Climate Dynamics (2019) 52:6053–6064
https://doi.org/10.1007/s00382-018-4494-7

Interdecadal change in the South China Sea summer monsoon withdrawal around the mid-2000s

Peng Hu[1,2] · Wen Chen[1,2] · Shangfeng Chen[1,2]

Received: 15 June 2018 / Accepted: 8 October 2018 / Published online: 13 October 2018

Abstract

In this study, a significant interdecadal change in the South China Sea (SCS) summer monsoon (SCSSM) withdrawal, which occurred around the mid-2000s, is revealed using NCEP-DOE reanalysis, CMAP rainfall, and OLR data. The withdrawal of the SCSSM occurred much later (about 2 weeks) after the mid-2000s. The westerlies and rainfall are stronger around the SCS during the period after the mid-2000s compared to those that occurred before the mid-2000s, which is consistent with the delayed SCSSM withdrawal. The robust and significant increases in rainfall and convection around the SCS and Philippine Sea are dynamically associated with the appearance of an anomalous low-level cyclone around the northern SCS, and the anomalous westerlies at approximately 10°N extend eastward from the Indo-China Peninsula to the western North Pacific (WNP). Anomalous mid-level ascending motion and upper-level divergence were also observed around the Philippine Sea, together with anomalous descending motion and upper-level convergence over the equatorial eastern Indian Ocean. Correspondingly, an anomalous zonal circulation formed between the WNP (upward motion) and eastern Indian Ocean (downward motion). Further analysis indicates that the increasing number and frequent visits to the SCS by the tropical cyclones and enhanced quasi-biweekly oscillation activities may both contribute to the delayed SCSSM withdrawal around the mid-2000s.

Keywords South China Sea · Summer monsoon withdrawal · Interdecadal change · Tropical cyclones · Intraseasonal oscillations

1 Introduction

The East Asian monsoon system has exhibited significant interdecadal changes during the past half century (e.g., Wang et al. 2009; Zhu et al. 2011; Ding et al. 2008, 2009, 2015; Zhang 2015; Turner and Wang 2016; Zhou et al. 2016; Li et al. 2017b; Huang et al. 2012, 2013, 2017). For example, the strength of the East Asian winter monsoon (EAWM) has re-amplified since the mid-2000s, which may partly result from changes in Arctic sea ice and Ural Mountain blocking activity (Wang and Chen 2014; Wang and Lu 2016). Ding et al. (2014) further investigated changes in the atmospheric circulation, temperature and cold surge activity associated with the interdecadal shift in the EAWM intensity around the mid-2000s. In addition to the winter, the summer rainfall over southern China experienced a significant increase around 1992/93 (Ding et al. 2008, 2009; Liu et al. 2011), which is likely due to the warming of the equatorial Indian Ocean (Wu et al. 2010) and changes in the tropical cyclone (TC) activity over the South China Sea (SCS) (Kwon et al. 2007; Chen et al. 2012, 2017; Li and Zhou 2014, 2015). Meanwhile, the extreme rainfall and soil moisture over southern China also underwent an interdecadal increase (Yao et al. 2008; Ning and Qian 2009).

In addition, the early-to-mid 1990s witnessed a robust interdecadal shift in the East Asian summer monsoon (EASM). For example, the leading-mode of summer precipitation over East Asia and the western North Pacific (WNP) was mainly associated with El Niño-Southern Oscillation (ENSO) prior to 1993/94, whereas it was closely linked to the WNP summer monsoon after the mid-1990s (Kwon et al. 2005; Lee et al. 2014a; Yim et al. 2008). Changes in the WNP subtropical high (WNPSH), which serves as the mediator between ENSO and EASM, may partly explain

✉ Wen Chen
chenw@mail.iap.ac.cn

1 Center for Monsoon System Research, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100190, China

2 University of Chinese Academy of Sciences, Beijing 100049, China

the changing ENSO-EASM relationship (Park et al. 2010). The mid-1990s interdecadal change can also be captured by several monsoon subsystems. The delayed withdrawal of the second Changma has led to a longer summer rainy period over the Korean Peninsula (Lee et al. 2017). The interannual variability of the summertime upper-level westerly jet over subtropical East Asia was significantly weakened after the mid-1990s (Lu et al. 2011). Some studies have reported that the South China Sea summer monsoon (SCSSM) also undergoes significant interdecadal changes around the mid-1990s (Wang et al. 2009; Ha et al. 2014; Choi et al. 2017), and the peak periods of intraseasonal oscillations (ISOs) over the SCS have shifted from approximately 64 days to 42 days (Kajikawa et al. 2009).

In addition to the abovementioned interdecadal changes in monsoon activities during winter and summer, the transition seasons and monsoon timing also underwent significant interdecadal shifts. The onset of the SCSSM, which heralds the onset of the EASM (Lau and Yang 1997; Wang et al. 2004), was significantly advanced for about 2 weeks after the mid-1990s (Kajikawa et al. 2012; Kajikawa and Wang 2012; Yuan and Chen 2013; Feng and Hu 2014; Chen 2015; Wang and Kajikawa 2015). Northwestward moving tropical convection and disturbances (such as ISOs and TCs), which originated from the WNP, are suggested to be partly responsible for the interdecadal change in the SCSSM onset (Kajikawa and Wang 2012; Yuan and Chen 2013). Several studies have also reported the important role of the sea surface temperature (SST) decadal warming around the Philippine Sea during this advanced SCSSM onset (Kajikawa and Wang 2012; Xiang and Wang 2013; Yuan and Chen 2013). The advanced SCSSM onset may not be a local phenomenon, since the monsoon onset from the Bay of Bengal to the Philippine Sea also tends to start earlier (Yu et al. 2012; Kajikawa and Wang 2012; Kajikawa et al. 2012). Based on model simulations, Xiang and Wang (2013) indicated that the interdecadal advance of the Asian summer monsoon onset may be attributed to the La Niña-like background SST change in the Pacific.

Compared to the significant advance in the SCSSM onset around the mid-1990s, Kajikawa and Wang (2012) reported that the difference in the withdrawal season of the SCSSM between 1979–1993 and 1994–2008 was insignificant. The SCSSM retreat data obtained by Luo and Lin (2017) also does not exhibit notable interdecadal changes. By contrast, Zhang et al. (2014) mentioned that the SCSSM retreat has tended to be late in recent years. The discrepancies in the literature suggest that changes in the SCSSM withdrawal on an interdecadal timescale need further investigation. A hint is the autumn rainfall on Hainan Island, which has significantly increased in recent years (Li et al. 2017a). Given that Hainan is in the northern SCS and monsoon retreat occurs in autumn, the interdecadal increase of autumn rainfall in Hainan naturally raises the following scientific questions: (1) Has the SCSSM withdrawal also exhibited significant interdecadal changes in recent years? (2) If so, what are the mechanisms responsible for these interdecadal changes? The intent of this study is to answer these two questions. The organization of this manuscript is as follows: the datasets and methods are introduced in Sect. 2. Section 3 investigates the interdecadal change in the SCSSM withdrawal around the mid-2000s, which includes its detection and possible mechanisms. Finally, a summary and discussion are presented in Sect. 4.

2 Data and methods

The datasets applied in this paper include (1) National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) reanalysis data (Kanamitsu et al. 2002), which has a resolution of 2.5° × 2.5°; (2) high quality Climate Data Record of Outgoing Longwave Radiation (OLR) data (Lee et al. 2014b), which has a horizontal resolution of 1° × 1°; (3) Climate Prediction Center Merged Analysis of Precipitation (CMAP) data (Xie and Arkin 1997), which has a horizontal resolution of 2.5° × 2.5°; (4) monthly extended reconstructed sea surface temperature version 4 (ERSSTv4) data (Huang et al. 2015), which has a horizontal resolution of 2° × 2°; (5) TC best-track data from the China Meteorological Administration (CMA; Ying et al. 2014) and the Regional Specialized Meteorological Center (RSMC) Tokyo–Typhoon Center (http://www.jma.go.jp/jma/jma-eng/jma-center/rsmc-hp-pub-eg/RSMC_HP.htm); (6) autumn (September and October, following Feng et al. 2013) rainfall data for Haikou (110.35°E, 20.03°N), which is the provincial capital of Hainan Island and is located in the northern SCS; and (7) the pentad data of SCSSM withdrawal from the East Asian Monsoon Year book (National Climate Center (NCC) of CMA, 2016; http://cmdp.ncc-cma.net/Monitoring/monsoon.php). The NCC (2016) defines the SCSSM withdrawal as the time when the low-level zonal wind consistently changes from a westerly to easterly, and the potential pseudo-equivalent temperature is steadily less than 340 K in the SCS region (110°–120°E, 10°–20°N; green rectangle in Fig. 4a). For all the dataset, the time periods are from 1979 to 2016, and the analyses were performed for the period of 1979–2016. The Student's *t* test suggests that the shift year for this mid-2000s delayed SCSSM withdrawal is most significant at 2005/06, which is confirmed by the Mann–Kendall test (not shown), thus a comparative analysis is based on the difference between 1995–2005 and 2006–2016.

