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The Weakening Relationship between ENSO and the South China Sea Summer Monsoon Onset in Recent Decades

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ABSTRACT

The El Niño-Southern Oscillation (ENSO) is traditionally regarded as the most important factor modulating the interannual variation of the South China Sea summer monsoon (SCSSM) onset. A preceding El Niño (La Niña) usually tends to be followed by a delayed (an advanced) monsoon onset. However, the close relationship between ENSO and SCSSM onset breaks down after the early-2000s, making seasonal prediction very difficult in recent years. Three possible perspectives have been proposed to explain the weakening linkage between ENSO and SCSSM onset, including interdecadal change of the ENSO teleconnection (i.e., the Walker circulation), interferences of other interannual variability (i.e., the Victoria mode), and disturbances on intraseasonal time scales (i.e., the quasi-biweekly oscillation). By comparing the epochs of 1979–2001 and 2002–19, it is found that the anomalous tropical Walker circulation generated by ENSO is much weaker in the latter epoch and thus cannot deliver the ENSO signal to the SCSSM onset. Besides, in recent years, the SCSSM onset is more closely linked to extratropical factors like the Victoria mode, and thus its linkage with ENSO becomes weaker. In addition to these interannual variabilities, the intraseasonal oscillations like the quasi-biweekly oscillation can disrupt the slow-varying seasonal march modulated by ENSO. Thus, the amplified quasi-biweekly oscillation may also contribute to the weakening relationship after the early-2000s. Given the broken relationship between ENSO and SCSSM onset, the extratropical factors should be considered in order to make skillful seasonal predictions of SCSSM onset, and more attention should be paid to the extended-range forecast based on intraseasonal oscillations.

Key words: South China Sea, summer monsoon onset, ENSO, interdecadal change

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Article Highlights:

- The in-phase relationship between ENSO and SCSSM onset breaks down after the early-2000s, indicating that ENSO cannot be used to predict SCSSM onset in recent years.
- The possible mechanisms for the weakening relationship include: change of ENSO teleconnection (Walker circulation), interferences of other interannual variability (Victoria mode), and tropical disturbances on intraseasonal time scales (quasi-biweekly oscillation).
- Extratropical factors should be considered in order to make skillful seasonal predictions of the SCSSM onset, and more attention should be paid to the extended-range forecast based on intraseasonal oscillations.

1. Introduction

The summer monsoon and wet season over the western North Pacific (WNP) and East Asia generally begins over the South China Sea (SCS; Li and Zhang, 2009; Kajikawa et al., 2012; Xiang and Wang, 2013; Liu et al., 2015; Bombardi et al., 2019, 2020). The onset of the South China Sea summer monsoon (SCSSM) is the most important subseasonal phenomenon of the wet season annual cycle and is signified by a firm establishment of the tropical southwesterly wind and a burst of monsoonal convection (Wang et al., 2009; Hu et al., 2018, 2019, 2020a, 2021; Geen, 2021). The SCSSM onset has always been a focus of monsoon research, since it is strongly linked to the extreme weather and climate events in late spring and summer over East Asia and the WNP. For example, the monsoon onset date is significantly negatively correlated with the number of tropical cyclones generated over the WNP in May (Huangfu et al., 2017a, b). An advanced SCSSM onset is accompanied by an earlier establishment of the monsoon trough, which facilitates the conversion of mean kinetic energy into eddy kin-

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etic energy and is favorable for tropical cyclone genesis (Huangfu et al., 2017a). Additionally, an advanced SCSSM onset tends to coincidence with reduced May rainfall in the middle and lower reaches of the Yangtze River basin (Jiang et al., 2018). Accompanying an early monsoon onset is the appearance of increased rainfall over the SCS and WNP, which excites an equatorial Rossby wave response (Hu et al., 2018; Jiang et al., 2018). Such a response manifests as an anomalous low-level cyclone, which can decrease the water vapor transport to subtropical East Asia (Jiang et al., 2018). In addition to the late spring, the SCSSM onset is also a good indicator of summertime climate anomalies. An advanced monsoon onset also tends to be followed by increased East Asian monsoon rainfall (He and Zhu, 2015) and more tropical cyclones that make landfall on mainland China (Wang and Chen, 2018).

