA in Niño 4 area, also could work in accordance to influence WNPSM. During the years of 2013, 2014, 2016, and 2017, the positive SSTA anomaly in tropical western Pacific can work alone to influence WNPSM; during the years of 1999, 2008, and 2011, the negative SSTA anomaly in Niño 4 area could work alone to exert impacts on WNPSM. Due to no or too few samples, the types of “Negative & Normal” and“Normal & Positive”are not discussed.

Based on 1994, 1997, 2002, 2004, 2015, and 2019 years, we conduct the composite analyses of SST and horizontal wind fields to explore the combination effect of the negative SSTA in the tropical Western Pacific and positive SSTA in the Niño 4 area on WNPSM (Fig. 8). As shown in Fig. 8a, it is reproduced that SSTA is positive in Niño 4 area, but negative in the tropical western Pacific during 1994, 1997, 2002, 2004, 2015, and 2019 years.

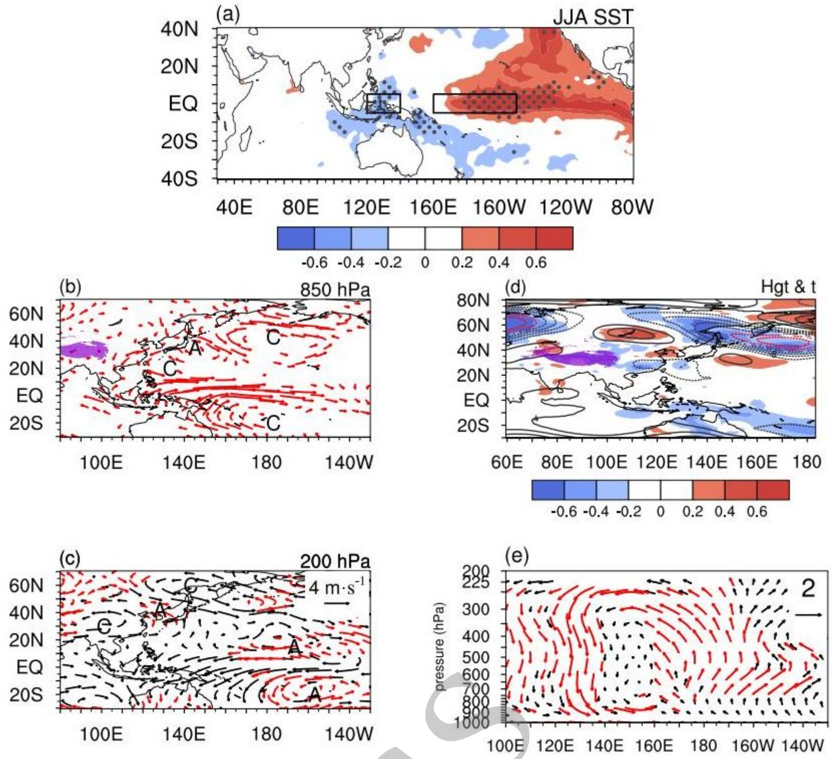

FIG. 8. The composite analyses of (a) SST, (b) 850-hPa horizontal wind (unit: m s^{-1}), (c) 200-hPa horizontal wind (unit: m s^{-1}), (d) 500-hPa geopotential height (unit: gpm) and 2-m temperature (unit: °C), (e) u and omega(multiplied by -30) based on 1994, 1997, 2002, 2004, 2015 and 2019 years. Red vectors, red contours, and dots represent the 95% confidence level. Light to dark shadings represent 90%, 95%, and 99% confidence level. Violet shading highlights the Tibetan Plateau.

The wind anomalies in Figs. 8b, 8c bear a great resemblance with those displayed in Figs. 5d, 5e, respectively, which are also more similar to Figs. 7b, 7c, compared to those displayed in Figs. 6b, 6c. In terms of the 500-hPa geopotential height anomaly and 2-m temperature anomaly, the circulation anomaly in Fig. 8d is less similar to that in Fig. 5f, with weaker significance in temperature anomaly and stronger geopotential height anomaly in the northernmost polarity of PJ-like pattern. From the circulation anomalies in Figs. 8b, 8c, both the positive phase PJ-like pattern and Gill response can be discerned. The anomalous years 1994, 1997, 2002, 2004, and 2015 are all El Niño developing year, except for 2019 year, based on that the SSTA must be less (greater) –0.5°C (0.5°C) lasting 6 months including June, July, and August. So, during the El Niño developing year in P2, the SSTA is positive in Niño 4 and negative in tropical Western Pacific, both of which can work in coherence to influence WNPSM by atmospheric Gill response connected with SSTA in Niño 4 and anomalous PJ-like circulation associate with western tropical Pacific. As shown in Fig. 8e, there exists an anomalous anti-Walker circulation between the Niño 4 area and tropical western Pacific, help to maintain the negative SSTA in tropical Western Pacific and positive SSTA in Niño 4 area. As displayed in Fig. 9, the statistical analyses also can be reproduced by the sensitive experiment when the SSTAs are added in the tropical Western Pacific and Niño 4 area, marked in Fig. 8a. The PJ-like pattern and the Gill response also can be approximately reproduced in 850 hPa (Fig. 9a), and only the Gill response can be reproduced in 200 hPa (Fig. 9b).