The ensemble empirical mode decomposition (EEMD), running average, and first-order Butterworth bandpass (Murakami 1979; Tong et al. 2009; Qiao et al. 2015) are employed in filtering the interested signals. EEMD is an improvement of the empirical mode decomposition (Huang et al. 1998), which is designed to analyze nonstationary and nonlinear time series. The EEMD can be regarded as an adaptive filter without priori determined basis (Wu and Huang 2009), which is very powerful in extracting the low frequency variability (e.g. Wei et al. 2015). The two-sided Student's t test is applied to estimate the statistical significances of linear regression, correlation, and the differences in mean.

3 Interdecadal delay of the SCSSM withdrawal after the mid-2000 s

3.1 Detection of the delayed monsoon withdrawal

Figure 1a shows the low-level westerlies averaged over the SCS region (110°–120°E, 10°–20°N) with the SCSSM withdrawal pentad time series. The SCSSM retreat exhibits a strong interannual and interdecadal variability, which is consistent with the demise of westerlies in early autumn. Corresponding to the delayed withdrawal of the SCSSM, more westerlies tend to be observed after the mid-2000s (Fig. 1a). The 9-year running Student's t tests for the differences in mean and the Mann–Kendall test suggest the year of the shift was 2005/06 (not shown). The mean SCSSM retreat occurs in pentad 53.5 (i.e., September 24) and pentad 56.9 (October 11) for the periods of 1995–2005 and 2006–2016, respectively. Thus, after the mid-2000s, the monsoon withdrawal was delayed for approximately two weeks compared to the climatology (pentad 54.4, September 29), which is roughly equal to the interdecadal advance of the monsoon onset around the mid-1990s (Kajikawa and Wang 2012; Yuan and Chen 2013). The 9-year running average and EEMD filtered interdecadal component of the SCSSM withdrawal also captures the mid-2000s delay (Fig. 1a). There also appears to be a low-frequency oscillation of approximate 15 years (Fig. 1a). In the following, two epochs (1995–2005 and 2006–2016) were selected for comparative analysis to investigate the possible reason for the delayed SCSSM withdrawal after the mid-2000s. Figure 1b compares the mean seasonal march of low-level zonal winds averaged over the SCS region for the two selected epochs. There appears to be a sharp shift in the zonal winds during mid-May, which corresponds to the onset of the SCSSM (Lau and Yang 1997; Wang et al. 2004, 2009). The significant anomalous westerlies around the end of September after the mid-2000s have prolonged the lifetime of the summer monsoon and led to a late monsoon demise (Fig. 1b).

To analyze the time range related to the interdecadal delay of the SCSSM retreat around the mid-2000s, the longitude-time cross-section of the precipitation, OLR, and low-level wind differences between 1995–2005 and 2006–2016 is shown in Fig. 2. There appears to be a significant increase in rainfall and an enhanced convection around the SCS and

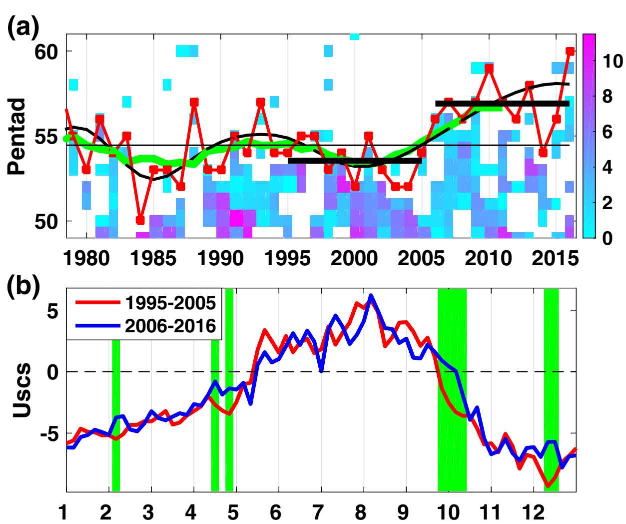

Fig. 1 Represents the (**a**) 850 hPa westerlies (shading, units in m s^{-1}) averaged over the SCS region (110°–120°E, 10°–20°N) and the pentad of the SCSSM withdrawal date (red line). The green and thin black lines denote the 9-year running average and the EEMD filtered interdecadal component of the withdrawal date, respectively. The thick black lines represent the mean SCSSM withdrawal for the periods of 1995–2005 and 2006–2016, respectively. **b** Mean seasonal march of the 850 hPa zonal winds (m s^{-1}) averaged over the SCS region for epochs 1995–2005 and 2006–2016, respectively. Shading denotes that the differences between the two epochs are significant at the 90% confidence level

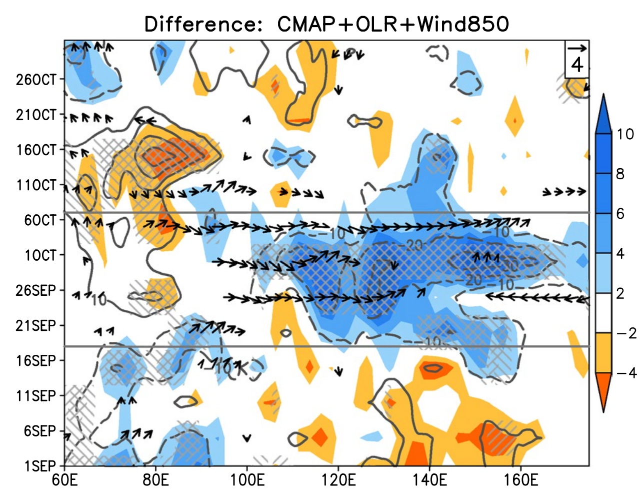

Fig. 2 The longitude-time cross-section of the epochal differences (2006–2016 − 1995–2005) in the CMAP precipitation (shading, units in mm day^{-1}), OLR (contour, units in W m^{-2}), and low-level wind (units in m s^{-1}) averaged over 10°–20°N. Gray lines denote pentads 53–56 (September 18 to October 7). Hatched areas denote the differences in precipitation or OLR, which are significant at the 90% confidence level. Only the significant (at the 90% confidence level) differences in winds are shown

Philippine Sea during pentads 53 to 56 (September 18 to October 7) for period 2006–2016, compared to those for 1995–2005. Meanwhile, significant anomalous westerlies are observed from the Indo-China Peninsula to the Philippine Sea, which is consistent with the delayed monsoon withdrawal derived from Fig. 1. In addition, the standard deviation of the SCSSM withdrawal date is approximately two pentads. Thus, the changes in pentads 53–56 can well depict the variation in the monsoon retreat (Hu et al. 2018a), which will be used in the analyses below. The interdecadal shift is further verified in Fig. 3, which shows the longitude-time cross-section of low-level zonal wind and anomalous precipitation averaged in pentads 53–56. Before the mid-2000s, anomalous easterlies appeared over the SCS, which indicated the summer monsoon had already retreated. By contrast, after the mid-2000s, the SCS and Philippine Sea were covered by westerlies, which indicates the delayed withdrawal of the SCSSM. Westerlies over the Indo-China Peninsula were stronger after the withdrawal than before the mid-2000s. In addition, rainfall anomalies were larger after the mid-2000s around the SCS. The time series of the 850 hPa zonal wind, precipitation, and convection averaged over the SCS during the monsoon retreat period also exhibited significant (at the 90% confidence level) interdecadal changes around the mid-2000s, as did the autumn rainfall recorded at the Haikou station (Fig. 3b, d). All of the above

