Pacific decadal oscillation and the decadal change in the intensity of the interannual variability of the South China Sea summer monsoon

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ABSTRACT
The decadal variation of the intensity of the interannual variability (IIV) of the South China Sea summer monsoon (SCSSM) was partly modulated by the Pacific Decadal Oscillation (PDO) during the twentieth century. The SCSSM shows larger (smaller) IIV in the warm (cold) phase of the PDO. Results show that the IIV of the tropical Pacific SST and the ENSO–SCSSM relationship play key roles in the modulation of the PDO on the SCSSM IIV. In the warm phase of the PDO, the variability of the SST in the tropical Pacific tends to be larger than that in the cold phase, along with stronger ENSO events. Subsequently, the interaction between the tropical Pacific SST and the SCSSM becomes stronger via changing the strength and position of the Walker circulation and the anomalous western North Pacific anticyclone. Therefore, the large IIV of the tropical Pacific SST and the close ENSO–SCSSM relationship lead to the large IIV of the SCSSM in the warm phase of the PDO, and vice versa.

1. Introduction
The interannual variability of the South China Sea summer monsoon (SCSSM) has received much attention since the SCSSM experiment in 1998 (Ding, Li, and Liu 2004). The interannual variability of the SCSSM depends mainly on air–sea interaction, especially on the influence of ENSO (Wang et al. 2009; Xu, Zhu, and Zhou 1998). An anomalous cyclonic (anticyclonic) circulation over the western North Pacific leads to a strong (weak) SCSSM during El Niño developing (decaying) summers (Wang, Wu, and Fu 2000; Wang et al. 2009). Wang et al. (2009) pointed out that the amplitude of the interannual variability of the SCSSM has increased since the early 1980s, which may be due to the decadal changes in ENSO forcing. However, further investigation is needed to demonstrate this conjecture. Studies have shown that the intensity of ENSO events exhibits significant decadal variation during the last century, which is partly caused by the Pacific Decadal Oscillation (PDO) (An and Wang 2000; Gu and Philander 1995). The PDO is able to modulate the variability of ENSO by changing the equatorial trade winds (Pierce, Barnett, and Latif 2000; Vimont, Wallace, and Battisti 2003), and El Niño events are usually stronger in the warm PDO phase (WPP) than those in the cold PDO phase (CPP) (Wang and Liu 2016). Moreover, the ENSO–monsoon relationship is unstable, partly due to the modulation of the PDO (Chan and Zhou 2005; Duan et al. 2013; He, Wang, and Liu 2013; Krishnamurthy and Krishnamurthy 2014; Wang, Chen, and Huang 2008; Wang and Liu 2016). Chan and Zhou (2005) suggested that the relationship between the summer

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monsoon rainfall over South China and ENSO is robust only when ENSO and the PDO are in phase. Krishnamurthy and Krishnamurthy (2014) indicated that in the WPP, the influence of El Niño (La Niña) on the monsoon rainfall is enhanced (reduced). Wang, Chen, and Huang (2008) suggested that ENSO’s impact on the East Asian winter monsoon is stronger (weaker) in the CPP (WPP). Wang and Liu (2016) indicated that the WPP (CPP) could strengthen (weaken) the effects of El Niño events on typhoons activities. Duan et al. (2013) suggested that the early summer South China rainfall has a closer relationship with the tropical Pacific SST in the WPP than that in the CPP.

Previous studies have focused mainly on the decadal changes of monsoon strength, whereas few studies have attempted to investigate the decadal changes in the intensity of the interannual variability (IIV) of the SCSSM. As IIV means the amplitude of the deviation from the mean state, a larger (smaller) IIV of the SCSSM tends to be associated with a stronger (weaker) SCSSM than its mean state (Fan, Xu, and Tian 2014). Extreme flood or drought conditions would occur frequently during a large SCSSM IIV period. Therefore, the decadal variation of SCSSM IIV is of great importance for research on climate change and climate prediction. Since the PDO can modulate the variability of ENSO and the East Asia summer climate, whether or not the decadal change in the IIV of the SCSSM can be modulated by the PDO is a natural question. The objective of this study is to answer this question and to determine how the PDO impacts upon the SCSSM IIV.