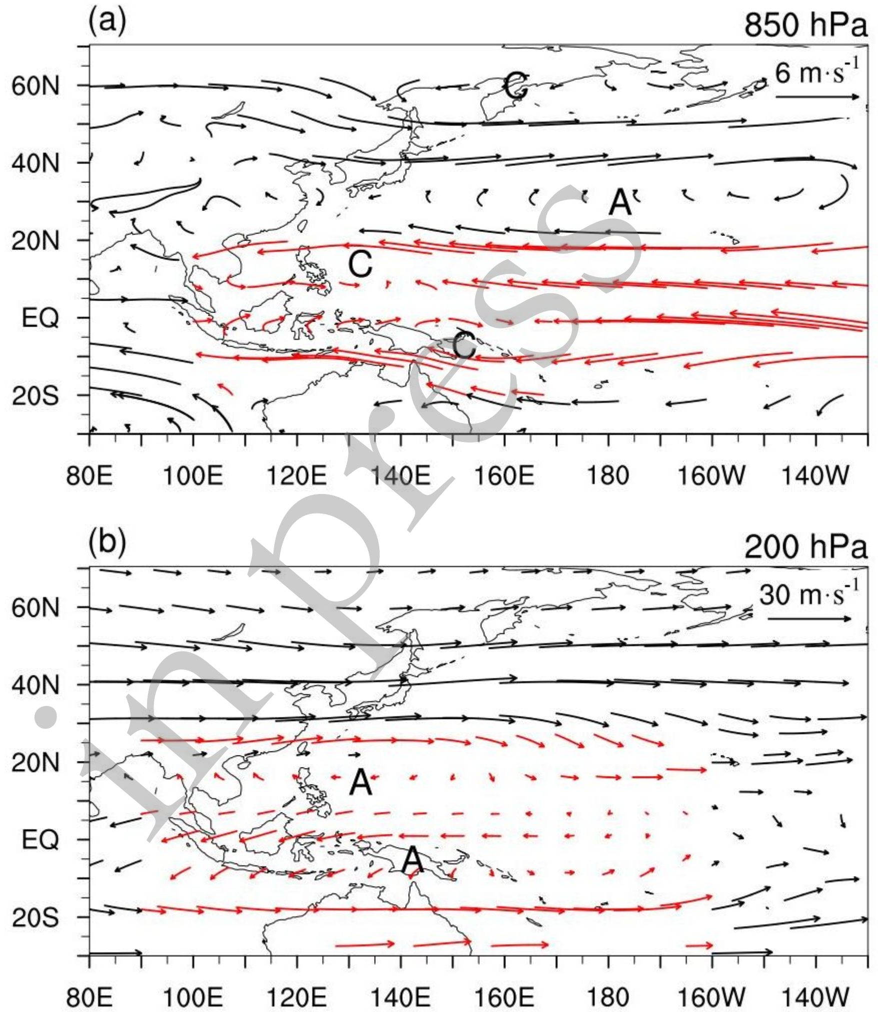

FIG. 9. The difference of sensitive experiment and control experiment when the negative SSTA is added in tropical western Pacific and positive SSTA added in Niño 4, marked by rectangle in Fig. 8(a) and detailed description shown in section 2. (a)/(b) for 850 hPa/200 hPa horizontal wind (unit: m s^{-1}), the key anomalies are marked by red vector.

Based on 1996, 1998, and 2010 years, we conduct the composite analyses of SST and horizontal wind fields to explore the combination effect of the positive SSTA in the tropical western Pacific and negative SSTA in Niño 4 area on WNPSM (Fig. 10). As shown in Fig. 10a, it is reproduced that SSTA is negative in the Niño 4 area, but positive in the tropical western Pacific during 1996, 1998, and 2010 years.