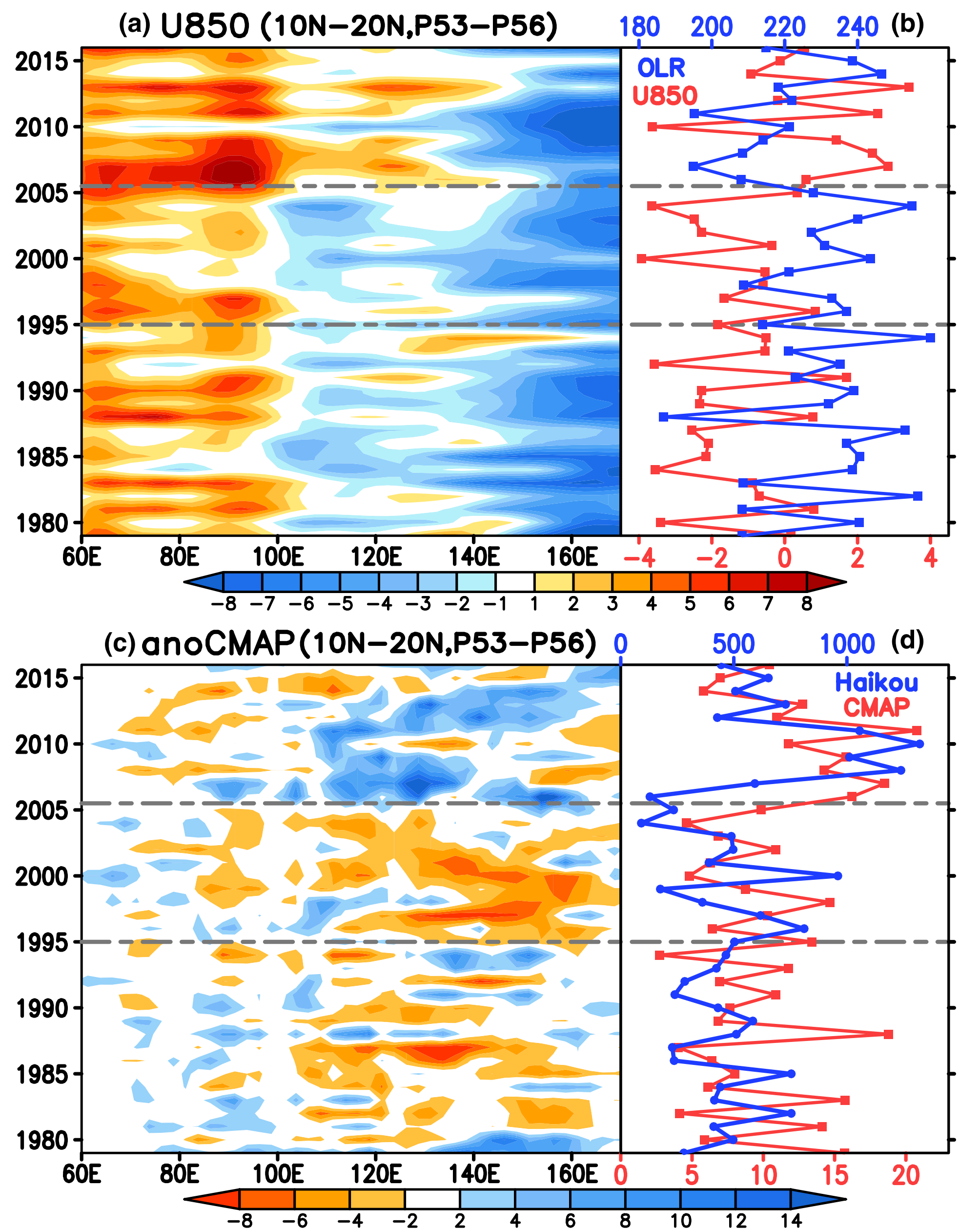

Fig. 3 **a** The longitude-time cross-section of the 850 hPa zonal winds (averaged over 10°–20°N, pentads 53–56). **b** The time series of OLR and 850 hPa zonal winds (averaged over 110°–120°E, 10°–20°N, pentads 53–56). **c** Same as **a** but for the anomalous CMAP precipitation (with climatology based on 1979–2016 removed). **d** Same as **b** but for the CMAP precipitation and autumn (September–October) rainfall in Haikou. Gray dashed lines denote the years 1995 and 2005/06

evidence demonstrates that the SCSSM withdrawal was relatively late after the mid-2000s.

Figure 4a shows the climatology of precipitation, low-level wind, and location of the western North Pacific (WNP) subtropical high (WNPSH) during the monsoon retreat period (i.e., pentad 53–56). The zonal wind is weak in the SCS, which is related to the transition from westerlies to easterlies during the monsoon withdrawal. The monsoon trough type intertropical convergence zone (ITCZ) over the SCS and Philippine Sea remains active. According to Liang (1990), the ITCZ can be divided into two types: the monsoon trough type and trade-wind trough type. The latter is the convergence between the northeast and southeast trade-winds, while the former is the convergence between the monsoonal westerlies and trade-wind easterlies, which is generally more active. Figure 4b displays the differences between 2006–2016 and 1995–2005. Increasing rainfall was seen over the SCS, especially the Philippine Sea, while decreasing rainfall occurred in the eastern Indian Ocean. An anomalous cyclone can be seen around the northern Philippine Sea, which is accompanied by significant westerly wind anomalies at approximately 10°N and extending eastward from the Indo-China Peninsula to the WNP. In addition, pronounced negative geopotential height anomalies appear in the mid-level over the northern SCS. These significant differences in the atmospheric circulation between the 2006–2016 and 1995–2005 periods can also be captured using the linear trend method in Fig. 4c. Moreover, the changes revealed by relatively independent data (CMAP and NCEP-DOE) are dynamically consistent. On the one hand, the rainfall is expected to overlay the low-level cyclonic vorticity and the associated boundary layer convergence, which are expected to be located to the north of the strongest westerlies. On the other hand, the latent heating induced by the increasing precipitation can induce a Rossby wave atmospheric response to the west (Matsuno 1966; Gill 1980), which would enhance the westerlies southwest of the strongest rainfall. Similar explanations have been reported by Wang et al. (2004) in defining the SCSSM onset. The above pattern is not confined to the SCSSM withdrawal period, and the pattern of rainfall changes and low-level circulation are very similar during early autumn (September–October). This suggests the mid-2000s interdecadal shift is robust and worthy of investigation.

Since the monsoon exhibits a three-dimensional structure, it is reasonable to further examine the mid-and-upper level circulation changes. Given that structures of the linear trend and differences between the two epochs are similar (Fig. 4), we only present results of the differences in the following. Figure 5a shows the epochal differences (2006–2016 − 1995–2005) in the OLR and mid-level vertical velocities. Significant ascending motion and related enhancements in the convection are found over the SCS

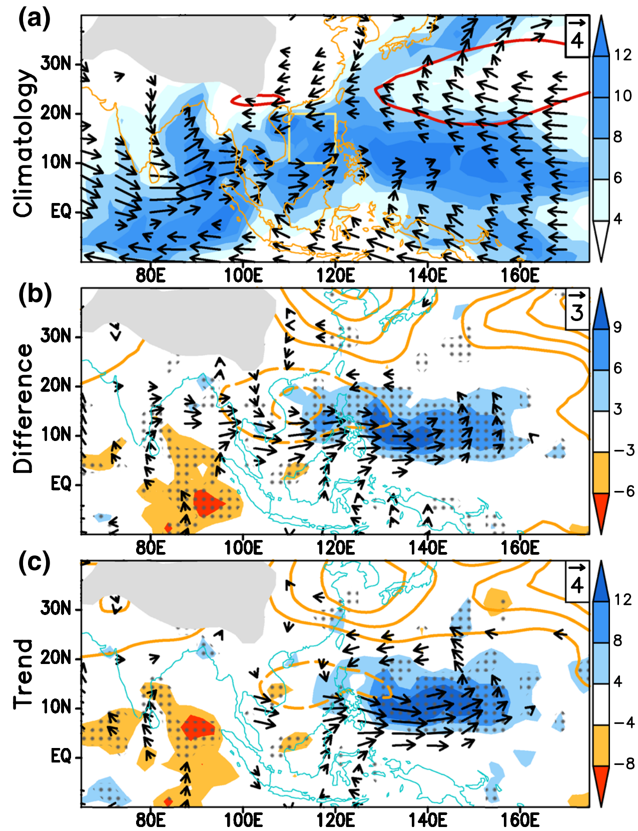

Fig. 4 **a** The climatology (based on 1995–2016) of the CMAP precipitation and 850 hPa winds averaged in the monsoon retreat period (pentads 53–56). Red line denotes 5880 m at 500 hPa (i.e., location for WNPSH). Winds speed less than 2 m s^{-1} are not shown. **b** The differences in CMAP precipitation, 850 hPa winds, and 500 hPa geopotential heights between 2006–2016 and 1995–2005. **c** Same as **b** but for the linear trend during 1995–2016. Note that all values in **c** were multiplied by 22 (years) to maintain their original units. Units are in mm day^{-1}, m s^{-1}, and m for precipitation, winds, and geopotential heights, respectively. Dotted areas denote that the difference or trend in precipitation is significant at the 90% confidence level, and only the significant (at 90% confidence level) differences or trends in the winds are shown. The contour intervals are 5 m and 10 m for geopotential heights in **b, c**, respectively. The zero lines are omitted in **a**–**c**. Gray shading masks the plateau higher than 1500 m

and Philippine Sea, which are accompanied by suppressed convection and descending motion around the equatorial eastern Indian Ocean. For the upper-level (Fig. 5b), there is a divergent center over the WNP and a convergent center over the equatorial Indian Ocean. Anomalous easterlies are found in the northern SCS and Maritime Continent. The ascending motion in the WNP and descending motion in equatorial Indian Ocean comprised an anomalous zonal circulation cell (Fig. 5c). Following Chen et al. (2014) and Huang et al. (2018), the divergent wind, rather than the wind itself, is employed in depicting this circulation cell. The changes in the mid-and-upper level circulation also indicate a delayed withdrawal of the SCSSM, which