The data and method used in this paper are introduced in Section 2. The decadal modulation of the PDO on the SCSSM IIV and the mechanism are discussed in Section 3. A summary is presented in Section 4.

### 2. Data and method

The monthly mean reanalysis data for the period 1920–2010 are from the ECMWF’s twentieth century reanalysis data-set (ERA 20C; Poli et al. 2013) on a 1° × 1° grid. The SST data, from 1920 to 2010, with 2° × 2° horizontal resolution, are from ERSST.4, provided by the NOAA (Huang et al. 2015). The PDO index from 1920 to 2010 is obtained from http://jisao.washington.edu/pdo.

The SCSSM index (SCSSMI) used in this study is defined in Wang et al. (2009) as

\[
\text{SCSSMI} = U850(5° – 15°N, 110° – 120°E) - U850(20° – 25°N, 110° – 120°E),
\]

where the first and second terms on the right-hand side represent 850 hPa zonal wind averaged over (5°–15°N, 110°–120°E) and (20°–25°N, 110°–120°E), respectively. A positive (negative) SCSSMI represents an active (break) phase of the SCSSM. The Niño3.4 index is calculated through the three-month mean of the SST anomalies over the Niño3.4 region (5°S–5°N, 170°–120°W). The Niño3 index is calculated through the three-month mean of the SST anomalies in the Niño3 region (5°S–5°N, 150°–90°W). In this paper, winter means the monthly average of December (in the previous year), January and February (DJF); spring means the monthly average of March, April, and May (MAM); and summer refers to the monthly average of June, July, and August (JJA).

The Student’s t-test is used to verify the significance of the correlation between two time series. The two-tailed F-test is used to test the significance of the difference between two SDs of two periods.

### 3. Results

The SCSSMI defined by Wang et al. (2009) is able to reasonably represent the strength of the SCSSM. Hence, we use this index to investigate the SCSSM IIV. Based on the decadal shifts of the PDO (1925, 1947, and 1977) during the last century (Mantua et al. 1997), the PDO is in warm phase during 1925–1946 and 1977–2000 and cold phase during 1947–1976. Our results show that the decadal change of the SCSSM IIV is significantly related with the PDO. After calculating the nine-year running SD of the SCSSM during 1925–2000 and comparing it with the PDO index (Figure 1(a)), it is found that the SCSSM shows large (small) IIV in the WPP (CPP). The correlation coefficient between the two curves during the whole period reaches 0.52, which is significant at the 99% confidence level estimated by the Student’s t-test. As shown in Table 1, the SD of the SCSSMI is 1.12 during 1930–1946 (WPP), which is significantly larger than that during 1960–1976 (CPP) (0.73), as estimated by the two-tailed F-test at a significance level of 0.1. Similarly, the SD is 1.17 during the period 1984–2000 (WPP), which is significantly larger than that during 1960–1976 (CPP). Note that previous studies have pointed out that the South China summer rainfall IIV (Fan, Xu, and Tian 2014; Xu, Fan, and Wang 2015) and the SCSSM (Wang et al. 2009; Wu et al. 2010) underwent a significant variation around 1992/1993. However, according to the two-tailed F-test at a significance level of 0.1, the SD of the SCSSM during 1993–2009 (1.19) shows no statistically significant increase relative to that during 1976–1992 (0.88).

The interannual variability of the SCSSM is mainly modulated by ENSO (Wang et al. 2009). However, the relationship
between the SCSSM and ENSO is not stationary, partly because of the modulation of the PDO. Some studies have indicated that in the WPP (CPP), ENSO events are often stronger (weaker), exerting stronger (weaker) influence on the summer climate of Asia (Krishnamurthy and Krishnamurthy 2014; Wang and Liu 2016). Results show that the coherence between ENSO and the SCSSM tends to be stronger (weaker) in the WPP (CPP) according to the wavelet coherence reanalysis (Grinsted, Moore, and Jevrejeva 2004). The SCSSMI and ENSO are significantly coherent, at a period of less than eight years during 1930–1946 (WPP) and at period of less than ten years during 1978–2000 (WPP). In contrast, during 1962–1976 (CPP) the SCSSMI and Niño3 index show no significant correlation (Figure 1(b)).