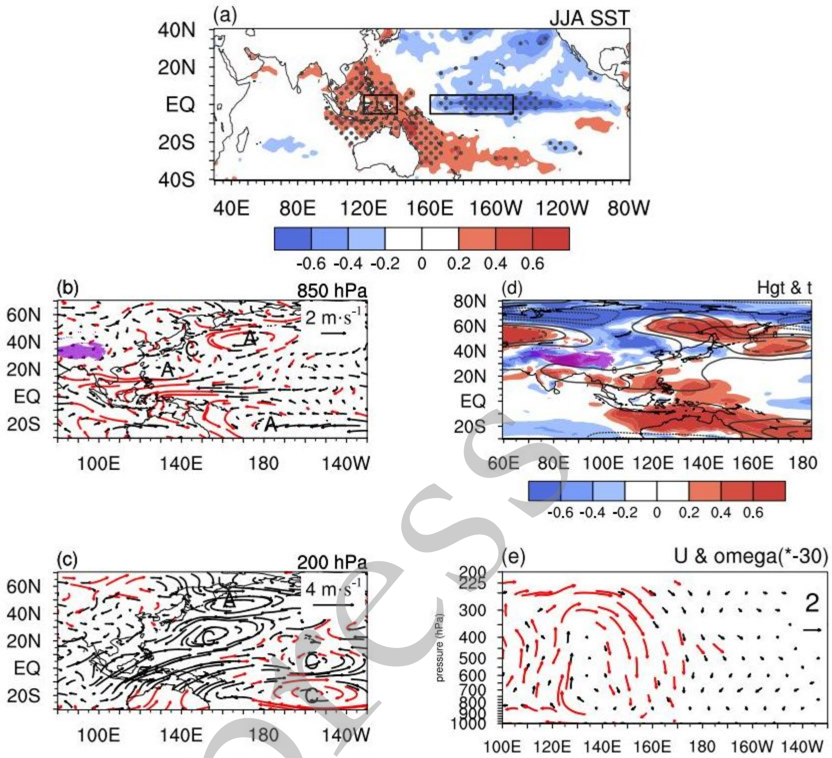

FIG. 10. Same as Fig. 8, but for 1996, 1998, and 2010 year.

The wind anomalies in Figs. 10b, 10c present a negative phase of PJ-like pattern, with the opposite phase to those displayed in Figs. 8b, 8c. Especially, the negative PJ-like circulation anomalies at 200 hPa do not pass through 95% confidence level, also with the lack of polarity near the equator (Fig. 10c). In terms of the 500-hPa geopotential height anomaly and 2-m temperature anomaly, the PJ-like pattern is much too weak (Fig. 10d). As shown in Fig. 10e, there exists an anomalous Walker circulation between the tropical western Pacific and tropical central Pacific, help to maintain the positive SSTA in the tropical western Pacific and negative SSTA in Niño 4 area. The anomalous years are La Niña developing year, except for 1996 year, so, during the La Niña developing year in P2, the SSTA is negative in Niño 4 and positive in the tropical western Pacific, both of which can work in coherence to influence

WNPSM, showing obvious symmetry, compared to Fig. 8. Because of the prominent symmetry, the opposite sensitive experiment to Fig. 9 has no need to carry out.

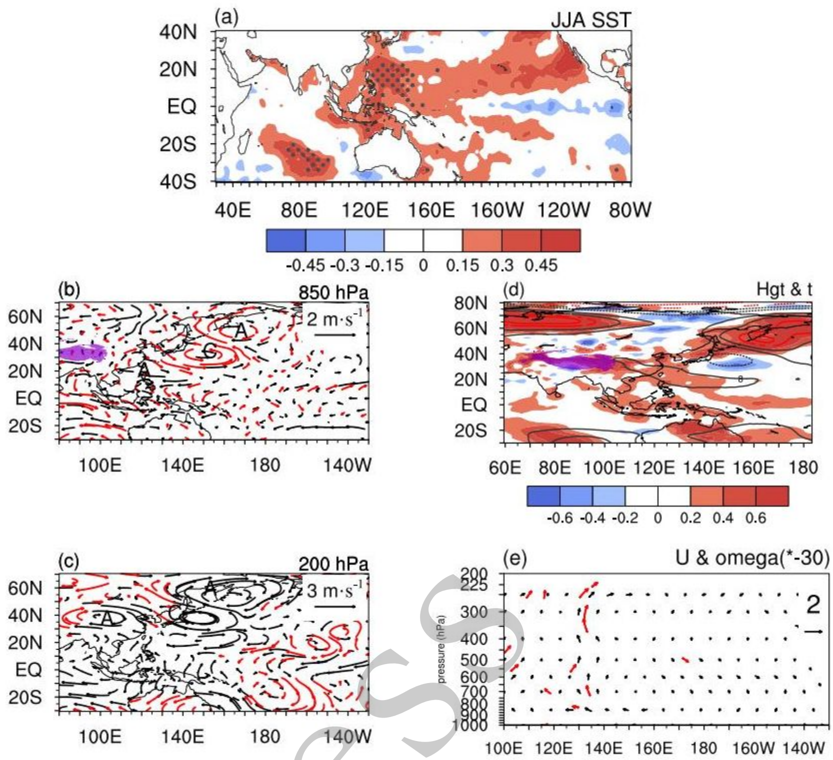

FIG. 11. Same as Fig. 8, but based on 2013, 2014, 2016 and 2017 years.