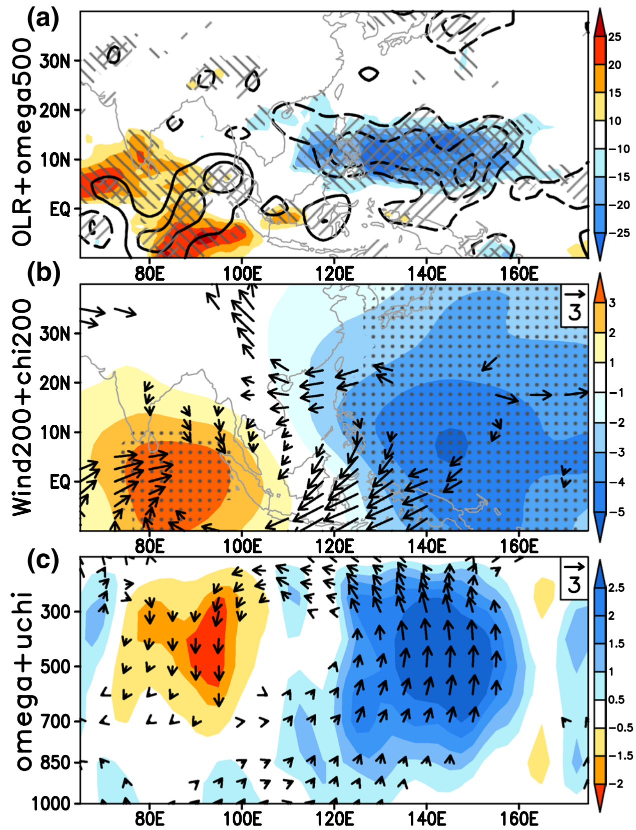

Fig. 5 **a** Same as in Fig. 4b but for OLR (shading, units in W m^{-2}) and 500 hPa vertical velocities (contour, units in Pa s^{-1}; interval of 0.02 Pa s^{-1} with zero lines omitted). Hatched areas denote the differences in OLR or vertical velocities, which are significant at the 90% confidence level. **b** Same as in Fig. 4b but for the 200 hPa wind (units in m s^{-1}) and velocity potential (shading, units in m^2 s^{-1}; multiplied by a factor of 10^{-6}). Dotted areas denote the difference in velocity potential, which is significant at the 90% confidence level, and only the significant (at the 90% confidence level) differences in winds are shown. **c** Longitude-height cross-section (5°S–20°N, averaged) of the differences in the vertical velocities (shading, units in Pa s^{-1}, multiplied by a factor of − 100) and divergent zonal wind (vector, units in m s^{-1}) between 2006–2016 and 1995–2005. Wind differences below the 90% confidence level are not shown in **c**

is consistent with the results obtained from the low-level circulation changes.

It deserves explanation for the discrepancies in literature concerning interdecadal change of SCSSM withdrawal (Kajikawa and Wang 2012; Zhang et al. 2014; Luo and Lin 2017), and there may be two possible reasons. First, Kajikawa and Wang (2012) and Luo and Lin (2017) only considered the zonal wind in defining the monsoon withdrawal, while NCC (2016) and Zhang et al. (2014) considered both the wind circulation and thermal conditions (i.e., the potential pseudo-equivalent temperature, which is commonly used in depicting the warm-humid airmass of summer monsoon). Second, Kajikawa and Wang (2012) and Luo and Lin (2017) focused on the central SCS (5°–15°N), while NCC (2016) and Zhang et al. (2014) focused on the northern SCS (10°–20°N). Compared to the abrupt SCSSM onset over the entire SCS, the SCSSM withdrawal occurs in a progressive way, and it takes four to five pentads for the monsoon to retreat from the northern SCS (pentad 54.4) to the central SCS (pentad 59) (see Hu et al. 2018a for detail).

3.2 Possible mechanisms for this delayed SCSSM withdrawal

Based on multiple datasets and different methods, the above analyses have shown a significant and robust interdecadal delayed SCSSM withdrawal after the mid-2000s. Thus, a question to be further addressed is: what are the mechanisms responsible for this interdecadal change? First, the differences in the SCSSM withdrawals between the two epochs (i.e., 1995–2005 and 2006–2016) are examined in Figs. 6 and 7. The most prominent feature of the SCSSM withdrawal is the westward intrusion of the WNPSH and the southwestward retreat of the monsoonal westerlies, which results in a shift of the zonal winds from easterlies to westerlies over the SCS (Hu et al. 2018a). Meanwhile, a significant decrease in rainfall appears around the SCS. During 1995–2005 (Fig. 6), after the SCSSM withdrawal, the monsoon trough type ITCZ changed to a trade-wind type ITCZ over the WNP and became less active. A decrease in rainfall appears over the northern Bay of Bengal, which extends eastward to the Philippine Sea. The anomalous anticyclone over the northern SCS and southern China resemble a Rossby wave response to the suppressed convection (Matsuno 1966; Gill 1980; Wang et al. 2009; Hu et al. 2018a).

Similar patterns are found during 2006–2016 (Fig. 7), which include the deceleration of the monsoonal southwesterly winds, weakening of the Somali cross equatorial flow, westward invasion of the WNPSH, and decrease in rainfall over the northern Bay of Bengal and SCS. There are several discrepancies between the two epochs. For example, the westerlies over the northern Indian Ocean in Fig. 7a–c are weaker than those in Fig. 6a–c, which may be related to the mean composited time during the latter epoch being later due to the delayed SCSSM withdrawal. As such, the annual cycle (weakening of the monsoonal westerlies during early autumn) is hidden in these compositions. In addition, even after the SCSSM withdrawal during 2006–2016 (Fig. 7c), the rainfall in the Philippine Sea remained obvious. For the low-level circulation, this active convection is accompanied by the monsoon trough type ITCZ in the Philippine Sea (Fig. 7c). By contrast, during the latter epoch, the decrease in rainfall over the Philippine Sea was insignificant (Fig. 7d). These discrepancies in precipitation and circulation agree well with the increased rainfall and anomalous cyclone derived from Fig. 4.

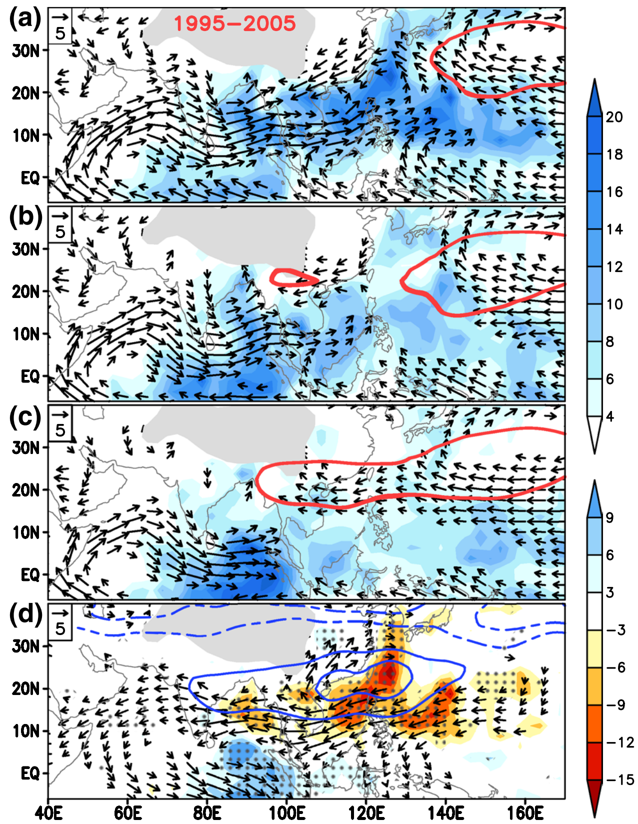

Fig. 6 Composite of 850 hPa wind (units in m s^{-1}, winds speed less than 2.5 m s^{-1} are not shown), precipitation (units in mm day^{-1}), 5880 m line at 500 hPa (the red line represents the WNPSH) from 1995 to 2005 for one pentad **a** before, **b** during, and **c** after the SCSSMW. **d** The difference between **c** and **a**, including 850 hPa winds (only those that are significant at the 90% confidence level are shown), precipitation (significant at the 90% confidence level are dotted), and 500 hPa geopotential (blue lines, contour interval of 10 m with zero lines omitted), which can reveal the changes during the SCSSMW. The gray shading masks the plateau higher than 1500 m