As indicated above, the relationship between the SCSSM and ENSO changes in different phases of the PDO. Therefore, we further investigate how the PDO modulates the relationship between the SCSSM and ENSO. Previous studies have suggested that the PDO can modulate the relationship between ENSO and Asian summer climate via SST anomaly patterns (Krishnamurthy and Krishnamurthy 2014; Mao, Chan, and Wu 2011) and the atmospheric response to ENSO (Duan et al. 2013; Wang and Liu 2016).

First, in the WPP (CPP), the feature of the entire SST pattern over the Pacific and the Indian Ocean is similar to an El Niño (La Niña) event, which persists from winter to the following summer (Mao, Chan, and Wu. 2011). Persistent anomalous atmospheric teleconnection patterns often come along with persistent SST anomaly patterns (Namias, Yuan, and Cayan 1988). As indicated by Watanabe and Yamazaki (2014), in the WPP, an anomalous wave train in the upper-level troposphere could generate geopotential anomalies over Asia. Second, ENSO events and related atmospheric anomalies are stronger (weaker) in the WPP (CPP) (Wang and Liu 2016). Pierce, Barnett, and Latif (2000) pointed out that, via the intermediary of the atmosphere, midlatitude SST anomalies over the North Pacific can induce surface wind stress anomalies extending to the tropics. Subsequently, anomalous surface wind stress changes the east–west slope of the equatorial ocean thermocline, thereby changing the strength of ENSO events. They also found that the influence of the PDO on ENSO is asymmetric in that the WPP is often associated with strong El Niño events while the CPP is not associated with strong La Niña events. Consequently, ENSO events are stronger (weaker) in the WPP (CPP) due to the asymmetric influence of the PDO. Meanwhile, anomalous Walker circulation patterns associated with El Niño events are stronger in the WPP, with stronger low-level convergence over the central Pacific and stronger low-level divergence over the Maritime Continent (Krishnamurthy and Krishnamurthy 2014; Wang and Liu 2016). The divergence anomaly strengthens the western North Pacific anticyclone, further influencing the SCSSM (Luo et al. 2016). However, the anomalous Walker circulation patterns associated with La Niña events show no difference between the two phases of the PDO (Wang and Liu 2016).

Our results indicate that the ENSO-related anomalous western North Pacific anticyclone (WN PAC) is indeed stronger (weaker) in the warm (cold) phase of the PDO. In this study, an El Niño (La Niña) event is characterized by the value of the normalized winter Niño3.4 index being larger than 1.0 (lower than –1.0). During 1925–1946, the

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**Figure 1.** (a) The standardized PDO index (dashed line) and the 9-year running standard deviation (SD) of the SCSSMI (solid line) during 1925–2000. The year marked with an SD is the beginning year of the 9 years; e.g. the SD in 1925 represents the SD during the period 1925–1933. (b) 19-year running correlation coefficient between the SCSSMI and the Niño3 index in winter (DJF) and spring (MAM) during 1920–2010. The solid line and dashed line represent the 0.1 and 0.01 significance level according to the t-test, respectively.

**Table 1.** Statistical values of the SCSSMI (South China Sea summer monsoon index) (standard deviation (SD) and F-test statistic (F)).

| Period         | SD    | F      |
|----------------|-------|--------|
| 1930–1946      | 1.12  | $> F_{0.1}(2.27)$ |
| 1960–1976      | 0.73  | $> F_{0.1}(2.27)$ |
| 1984–2000      | 1.17  | $> F_{0.1}(2.27)$ |
the El Niño years are 1958, 1964, 1966, and 1973; and the La Niña years are 1971, 1974, and 1976. During 1977–2000, the El Niño years are 1983, 1987, 1992, and 1998; and the La Niña years are 1989, 1999, and 2000. As shown in Figure 2, in the WPP (1925–1946 and 1977–2000), the anomalous WNPAC is located around the Philippines, resulting in stronger southerlies prevailing over the South China Sea (Figures 2(a) and (c)) after El Niño events than after La Niña events. This indicates a significant impact of ENSO on the SCSSM in the WPP. In contrast, there is no significant anomalous WNPAC in El Niño years during 1953–1976 (CPP) (Figure 2(b)), indicating the ENSO–SCSSM relationship is relatively weak in the CPP. Notably, the La Niña events are less affected by the CPP. Overall, in the WPP, SST anomalies over the North Pacific induce westerly anomalies over the equatorial Pacific to enhance the occurrence of El Niño events. Moreover, anomalous Walker circulation and the WNPAC associated with El Niño events are stronger in the WPP than in the CPP, thereby exerting a stronger impact on the SCSSM. Consequently, the ENSO–SCSSM relationship is strong (weak) in the WPP (CPP).