As shown in Table 1, 2013, 2014, 2016 and 2017 are positive anomalous years of the tropical western Pacific SSTA and Niño 4 normal year, based on these years, to conduct composite analyses helps to isolate the independent influence from tropical western Pacific on WNPSM. As shown in Fig. 11a, during these years, anomalous SSTA in the tropical western Pacific and no significant anomaly over Niño 4 area are reproduced. In Fig. 11b, at 850 hPa, also there is a negative phase PJ-like wave, when there is positive SSTA in the tropical western Pacific. At 200 hPa, Fig. 11c also demonstrate some similarities to Figs. 5e, 7c, but only out of phase. The geopotential height and temperature anomalies in Fig. 11d also can reappear the out-of-phase circulation pattern anomalies, compared to Fig. 5f. As shown in Fig. 11e, the anomalous ascending motion appears in the tropical western Pacific. The analyses about the "Positive & Negative" type, namely positive SSTA in the tropical western Pacific and normal SSTA in Niño 4, show that tropical SSTA can influence WNPSM by PJ-like wave. When the SSTA in tropical western Pacific is positive (negative), a negative (positive) phase PJ-like wave appears, and weaken (strengthen) the WNPSM (Figs. 7a–f, 10a–e).

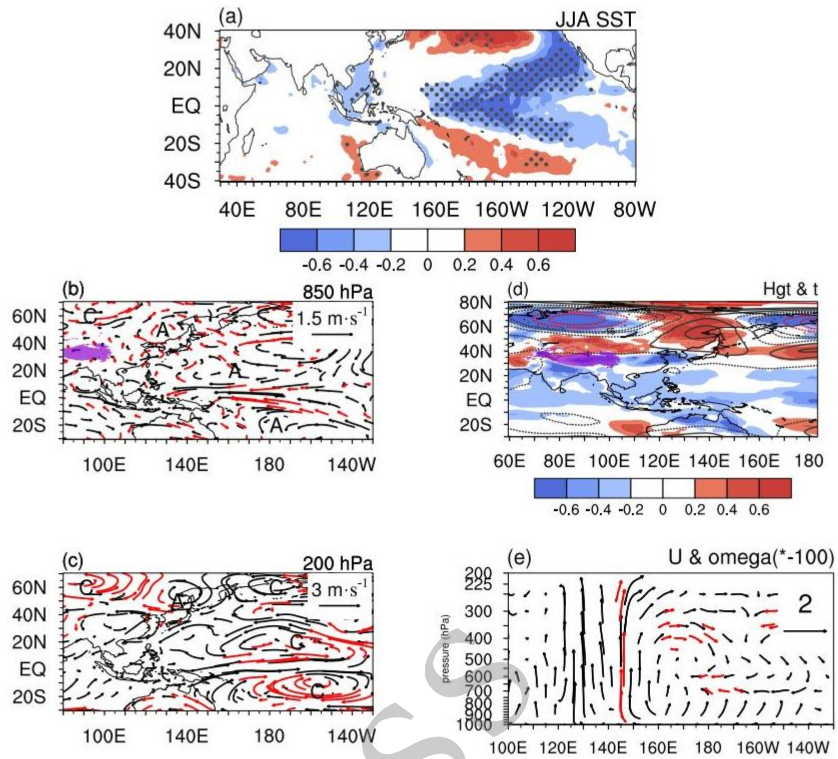

FIG. 12. Same as Fig. 8, but based on 1999, 2008, and 2011 years.

As shown in Table 1, 1999, 2008, and 2011 are normal years of tropical western Pacific SSTA and negative anomaly of SSTA in Niño 4, based on these years, to conduct composite analyses helps to isolate the independent influence from Niño 4 on WNPSM. As shown in Fig. 12a, during these years, negatively anomalous SSTA in Niño 4 and no significant anomaly over tropical western Pacific are reproduced. In Fig. 12b, at 850 hPa, there is an abnormal anticyclone to the north and south sides of the equator, respectively and at 200 hPa, they develop into cyclones (Fig. 12c), which further confirms that the Niño 4 exerts influences on WNPSM by Gill response, consistent with the results obtained in Fig. 6b–c. The geopotential height and temperature anomalies in Fig. 12d also present weaker circulation anomalies, compared to Fig. 6d. At the same time, the anomalous Walker circulation is very weak, with weak descending motion over Niño 4 area (Fig. 12e). 1999, 2008, 2011 are also CP La Niña developing years, in which the negative SSTA in Niño 4 area works alone on WNPSM. When the SSTA in Niño 4 is negative (positive), the abnormal anticyclone (cyclone) in WNP at 850 hPa can weaken (enhance) the WNPSM (Figs. 6a–f, 12a–e). Besides, there is a BBC-like wave appearing in 40°–80°N, along with the occurrence of Gill response (Fig. 12b, c), and whether the BBC plays a role in influencing WNPSM or not needs to further be investigated in future studies.

On the whole, during the El Niño (La Niña) developing year in P2, the negative (positive) SSTA in the tropical western Pacific and positive (negative) SSTA in the Niño 4 area, could work together to influence WNPSM, enhancing (weakening) the WNPSM, by the positive (negative) phase PJ-like wave and Gill response. In some years, the positive SSTA in the tropical western Pacific can work alone to influence WNPSM in P2, weakening the WNPSM, by the negative phase PJ-like wave. During CP La Niña developing years, the negative SSTA anomaly in the Niño 4 area can work alone to exert impact on WNPSM in P2, weakening the WNPSM, by the Gill response with an anomalous anticyclone in WNP. Both of them further confirm that SSTA in the tropical western Pacific (Niño 4) exerts influences on WNPSM by PJ-like wave (Gill response), consistent with the results displayed in section 4.