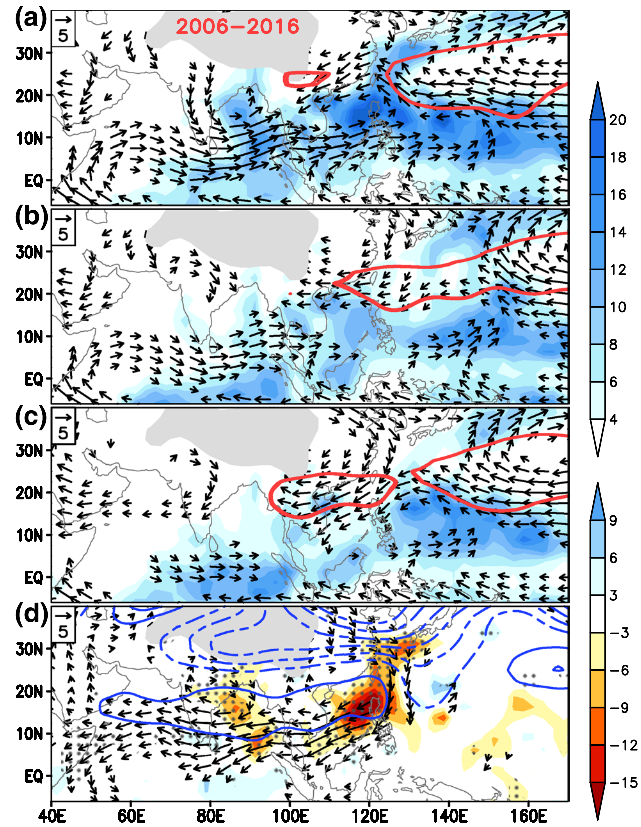

Fig. 7 Same as in Fig. 6 but for the composite and related differences based on the period of 2006–2016

Most TCs are generated within the ITCZ over the WNP (e.g., Liang 1990; Molinari and Vollaro 2013). Hence, the discrepancy of the ITCZ (Figs. 6, 7) is expected to have an influence on the TC activity. Conversely, the TC activity may be an important factor for the interdecadal shift of the SCSSM withdrawal. The reasons for the contribution of the TC to the interdecadal shift are shown as follows. First, although this manuscript begins its analysis from the perspective of low-level wind (Fig. 1), the results show that changes in precipitation and convection are closely and dynamically connected to the circulation variations (Fig. 4). The abundant rainfall induced by the TCs may be an important source for the increasing precipitation around the Philippine Sea. Second, TCs are reported to be important contributors to the autumn rainfall on Hainan Island (Wu et al. 2007; Cai et al. 2013; Feng et al. 2013; Li and Zhou 2015; Jiang et al. 2018), which also underwent an interdecadal increase after the mid-2000s (Li et al. 2017a; Fig. 3d). Third, previous work has shown that TCs can trigger the SCSSM onset, on both interannual and interdecadal time scales (Mao and Wu 2008; Chen 2015; Wang and Kajikawa 2015; Huangfu et al. 2017a). Thus, based on the above evidence, TCs may also be important in prolonging the summer monsoon season. Figure 8 shows the tracks for the TCs generated within pentads 53–56 (September 18–October 7) for the two epochs. The results obtained from the CMA are similar to those derived from the RSMC of Tokyo. More TCs are generated in the WNP during the latter epoch than the former epoch, which may contribute to the enhanced convection around the Philippine Sea and the delayed SCSSM withdrawal. Moreover, an increasing number of TCs visiting the SCS may also be in favor of the late monsoon retreat after the mid-2000s. It should be mentioned that the active monsoon trough type ITCZ over the Philippine Sea during 2006–2016 may also favor for the TC genesis therein. For example, a recent study by Huangfu et al. (2017b) reported that the interdecadal advanced SCSSM onset after late-1990s contributes partly to the interdecadal increase of TC genesis during May. The interaction between the TC activity and the SCSSM withdrawal and the related physical process should be further investigated.

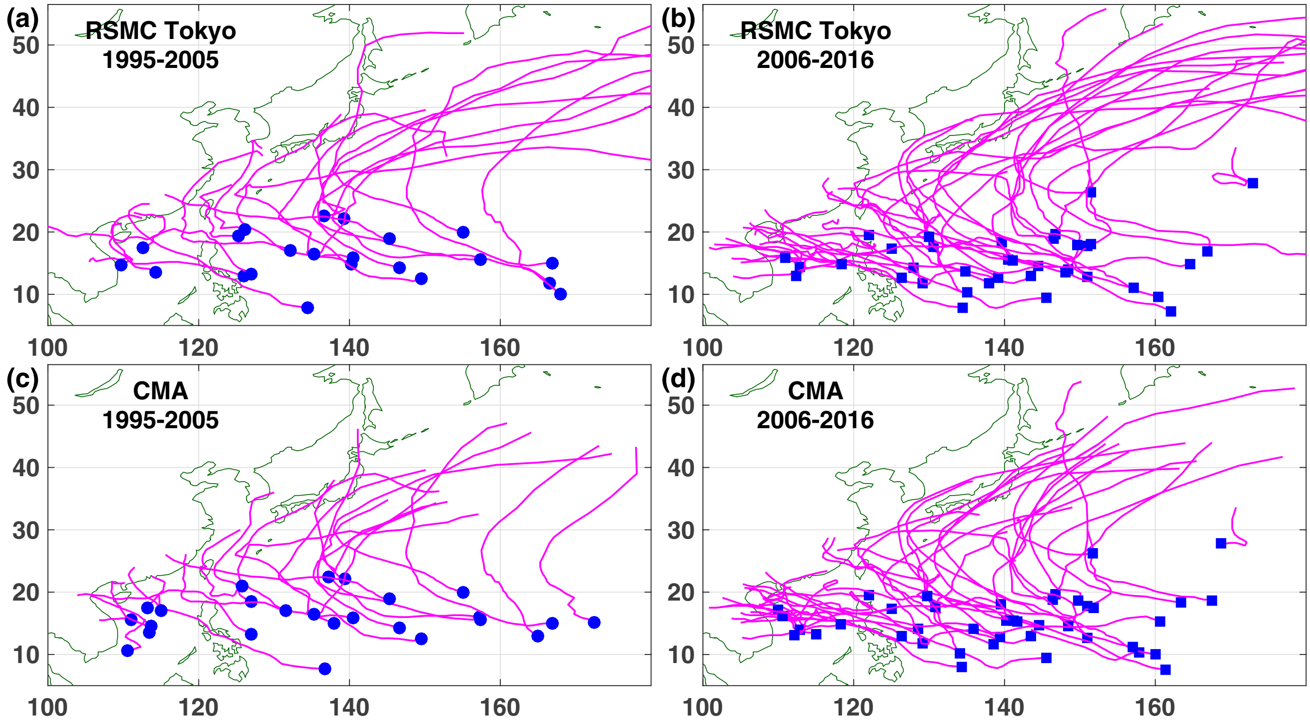

Fig. 8 Tracks for TCs generated within pentads 53 to 56 during **a, c** 1995–2005 and **b, d** 2006–2016, based on the data obtained from **a, b** RSMC of Tokyo and **c, d** CMA

In addition to the TCs, ISOs may be another potential contributor for this interdecadal shift and the reasons are as follows. First, similar to TCs, ISOs are also regarded as an important factor in the wet autumn on Hainan Island (Feng et al. 2013; Qiao et al. 2015; Wang et al. 2016; Li et al. 2017a). Second, similar to TCs, ISOs can also trigger the SCSSM onset on both interannual and interdecadal time scales, which has been demonstrated in previous studies (Tong et al. 2009; Kajikawa and Wang 2012; Lee et al. 2013). There are two dominant modes of ISOs over the SCS (e.g., Mao and Chan 2005; Wang et al. 2009; Feng et al. 2013): one is on a time scale of 10–25 days [also known as quasi-biweekly oscillation (QBWO)] and the other is 30–80 days [usually associated with the eastward propagating Madden–Julian Oscillation (MJO)]. Following Kajikawa and Wang (2012) who analyzed the interdecadal advance of the SCSSM onset, changes in the ISOs strength is calculated as follows. First, the first-order Butterworth bandpass (Murakami 1979; Tong et al. 2009; Qiao et al. 2015) is used to extract the 10–25 days and 30–80 days oscillations of the OLR. Then, the standard deviations of these oscillations during September 1 to October 10 for each year are calculated. Figure 9 displays the differences (2006–2016 − 1995–2005) in this mean standard deviation between the two epochs. The results are similar when using other filters such as the difference in the two running averages (e.g., Cao and Wu 2018), or changes in the time range (e.g., starting from August 22 or September 11).