As shown in Figure 3, the tropical Pacific SST IIV is larger in the WPP than in the CPP. The SSTs over the tropical Pacific – especially over the warm pool – exhibit larger IIV during 1925–1946 (WPP) than during 1953–1976 (CPP) (Figure 3(a)). Similarly, the SST IIV during 1977–2000 (WPP) is larger than that during 1953–1976 (CPP) (Figure 3(b)). The reason for the larger SST IIV over the tropical Pacific in the WPP may be the asymmetric influence of the PDO on ENSO. The WPP can induce stronger El Niño events, whereas the CPP cannot induce stronger La Niña events (Pierce, Barnett, and Latif 2000). Therefore, the stronger ENSO events in the WPP contribute to the larger tropical SST IIV.

In conclusion, in the WPP (CPP), the influence of ENSO on the SCSSM is enhanced (reduced), along with a larger (smaller) IIV of the tropical Pacific SST, and the SCSSM IIV is subsequently larger (smaller) in the WPP (CPP).

4. Summary

The IIV of the SCSSM underwent two decadal variations during the last century, with the IIV decreasing around the late 1940s and increasing around the late 1970s. Our results show that decadal change in the SCSSM IIV was partly modulated by the PDO during the twentieth century. The SCSSM shows a larger (smaller) IIV in the WPP (CPP). The ENSO–SCSSM relationship and the IIV of the tropical Pacific SST play key roles in the modulation of the PDO upon the SCSSM IIV. First, the WPP (CPP) leads to a stronger (weaker) relationship between the SCSSM and ENSO. Only in the WPP do El Niño events induce a strong Walker circulation anomaly and significant anomalous WNPAC to impact upon the SCSSM. Meanwhile, the

Figure 2. Composite difference of summer (JJA) mean circulation between El Niño and La Niña during (a) 1925–1946, (b) 1953–1976, and (c) 1977–2000. Light (dark) shading represents the 0.1 (0.05) significance level according to the t-test.

Figure 3. Difference in SST (DJF) IIV (%) (a) between 1925–1946 and 1953–1976 and (b) between 1977–2000 and 1953–1976, with the shaded area passing the 0.05 significance level according to the F-test.
tropical Pacific SST IV is larger in the WPP than that in the CPP. The asymmetric impacts of the PDO on El Niño and La Niña events result in a greater occurrence of stronger ENSO events in the WPP than in the CPP (Pierce, Barnett, and Latif 2000). Consequently, more strong ENSO events in the WPP may contribute to the larger IV of tropical Pacific SST than that in the CPP. Therefore, the mechanism can be concluded as: The WPP (CPP) → stronger (weaker) ENSO → a larger (smaller) IV of tropical Pacific SST and a stronger (weaker) ENSO–SCSSM relationship → a larger (smaller) SCSSM IV (Figure 4).

However, the PDO is not the only reason for the variation of the SCSSM IV. Changes in spring snow depth over the southeastern Tibetan Plateau and the mid-tropospheric meridional gradient of temperature over East Asia (Fan, Xu, and Tian 2014), as well as the SST over the tropical Atlantic and the Atlantic Multidecadal Oscillation (Chen, Dong, and Lu 2010; Li and Luo 2013; Xu, Fan, and Wang 2015), may influence the East Asia summer climate IV. Further explorations regarding how other factors induce the variation of the SCSSM IV will be made in future work.

Disclosure statement

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