6. Summary and Discussion

In view of the analyses above, it could be obtained that the correlation between WNPSM and SSTA in the tropical Pacific underwent a dramatically interdecadal shift around the early 1990s, with the enhanced linkage to tropical western Pacific and Niño 4 SSTA during the summertime from P1 to P2. The rainfall and circulation connected with WNPSM also display similar features, with a significant PJ-like pattern during P1, and when the influence of Niño 3 in the preceding winter is removed, the PJ-like pattern disappears. Those imply that Niño 3-related SSTA is the most important factor of generating influence on WNPSM during P1. During P2, the associated precipitation shows a zonal dipole pattern, connected with both Niño 4 area and tropical western Pacific. The SSTA in the Niño 4 area exerts impacts on WNPSM by atmospheric Gill response, with stronger (weaker) WNPSM along with positive (negative) SSTA in Niño 4 and SSTA associated with the tropical western Pacific exerts influences on WNPSM by PJ-like wave, with stronger (weaker) WNPSM along with negative (positive) SSTA in the tropical western Pacific.

In the combination of “Negative & Positive” (“Positive & Negative”) of TWPI and Niño4, namely during the El Niño (La Niña) developing year in P2, the negative (positive) SSTA in the tropical western Pacific and positive (negative) SSTA in the Niño 4 area, could work in accordance to influence WNPSM, enhancing (weakening) the WNPSM, by the positive (negative) phase PJ-like wave and Gill response, with an anomalous cyclone (anticyclone) located in WNPSM, which shows obvious symmetry. During the combination of “Positive & Normal”, the positive SSTA in tropical western Pacific can work alone to influence WNPSM in P2, weakening the WNPSM, by the negative phase PJ-like wave. During the combination of “Normal & Positive”, namely during CP La Niña developing years, the negative SSTA anomaly in Niño 4 area can work alone to exert impacts on WNPSM in P2, weakening the WNPSM, by the Gill response with an anomalous anticyclone in WNP. In addition, westerly wind bursts (WWBs) play an important role in ENSO prediction, through affecting surface zonal currents and triggering eastward downwelling Kelvin waves (McPhaden et al. 1992; Lengaigne et al. 2004). In the last several years, using parameterized WWBs could obviously improve the WWBs representation in coupled models and lead to more accurately simulation of extreme El Niño and central Pacific El Niño (Tan et al. 2020). With the improvement of Niño 4 prediction skill, the results obtained in this paper would have important implications for WNPSM prediction. According to the research results, it may be necessary to adjust the strategy of the WNPSM prediction according to the early SST precursor signals in different decades (before and after the 1990s).

The interdecadal enhancement of the relationship between WNPSM and SST in the tropical central-west Pacific from P1 to P2, maybe is linked to the ENSO decadal shift, with more CP ENSO events in P2, which is more closely related to the enhanced influences from the Atlantic multidecadal oscillation (AMO) (Yu et al. 2015; Wang et al. 2017) and the variations of anomalous cyclone/anticyclone in western North Pacific and atmosphere-ocean interaction related to WPSH (Wang et al. 2003; Huang et al. 2018), both of which maybe have direct or indirect connection with WNPSM. However, Wu and Wang (2019) argued that the concurrent tropical Atlantic (Indian) ocean SST anomalies could constructively reinforce (destructively mitigate) the WNPSM anomalies induced by the summertime Niño 3.4 SST, thus boosting (muting) the correlation between the summertime Niño 3.4 SST and the WNPSM index after (before) the early 1990, which maybe is associated with more frequent occurrences of CP El Niño and the interdecadal changes in ENSO-associated SST anomalies. In addition, the relationship between ENSO and monsoon can be modulated by PDO and IPO. Such as, the ENSO has little (strong) effect on monsoonal winds during the warm (cold) PDO phase (Wu, 2013); and the IPO negative phase corresponds to a La Niña-like SST anomalies, which strengthens the Walker circulation in the tropical Pacific (Zhao et al. 2018), and maybe exerts influences on WNPSM. These need to be further investigated in the future research.