Significant increases in the QBWO activities are seen over the Philippine Sea and the Indo-China Peninsula after the mid-2000s (Fig. 9a). Differences in the strength of the 30–80 days oscillation are small in the SCS and Philippine Sea (except for the weakening confined to the northern SCS) during the two epochs (Fig. 9b). Thus, the enhancement of the QBWO may also be in favor of the late monsoon retreat. One such case occurs in October 2010, which is when the QBWO is rather strong, and Hainan Island has experienced the strongest autumn rain ever recorded (Feng et al. 2013; Cai et al. 2013; Qiao et al. 2015; Wang et al. 2016; Li et al. 2017a). The SCSSM withdrawal was delayed for approximately 1 month in 2010, which may have resulted from the strong ISOs activities and the associated westerly burst event (paper in preparation). Moreover, the enhanced QBWO activities may also have some modulation on the generation of TCs (e.g., Zhao et al. 2016), whose possible contribution has been addressed above. Fong et al. (2007) reported that after the SCSSM withdrawal, the QBWO activities remains unchanged. This implies that the interdecadal change in the SCSSM withdrawal may not have a significant impact on the QBWO activities. By contrast, the enhanced QBWO over a certain period (i.e., September–October) may favor for the delayed monsoon withdrawal around the mid-2000s.

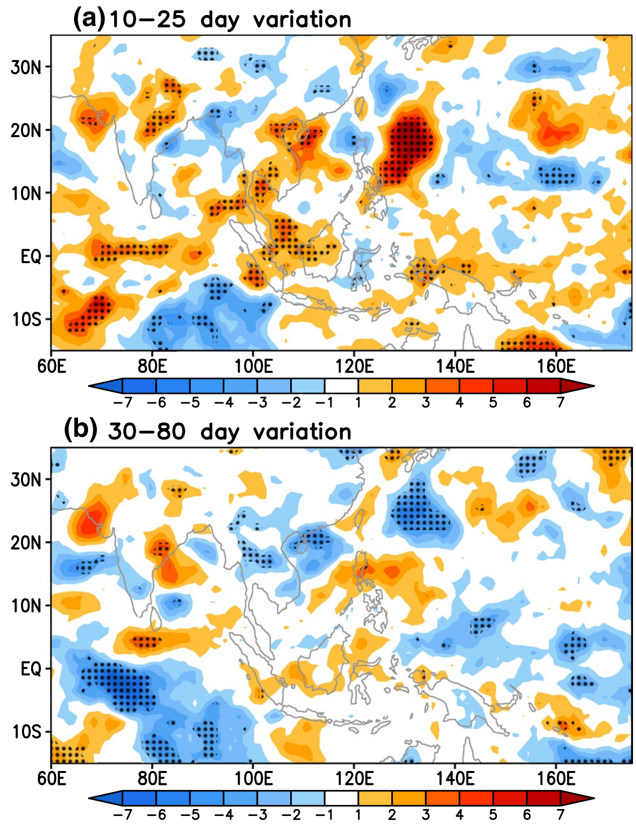

Fig. 9 Difference in the bandpass filtered OLR anomalies on **a** 10–25 days and **b** 30–80 days time scales during September 1 to October 10 between 2006–2016 and 1995–2005. Units are in W m^{-2}, and the dotted areas denote that the differences are significant at the 90% confidence level

4 Summary and discussion

This study investigates the interdecadal change in the SCSSM withdrawal based on the OLR data, rainfall data from the CMAP, and the atmospheric data provided by the NCEP-DOE reanalysis. The SCSSM withdrawal experienced a pronounced interdecadal change around the mid-2000s. Specifically, the SCSSM withdrawal became much later, compared to before the mid-2000s. After the mid-2000s, more westerlies were observed over the SCS, compared to those before the mid-2000s, which corresponds well to the delayed SCSSM withdrawal. In addition, the rainfall and convection are significantly increased over the SCS and Philippine Sea after the mid-2000s. The increase in rainfall is dynamically correlated to the appearance of an anomalous, low-level cyclone around the northern SCS as well as anomalous westerlies from the Indo-China Peninsula to the WNP at approximately 10°N. Furthermore, there also appears to be an anomalous, mid-level ascending motion and upper-level divergence around the Philippine Sea, whereas there is descending motion and upper-level convergence in the equatorial eastern Indian Ocean. Thus, an anomalous zonal circulation is located between the WNP (upward motion) and eastern Indian Ocean (downward motion). Further analyses indicate that the increasing number and frequency of TC visits to the SCS and the enhanced QBWO activities after the mid-2000s are suggested to be the two possible contributors for this delayed SCSSM withdrawal. The physical processes for the influence of the TCs and QBWO activities on the interdecadal change in the SCSSM withdrawal around the mid-2000s are still unclear at present, which will be investigated in a future study.

This study mainly addresses the internal atmospheric causes, and the possible external forcing remains to be explored. Following Xiang and Wang (2013), Fig. 10 shows correlation of SST in the preceding September with the SCSSM withdrawal date and the averaged low-level zonal winds for 1995–2016. Corresponding to the late SCSSM withdrawal and anomalous westerlies over the SCS, significant warm SST anomalies appear in the Philippine Sea. Previous studies also reported the important role of the SST decadal warming around the Philippine Sea in the interdecadal advanced SCSSM onset (Kajikawa and Wang 2012; Xiang and Wang 2013; Yuan and Chen 2013). Thus, the decadal SST warming in the Philippine Sea in September may be a crucial external forcing for the delayed SCSSM withdrawal around the mid-2000s. The detailed physical mechanisms for the impact of the SST warming in the Philippine Sea on the SCSSM withdrawal will be further pursued in the future.

The monsoon-TC relationship has always been the focus of the monsoon community. Kajikawa and Wang (2012) argued that the decadal warming of SST in the equatorial western Pacific favors for the increasing number of TC, which serves as a trigger of the advanced SCSSM onset around the mid-1990s. Li and Zhou (2014) suggested that the interdecadal change in TC activity over the SCS is associated with the zonal SST gradient between the northern Indian Ocean and the WNP. Thus, the causes for the increasing number of TCs during the monsoon withdrawal season after mid-2000s are also worthy of study. Some studies (Chen et al. 2012, 2017; Li and Zhou 2015) have quantitatively evaluated the precipitation induced by TC, and what portion of the increasing rainfall in the SCS and Philippine Sea could be attributing to TC remain to be explored.

While the interdecadal change of both the EAWM (Wang and Chen 2014; Ding et al. 2014; Wang and Lu 2016) and SCSSM withdrawal occurs in the mid-2000s, it seems that they are resulted from different causes. The re-amplification of EAWM is reported to be resulted from the middle and high latitude systems, while the delayed SCSSM withdrawal is largely resulted from the tropical systems. In addition, Fig. 7 does show some signals in the mid-latitudes (e.g., negative geopotential height changes). Several studies already

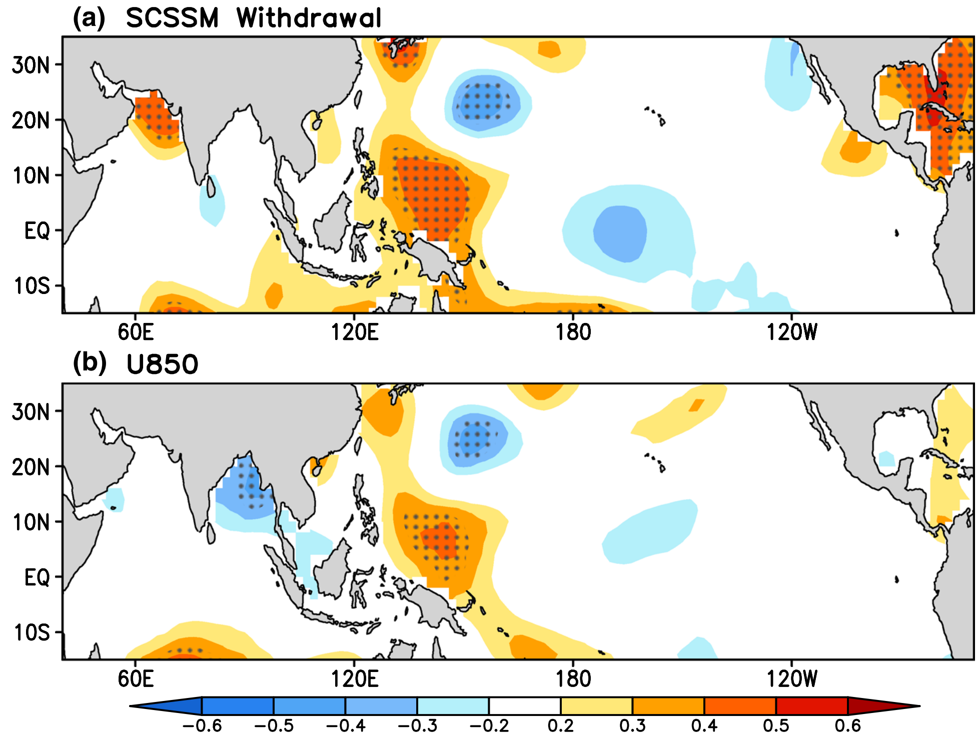

Fig. 10 Correlation coefficients of **a** the SCSSM withdrawal date (red line in Fig. 1a), and **b** the 850 hPa zonal winds (averaged over 110°–120°E, 10°–20°N, pentads 53–56; red line in Fig. 3b) with the September SST for 1995–2016. Dotted areas denote that the correlations are significant at the 90% confidence level

revealed the linkage between the EAWM and EASM (e.g., Chen et al. 2013; Feng and Chen 2014; Hu and Chen 2018). Hence, the linkage between the SCSSM withdrawal and the EAWM variability is also an important issue.

The interdecadal advanced SCSSM onset and delayed SCSSM withdrawal does not occur concurrently. Specifically, the advanced onset occurs in mid-1990s while the delayed withdrawal occurs in mid-2000s. The correlation between the SCSSM onset and withdrawal is not significant at 90% confidence level for both the original and the 9-year low-pass filtered data. These poor correlations suggest that there may be no clear relationship between the SCSSM onset and withdrawal. However, it seems that the advanced onset and delayed withdrawal may be both resulted from the tropical systems including TCs and ISOs, thus the linkage and similarities between the SCSSM onset and withdrawal may hidden in the trigger mechanisms. Previous papers reported that the SCSSM onset can be influenced by various factors, for example: TC (Kajikawa and Wang 2012), cold front (Tong et al. 2009), cross-equatorial flow (Hu et al. 2018b), ITCZ (Zhou et al. 2005), ISOs including MJO (Tong et al. 2009) and QBWO (Lee et al. 2013), and ENSO (Zhou and Chan 2007), etc. Whether these factors could also affect SCSSM withdrawal is a prominent issue and deserves further studies.

Acknowledgements We thank the two anonymous reviewers for their valuable comments and suggestions, which led to significant improvement in the manuscript. This study is supported jointly by the National Key Research and Development Program of China (Grant No.2016YFA0600604), the National Natural Science Foundation of China (Grant 41721004), and the Chinese Academy of Sciences Key Research Program of Frontier Sciences (QYZDY-SSW-DQC024). PH thanks Yaheng Tan and Shaorou Dong of Sun Yat-sen University and Zhiang Xie and Shuoyi Ding of the Institute of Atmospheric Physics for helpful advice and several discussions.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Cai Q, Feng W, Li X et al (2013) Technical manual for weather forecast in Hainan Province. China Meteorological Press, Beijing
Cao X, Wu R (2018) Origins and interrelationship of Intraseasonal rainfall variations around the Maritime Continent during boreal winter. Theor Appl Climatol 132:543–554
Chen G (2015) Comments on "Interdecadal change of the South China sea summer monsoon onset". J Clim 28(22):9029–9035
Chen J, Wu R, Wen Z (2012) Contribution of South China Sea tropical cyclones to an increase in southern China summer rainfall around 1993. Adv Atmos Sci 29(3):585–598
Chen W, Feng J, Wu R (2013) Roles of ENSO and PDO in the link of the East Asian winter monsoon to the following summer monsoon. J Clim 26(2):622–635
Chen S, Wei K, Chen W et al (2014) Regional changes in the annual mean Hadley circulation in recent decades. J Geophys Res 119:7815–7832

Chen J, Wen Z, Wang X (2017) Relationship over southern China between the summer rainfall induced by tropical cyclones and that by monsoon. Atmos Oceanic Sci Lett 10(1):96–103
Choi KS, Kim HD, Kang SD et al (2017) Interdecadal change of South China Sea summer monsoon intensity in the mid-1990s. Int J Climatol 37(2):559–569
Ding Y, Wang Z, Sun Y (2008) Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: observed evidences. Int J Climatol 28:1139–1161
Ding Y, Sun Y, Wang Z et al (2009) Inter-decadal variation of the summer precipitation in China and its association with decreasing Asian summer monsoon Part II: possible causes. Int J Climatol 29:1926–1944
Ding Y, Liu Y, Liang S et al (2014) Interdecadal variability of the East Asian winter monsoon and its possible links to global climate change. J Meteorol Res 28(5):693–713
Ding Y, Liu Y, Song Y et al (2015) From MONEX to the global monsoon: a review of monsoon system research. Adv Atmos Sci 32(1):10–31
Feng J, Chen W (2014) Interference of the East Asian winter monsoon in the impact of ENSO on the East Asian summer monsoon in decaying phases. Adv Atmos Sci 31(2):344–354
Feng J, Hu D (2014) How much does heat content of the western tropical Pacific Ocean modulate the South China Sea summer monsoon onset in the last four decades? J Geophys Res 119(7):4029–4044
Feng X, Wu R, Chen J et al (2013) Factors for interannual variations of September–October rainfall in Hainan, China. J Clim 26(22):8962–8978
Fong S, Wang A, Liang J et al (2007) Climatic characteristics of the retreat of South China Sea summer monsoon I 40-year means. J Trop Meteor 23:7–13
Gill AE (1980) Some simple solutions for heat-induced tropical circulation. Q J R Meteorol Soc 106:447–462
Ha Y, Zhong Z, Sun Y et al (2014) Decadal change of South China Sea tropical cyclone activity in mid-1990s and its possible linkage with intraseasonal variability. J Geophys Res 119:5331–5344
Hu P, Chen W (2018) The relationship between the East Asian winter monsoon anomaly and the subsequent summer monsoon onset over the South China Sea and the impact of ENSO. Clim Environ Res 23(4):401–412
Hu P, Chen W, Huang R et al (2018a) Climatological characteristics of the synoptic changes accompanying South China Sea summer monsoon withdrawal. Int J Climatol. https://doi.org/10.1002/joc.5828
Hu P, Chen W, Huang R et al (2018b) On the weakening relationship between the South China Sea summer monsoon onset and cross-equatorial flow after the late 1990s. Int J Climatol 38:3202–3208
Huang NE, Shen Z, Long SR et al (1998) The empirical mode decomposition and the hilbert spectrum for nonlinear and non-stationary time series analysis. Proc Math Phys Eng Sci 454:903–995
Huang R, Chen J, Wang L et al (2012) Characteristics, processes, and causes of the spatio-temporal variabilities of the East Asian monsoon system. Adv Atmos Sci 29(5):910–942
Huang R, Liu Y, Feng T (2013) Interdecadal change of summer precipitation over Eastern China around the late-1990s and associated circulation anomalies, internal dynamical causes. Chin Sci Bull 58(12):1339–1349
Huang B, Banzon VF, Freeman E et al (2015) Extended reconstructed sea surface temperature version 4 (ERSST. v4). Part I: upgrades and intercomparisons. J Clim 28(3):911–930
Huang R, Liu Y, Du Z et al (2017) Differences and links between the East Asian and South Asian summer monsoon systems: characteristics and variability. Adv Atmos Sci 34(10):1204–1218
Huang R, Chen S, Chen W et al (2018) Interannual variability of regional Hadley circulation intensity over western Pacific during boreal winter and its climatic impact over Asia–Australia region. J Geophys Res 123:344–366
Huangfu J, Huang R, Chen W (2017a) Statistical analysis and a case study of tropical cyclones that trigger the onset of the South China Sea summer monsoon. Sci Rep 7:12732
Huangfu J, Huang R, Chen W (2017b) Interdecadal increase of tropical cyclone genesis frequency over the western north Pacific in May. Int J Climatol 37:1127–1130
Jiang X, Ren F, Li Y et al (2018) Characteristics and preliminary causes of tropical cyclone extreme rainfall events over Hainan Island. Adv Atmos Sci 35(5):580–591
Kajikawa Y, Wang B (2012) Interdecadal change of the South China Sea summer monsoon onset. J Clim 25(9):3207–3218
Kajikawa Y, Yasunari T, Wang B (2009) Decadal change in intraseasonal variability over the South China Sea. Geophys Res Lett 36:L06810
Kajikawa Y, Yasunari T, Yoshida S et al (2012) Advanced Asian summer monsoon onset in recent decades. Geophys Res Lett 39(3):L03803
Kanamitsu M, Ebisuzaki W, Woollen J et al (2002) NCEP–DOE AMIP-II reanalysis (R-2). Bull Am Meteorol Soc 83:1631–1643
Kwon MH, Jhun JG, Wang B et al (2005) Decadal change in relationship between east Asian and WNP summer monsoons. Geophys Research Lett 32:L16709
Kwon MH, Jhun JG, Ha KJ (2007) Decadal change in east Asian summer monsoon circulation in the mid-1990 s. Geophys Res Lett 34:L21706
Lau KM, Yang S (1997) Climatology and interannual variability of the Southeast Asian summer monsoon. Adv Atmos Sci 4(2):141–162
Lee JY, Wang B, Wheeler MC et al (2013) Real-time multivariate indices for the boreal summer intraseasonal oscillation over the Asian summer monsoon region. Clim Dyn 40(1–2):493–509
Lee EJ, Ha KJ, Jhun JG (2014a) Interdecadal changes in interannual variability of the global monsoon precipitation and interrelationships among its subcomponents. Clim Dyn 42:2585–2601
Lee HT, Schreck CJ, Knapp KR (2014b) Generation of the daily OLR climate data record. In: 2014 EUMETSAT meteorological satellite conference. 22–26 September 2014, Geneva, Switzerland
Lee JY, Kwon MH, Yun KS et al (2017) The long-term variability of Changma in the East Asian summer monsoon system: a review and revisit. Asia Pac J Atmos Sci 53(2):257–272
Li RCY, Zhou W (2014) Interdecadal change in South China Sea tropical cyclone frequency in association with zonal sea surface temperature gradient. J Clim 27(14):5468–5480
Li RCY, Zhou W (2015) Interdecadal changes in summertime tropical cyclone precipitation over southeast China during 1960–2009. J Clim 28(4):1494–1509
Li J, Ye Q, Li F et al (2017a) Effects of atmospheric oscillations at different time scales on persistent autumn rainstorms in Hainan, China. J Atmos Sol Terr Phy 164:243–258
Li Y, Ding Y, Li W (2017b) Interdecadal variability of the Afro-Asian summer monsoon system. Adv Atmos Sci 34(7):833–846
Liang B (1990) Tropical meteorology. Sun Yat-Sen University Press, Guangzhou
Liu Y, Huang G, Huang R (2011) Inter-decadal variability of summer rainfall in Eastern China detected by the Lepagetest. Theo Appl Climatol 106:481–488
Lu R, Ye H, Jhun JG (2011) Weakening of interannual variability in the summer East Asian upper-tropospheric westerly jet since the mid-1990s. Adv Atmos Sci 28(6):1246–1258
Luo M, Lin L (2017) Objective determination of the onset and withdrawal of the South China Sea summer monsoon. Atmos Sci Lett 18(6):276–282
Mao J, Chan JCL (2005) Intraseasonal variability of the South China Sea summer monsoon. J Clim 18(13):2388–2402