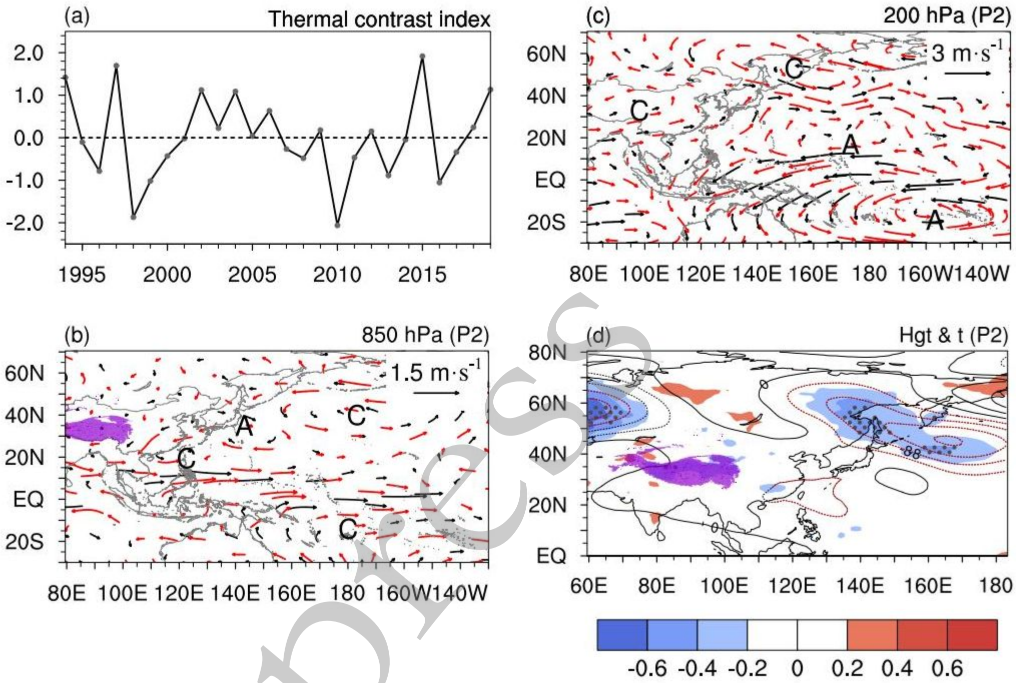

FIG. 13. (a) Same as Fig. 6, but for TCWI.

If use the TCWI instead of Niño 4 and TWPI to study the influence of tropical central-western Pacific on WNPSM, we could get the Fig. 13. The circulation anomaly in Fig. 13b is more same as that in Fig. 7b, but the anomalous pattern in Fig. 13c is more similar to that in Fig. 6c. As shown in Fig. 13d, the anomalous circulations in 500 geopotential height and 2-m temperature are more similar to Fig. 6d, compared to Fig. 7d. To use TCWI to study the influence of tropical central-western Pacific on WNPSM can not distinguish the relative contribution of Niño 4 and tropical western Pacific to WNPSM. So, in the paper, we use Niño 4 and TWPI, but not TCWI, to study the interdecadal enhancement in the relationship between WNPSM and SSTA in the tropical central-western Pacific. In addition, the reanalysis data used in the paper is replaced by NCEP or EAR-40, the results are also robust.

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Data Availability Statement

The JRA-55 monthly reanalysis data is freely available at http://jra.kishou.go.jp/JRA-55/. The GPCP data is available at https://psl.noaa.gov/data/gridded/data.gpcp.html. The HadISST data is available at https://www.metoffice.gov.uk/hadobs/hadisst/. The Community Atmospheric Model of version 5.0 can be downloaded at https://www.cesm.ucar.edu/models/cesm1.1/. The analysis scripts are available upon request from the corresponding author.

REFERENCES

Adler, R. F., and Coauthors, 2003: The version2 global precipitation climatology project (GPCP) monthly precipitation analysis (1979 present). *J. Hydrometeorol.*, **4(6)**, 1147-1167.

Briegel, L. M., and W. M. Frank, 1997: Large-scale influences on tropical cyclogenesis in the western North Pacifific. *Mon. Wea. Rev.*, **125**, 1397-1413, doi:10.1175/1520-0493(1997)125,1397: LSIOTC.2.0.CO;2.

Cao, X., T. Li, M. Peng, W. Chen, and G. Chen, 2014: Effects of monsoon trough interannual variation on tropical cyclogenesis over the western North Pacific. *Geophys. Res. Lett.*, **41**, 4332-4339, doi:10.1002/2014GL060307.

Choi, K. S., Y. Cha, H. D. Kim, and S. D. Kang, 2016: Possible influence of western North Pacific monsoon on TC activity in mid-latitudes of East Asia. *Climate Dyn.*, **46**, 1-13, https:// doi.org/10.1007/s00382-015-2562-9.

Chou, C., J. Tu, and J. Yu, 2003: Interannual variability of the western north pacific summer monsoon: differences between enso and non-ENSO years. *J. Climate*, **16(13)**, 2275-2287.

Feng, X., and L. Wu, 2021: Roles of interdecadal variability of the western North Pacific monsoon trough in shifting tropical cyclone formation. *Climate Dyn.*, 1-9. https://doi.org/10.1007/s00382-021-05891-w.

Fu, C., and D. Ye, 1988: The tropical very Low-frequency Oscillation on interannual scale. *Adv. Atmos. Sci.*, **5**, 369-388.

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 669-700, doi:10.1175/1520-0493(1968)096,0669:GVOTOO.2.0.CO;2.

Guan, B., and J. C. Chan, 2006: Nonstationarity of the intraseasonal oscillations associated with the western North Pacific summer monsoon. *J. Climate*, **19**, 622-629, https://doi.org/ 10.1175/JCLI3661.1.

He, B., Y. Zhang, T. Li, and W. T. Hu, 2017: Interannual variability in the onset of the South China Sea summer monsoon from 1997 to 2014. *Atmos. Oceanic Sci. Lett.*, **10**, 73-81, https:// doi.org/10.1080/16742834.2017.1237853.

Hu, K., and S.-M., Long, 2020: The optimal heat source for interannual variability of the Western North Pacific summer monsoon, *Atmos. Oceanic Sci. Lett.*,**13(1)**, 41-47, https://doi.org/10.1080/16742834.2019.1680087.

Huang, Y., B. Wang, X. Li, and H. Wang, 2018: Changes in the influence of the western Pacific subtropical high on Asian summer monsoon rainfall in the late 1990s. *Climate Dynamics*, **51(1)**, 443-455.

Janowiak, J. E., and P. Xie, 2003: A global-scale examination of monsoon-related precipitation. *J. Climate*, **16(24)**, 4121-4133.

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 reanalysis: general specifications and basic characteristics. *J. Meteor. Soc. Japan*, **93**, 5-48.

Kosaka, Y., and H. Nakamura, 2010: Mechanisms of meridional teleconnection observed between a summer monsoon system and a subtropical anticyclone. Part I: The Pacific–Japan pattern. *J. Climate*, **23**, 5085-5108.

Kwon, M., J. G. Jhun, B. Wang, S. I. An, and J. S. Kug, 2005: Decadal change in relationship between east Asian and WNP summer monsoons. *Geophysical research letters*, **32(16)**, *L16709, https://doi.org/10.1029/2005GL023026.*

Lee, E. J., K. J. Ha, and J. G. Jhun, 2014: Interdecadal changes in interannual variability of the global monsoon precipitation and interrelationships among its subcomponents. Climate Dyn., **42(9-10)**, 2585-2601, https://doi.org/10.1007/s00382-013-1762-4.

Lengaigne, M., J. P. Boulanger, C. Menkes, P. Delecluse, and J. Slingo, 2004: Westerly wind events in the tropical pacific and their influence on the coupled ocean-atmosphere system: A review. Geophysical Monograph Series, 147, 49-69. https://doi.org/10.1029/ 147GM03.

*Li, T., and B. Wang, 2005: A review on the western North Pacific monsoon: Synoptic-to-interannual variabilities. Terr. Atmospheric Ocean. Sci.,***16**, 285-314, https://doi.org/10.3319/TAO.2005.16.2.285(A).

McPhaden, M. J., F. Bahr, Y. Du Penhoat, E. Firing, S. P. Hayes, P. P. Niiler, et al. 1992: The response of the western equatorial Pacific Ocean to westerly wind bursts during November 1989 to January 1990. Journal of Geophysical Research: Oceans, 97(C9), 14289-14303.

Molinari, J., and D. Vollaro, 2013: What percentage of western North Pacific tropical cyclones form within the monsoon trough? *Mon. Wea. Rev.*, **141**, 499-505, doi:10.1175/MWR-D-12-00165.1.

Neale, R. B., and Coauthors, 2010: Description of the NCAR community atmosphere model (CAM 5.0). NCAR Tech. Note NCAR/TN-4861 STR, 274 pp.

Rayner, N. A., D. E. Parker, E. B. Horton, C. K. Folland, L. V. Alexander, D. P. Rowell, E. C. Kent, and A. Kaplan, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J Geophys. Res*, **108 (D14)**, doi 10.1029/2002JD002670.

Tan, X., Y. Tang, T. Lian, S. Zhang, T. Liu, and D. Chen, 2020: Effects of semistochastic westerly wind bursts on ENSO predictability. Geophysical Research Letters, 47(14), e2019GL086828.

Vega, I., P. Ribera, and D. Gallego, 2020: Characteristics of the onset, withdrawal, and breaks of the western north pacific summer monsoon in the 1949–2014 period. *J. Climate*, **33(17)**, 7371-7389.

Wang, B., R. Wu, and X. Fu, 2000: Pacific–East Asia teleconnection: How does ENSO affect East Asian climate? *J. Climate*, **13**, 1517-1536.

Wang, B., R. G. Wu, and K. M. Lau, 2001: Interannual variability of the Asian summer monsoon: Contrasts between the Indian and the western North Pacific-East Asian monsoons. *J. Climate*, **14**, 4073-4090.

Wang, B., and Z. Fan, 1999: Choice of South Asian summer monsoon indices. *Bull. Amer. Meteor. Soc.*, **80**, 629-638.

Wang, B., and X. Xu, 1997: Northern Hemisphere summer monsoon singularities and climatological intraseasonal oscillation. *J. Climate*, **10(5)**, 1071-1085.

Wang, B., 2002: Rainy season of the Asian–Pacific summer monsoon. *J. Climate*, **15(4)**, 386-398.

Wang, B., R. Wu, and T Li, 2003*: Atmosphere‐warm ocean interaction and its impacts on Asian‐Australian monsoon variation. Journal of Climate, 16(8), 1195-1211.*

Wang, L., J. Y. Yu, and H. Paek, 2017: Enhanced biennial variability in the Pacific due to Atlantic capacitor effect. *Nat. Commun.*, **8(1)**,1-7.