Mao J, Wu G (2008) Influences of Typhoon Chanchu on the 2006 South China Sea summer monsoon onset. Geophys Res Lett 35:L12809
Matsuno T (1966) Quasi-geostrophic motions in the equatorial area. J Meteorol Soc Jpn 44:25–43
Molinari J, Vollaro D (2013) What percentage of western North Pacific tropical cyclones form within the monsoon trough? Mon Weather Rev 141:499–505
Murakami M (1979) Large-scale aspects of deep convective activity over the GATE area. Mon Weather Rev 107(8):994–1013
National Climate Center (2016) East Asian monsoon yearbook 2015. China Meteorological Press, Beijing
Ning L, Qian Y (2009) Interdecadal change in extreme precipitation over South China and its mechanism. Adv Atmos Sci 26(1):109–118
Park JY, Jhun JG, Yim SY et al (2010) Decadal changes in two types of the western North Pacific subtropical high in boreal summer associated with Asian summer monsoon/El Niño–Southern Oscillation connections. J Geophys Res 115:D21129
Qiao Y, Zhang C, Jian M (2015) Role of the 10–20-day oscillation in sustained rainstorms over Hainan, China in October 2010. Adv Atmos Sci 32(3):363–374
Tong HW, Chan JCL, Zhou W (2009) The role of MJO and mid-latitude fronts in the South China Sea summer monsoon onset. Clim Dyn 33(6):827–841
Turner AG, Wang B (2016) Interdecadal variability of the Asian summer monsoons. In: Chang C, Kuo P, Lau HC N C, et al. (eds) The global monsoon system: research and forecast, 3rd edn. World Scientific, London, pp 289–301
Wang L, Chen W (2014) The East Asian winter monsoon: re-amplification in the mid-2000s. Chin Sci Bull 59(4):430–436
Wang B, Kajikawa Y (2015) Reply to "Comments on 'Interdecadal Change of the South China Sea Summer Monsoon Onset'". J Clim 28(22):9036–9039
Wang L, Lu MM (2016) The East Asian winter monsoon. In: Chang C, Kuo P, Lau HC N C, et al. (eds) The global monsoon system: research and forecast, 3rd edn. World Scientific, London, pp 51–61
Wang B, Lin H, Zhang Y et al (2004) Definition of South China Sea monsoon onset and commencement of the East Asian summer monsoon. J Clim 17(4):699–710
Wang B, Huang F, Wu ZW et al (2009) Multi-scale climate variability of the South China Sea monsoon: a review. Dyn Atmos Oceans 47:15–37
Wang H, Sun J, Zhao S et al (2016) The multiscale factors favorable for a persistent heavy rain event over Hainan Island in October 2010. J Meteorol Res 30(4):496–512
Wei M, Qiao F, Deng J (2015) A quantitative definition of Global Warming Hiatus and 50-year prediction of global-mean surface temperature. J Clim 72:3281–3289
Wu Z, Huang NE (2009) Ensemble empirical mode decomposition: a noise-assisted data analysis method. Adv Adapt Data Anal 1(1):1–41
Wu Y, Wu S, Zhai P (2007) The impact of tropical cyclones on Hainan Island's extreme and total precipitation. Int J Climatol 27(8):1059–1064
Wu R, Wen Z, Yang S et al (2010) An interdecadal change in southern China summer rainfall around 1992/93. J Clim 23(9):2389–2403
Xiang B, Wang B (2013) Mechanisms for the advanced Asian summer monsoon onset since the mid-to-late 1990s. J Clim 26(6):1993–2009
Xie P, Arkin PA (1997) Global precipitation: a 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs. Bull Am Meteorol Soc 78:2539–2558
Yao C, Yang S, Qian W et al (2008) Regional summer precipitation events in Asia and their changes in the past decades. J Geophys Res 113:D17107
Yim SY, Jhun JG, Yeh SW (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
Ying M, Zhang W, Yu H et al (2014) An overview of the China Meteorological Administration tropical cyclone database. J Atmos Oceanic Technol 31:287–301
Yu W, Li K, Shi J et al (2012) The onset of the monsoon over the Bay of Bengal: the year-to-year variations. Atmos Oceanic Sci Lett 5(4):342–347
Yuan F, Chen W (2013) Roles of the tropical convective activities over different regions in the earlier onset of the South China Sea summer monsoon after 1993. Theor Appl Climatol 113:175–185
Zhang R (2015) Changes in East Asian summer monsoon and summer rainfall over eastern China during recent decades. Sci Bull 60(13):1222–1224
Zhang L, Li D, Li X (2014) Definition of onset and retreat date of the South China Sea summer monsoon and the relation with its strength under the background of climate warming. J Trop Meteorol 30(6):1037–1047
Zhao H, Wang C, Yoshida R (2016) Modulation of tropical cyclogenesis in the western North Pacific by the quasi-biweekly oscillation. Adv Atmos Sci 33(12):1361–1375
Zhou W, Chan JCL (2007) ENSO and the South China Sea summer monsoon onset. Int J Climatol 27(2):157–167
Zhou W, Chan JCL, Li C (2005) South China Sea summer monsoon onset in relation to the off-equatorial ITCZ. Adv Atmos Sci 22(5):665–676
Zhou T, Song F, Ha K et al (2016) Decadal change of East Asian summer monsoon: contributions of internal variability and external forcing. In: Chang CP, Kuo HC, Lau NC et al (eds) The global monsoon system: research and forecast, 3rd edn. World Scientific, London, pp 327–336
Zhu Y, Wang H, Zhou W et al (2011) Recent changes in the summer precipitation pattern in East China and the background circulation. Clim Dyn 36:1463–1473