Wang, L., and J. Y. Yu, 2018: A recent shift in the monsoon centers associated with the tropospheric biennial oscillation. J. Climate, ***31(1)****, 325-340, https://doi.org/10.1175/JCLI-D-17-0349.1.*

Wu, C. R. 2013: Interannual modulation of the Pacific Decadal Oscillation (PDO) on the low-latitude western North Pacific. Progress in Oceanography, ***110****, 49-58.*

Wu, L., Z. Wen, R. Huang, and R. Wu, 2012: Possible linkage between the monsoon trough variability and the tropical cyclone activity over the western North Pacific. *Mon. Wea. Rev*., **140**, 140-150, doi:10.1175/MWR-D-11-00078.1.

Wu, M., and L. Wang, 2019: Enhanced correlation between ENSO and western North Pacific monsoon during boreal summer around the 1990s. Atmos. Ocean. Sci. Lett., 12(5), 376-384, https://doi.org/10.1080/16742834.2019.1641397.

Wu, R., and B. Wang, 2000: Interannual variability of summer monsoon onset over the western North Pacific and the underlying processes. *J. Climate*, **13(14)**, 2483-2501, https://doi.org/10.1175/ 1520-0442.

Wu, R., 2002: Processes for the northeastward advance of the summer monsoon over the western North Pacific. *J. Meteor. Soc. Japan, Ser. II,* **80(1)**, 67-83. https://doi.org/10.2151/jmsj.80.67.

Xu, K., and R. Lu, 2018: Decadal change of the western North Pacific summer monsoon break around 2002/03. *J. Climate*, **31**, 177-193.

Xu, K., and R. Lu, 2015: Break of the western North Pacific summer monsoon in early August. *J. Climate*, **28**, 3420-3434.

Xie, S. P., K. M. Hu, J. Hafner, H. Tokinaga, Y. Du, G. Huang, and T. Sampe, 2009: Indian Ocean Capacitor Effect on Indo-Western Pacific Climate during the Summer following El Niño. *J. Climate*, **22**, 730-747.

Xie, Y., Q. Huang, J. Chang, S. Liu, and Y. Wang, 2016: Period analysis of hydrologic series through moving-window correlation analysis method. Journal of Hydrology, 538, 278-292.

Xu, K., and R. Lu, 2016: Change in tropical cyclone activity during the break of the western North Pacific summer monsoon in early August. *J. Climate*, **29**, 2457-2469.

Xu, P., L. Wang, and W. Chen. 2019: The British–Baikal corridor: A teleconnection pattern along the summertime polar front jet over Eurasia. *J. Climate*, **32(3)**, 877-896.

Yim, S.-Y., J.-G. Jhun, and S.-W. Yeh, 2008: Decadal change in the relationship between east Asian-western North Pacific summer monsoons and ENSO in the mid-1990s. *Geophys. Res. Lett*., **35**, L20711, doi:10.1029/2008GL035751.

Yu, J.-Y., P.-K. Kao, H. Paek, H.-H. Hsu, C.-W. Hung, M.-M. Lu, and S.-I. An, 2015: Linking emergence of the central Pacific El Niño to the Atlantic Multi-decadal Oscillation. *J. Climate*, 28, 651–662, https://doi.org/10.1175/JCLI-D-14-00347.1.

Zhang, R., A. Sumi, and M. Kimoto, 1996: Impact of El Niño on the East Asian Monsoon: A Diagnostic Study of the ‘86/87 and ‘91/92 Events. *Journal of the Meteorological Society of Japan*, **74**, 49-62.

Zhao, J., R. Zhan, Y. Wang, and H. Xu, 2018: Contribution of the interdecadal Pacific oscillation to the recent abrupt decrease in tropical cyclone genesis frequency over the western North Pacific since 1998. *J. Climate*, **31**(20), 8211-8224.

Zhao, H., S. Chen, and P. J. Klotzbach, 2019: Recent strengthening of the relationship between the Western North Pacific monsoon and Western North Pacific tropical cyclone activity during the Boreal summer. *J. Climate*, **32**, 8283-8299, doi:10.1175/JCLI-D-19-0016.1.

Zeng, X., and E. Lu, 2004: Globally unified monsoon onset and retreat indexes. *J. Climate*, **17(11)**, 2241-2248.

Zong, H., and L. Wu, 2015: Re-examination of tropical cyclone formation in monsoon troughs over the western North Pacific. *Adv. Atmos. Sci.*, **32**, 924-934, doi:10.1007/s00376-014-4115-2.

Zhou，W.， and J.C.L. Chan, 2007: ENSO and South China Sea summer monsoon onset. International Journal of Climatology , 27, 157-167.

Zhou, W., and J.C.L. Chan ,2005: Intraseasonal oscillations and the South China Sea summer monsoon onset. International Journal of C1imatology , 25, 1585-1609.