Due to the importance of monsoon onset stated above, extensive efforts have been devoted to understanding the factors that modulate the SCSSM onset (Hu et al., 2020a; and references therein; Geen, 2021; Hu et al., 2021; Liu and Zhu, 2021). These factors cover different time scales, including the cold front and tropical disturbances on the synoptic scale (Huangfu et al., 2017b, 2018; Hu et al., 2020a; Liu and Zhu, 2020), quasi-biweekly oscillation and 30–80 day oscillation on the intraseasonal time scale (Shao et al., 2015; Wang et al., 2018; Hu et al., 2019; Li et al., 2019; Liu and Zhu, 2021), and Indo-Pacific Ocean sea surface temperature (SST) and heat content on the interannual and interdecadal time scales (Kajikawa and Wang, 2012; Xiang and Wang, 2013; Feng and Hu, 2014; He et al., 2017; Luo and Lin, 2017; Lin and Zhang, 2020; Feng et al., 2021; Liu and Zhu, 2021). Among these factors, ENSO is regarded as the most important (Zhu and Li, 2017; Martin et al., 2019); an advanced (a delayed) SCSSM onset usually tends to follow a preceding La Niña (El Niño) event. Various pathways connecting ENSO and SCSSM onset have been identified. Take the delayed SCSSM onset following El Niño events for example: The warm SST anomalies in the equatorial central-eastern Pacific can persist from the preceding winter to the late spring via air–sea interaction processes. Then, the late spring SST anomalies can force the overlying atmospheric circulation, inducing notable low-level convergence, upper-level divergence, and ascending motion over the equatorial central-eastern Pacific. Via the large-scale divergent circulation (i.e., Walker circulation), upper-level convergence, descending motion, and low-level divergence can be induced over the WNP, which hinder the development of monsoonal convection and lead to the delayed monsoon onset (Liang et al., 2013; Luo et al., 2016; Wu and Mao, 2019; Feng et al., 2021). In addition, ENSO can also indirectly affect the SCSSM onset date via the WNP. Namely, the cold SST anomalies over the WNP accompanying El Niño excite an equatorial Rossby wave response to its west (Matsuno, 1966; Gill, 1980), which is known as the Philippine Sea anticyclone (Zhang et al., 1996; Wang et al., 2000, 2003; Wang and Zhang, 2002). Due to the wind–evaporation–SST feedback, the anomalous low-level anticyclone and cold SSTA can persist from the winter to the spring (Wang et al., 2000; Xie et al., 2016; Li et al., 2017; Zhang et al., 2017). The anomalous easterly wind to the south of the anticyclone hinders the establishment of the monsoonal southwesterly wind, thus resulting in the delayed SCSSM onset. Additionally, ENSO may also indirectly modulate the SCSSM onset date via the upper-level South Asian High (Liu et al., 2016; Zeng et al., 2021), the snow depth over the Tibetan Plateau (Shaman and Tziperman, 2005; Yu and Hu, 2008), and the Bay of Bengal summer monsoon onset (Liu et al., 2002; Wu et al., 2005; Li et al., 2018; Wu and Mao, 2019). As such, ENSO serves as the most important predictor of SCSSM onset in both statistical model predictions (Zhu and Li, 2017) and dynamical model predictions (Martin et al., 2019).

However, the relationship between ENSO and SCSSM onset is not stationary and exhibits remarkable interdecadal changes. Geen (2021) reported that the linkage between monsoon onset and equatorial central Pacific SST anomalies is not significant during 1958–88 but becomes evident during 1989–2019. However, the ENSO–SCSSM onset relationship breaks down again in recent years (e.g., Jiang and Zhu, 2021). For example, an extremely late SCSSM onset occurs in 2018 following the 2017/18 La Niña event (Liu and Zhu, 2019; Deng et al., 2020; Lu et al., 2020), while an extremely early SCSSM onset occurs in 2019 following the 2018/19 El Niño event (Hu et al., 2020a; Liu and Zhu, 2020, 2021). Several case studies have been conducted to understand this weakening relationship. Several studies (Liu and Zhu, 2019; Liu et al., 2020; Deng et al., 2020) highlighted the combined impacts of extratropical circulation (i.e., atmospheric Rossby wave train) and tropical circulation (i.e., 30–80 day oscillation) in the abnormal monsoon onset of 2018. Hu et al. (2020a) reported that the 30–80 day oscillation, monsoon onset vortex over the Bay of Bengal, and cold front associated with a midlatitude trough collectively triggered the SCSSM onset in 2019. Meanwhile, Liu and Zhu (2020) mainly attributed the SCSSM onset in 2019 to the monsoon onset vortex over the Bay of Bengal, which was strong enough to eventually develop into a tropical cyclone. To the authors' knowledge, the recent study by Jiang and Zhu (2021) is the first attempt to investigate the weakening relationship between ENSO and SCSSM onset from the statistical point of view. They argued that the weakening relationship can be attributed to the disturbance of "cold tongue" La Niña events, which are identified by surface meridional wind divergence and narrow cold SST anomalies over the eastern Pacific (Jiang and Zhu, 2020, 2021). However, Jiang and Zhu (2021) focused only on three "cold tongue" La Niña events (i.e., 2013, 2014, and 2018), which does not provide enough information to explain the weakening relationship between ENSO and SCSSM onset in recent years. For example, the extremely late monsoon onset in 2019 following an El Niño event (Hu et al., 2020a; Liu and Zhu, 2020) certainly cannot be attributed to a "cold tongue"

La Niña. Based on the case analyses mentioned above, the question of how to statistically understand the weakening ENSO–SCSSM onset relationship in recent years remains. This scientific question is the focus of the present study. The rest of this study is organized as follows: section 2 introduces the datasets and methods, section 3 investigates the weakening relationship between ENSO and SCSSM onset from three different points of view, and finally, section 4 presents the summary and discussion.

2. Data and methods

The major datasets employed in this study include: (a) daily and monthly mean National Centers for Environmental Prediction-Department of Energy (NCEP-DOE) reanalysis data (Kanamitsu et al., 2002), which has a horizontal resolution of 2.5° × 2.5° and covers 1979–2019, and (b) monthly mean Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) data (Rayner et al., 2003), which has a horizontal resolution of 1° × 1° and covers 1948–2019. Following previous studies (Bond et al., 2003; Ding et al., 2015, 2018), EOF (empirical orthogonal function) analysis is performed to the North Pacific SST anomalies. EOF1 and EOF2 are known as the Pacific Decadal Oscillation (Newman et al., 2016 and references therein) and Victoria mode (Ding et al., 2015 and references therein), respectively. Following Ding et al. (2015), the corresponding PC2 is defined as the Victoria mode index.

The recent study by Geng et al. (2018) proposed a new method to interpret the nonstationary running correlations. Following Geng et al. (2018), the running correlation of two time series (say, X and Y) can be written as

$$\widetilde{r} = \frac{\overline{XY} + \Delta\widetilde{XY}}{\sqrt{(\overline{X^2} + \Delta\widetilde{X^2})(\overline{Y^2} + \Delta\widetilde{Y^2})}}\ , \quad (1)$$

where a tilde denotes the running correlation, running covariance, or running variance, and an overbar denotes the same variables over the entire time period. Using the first-order Taylor expansion, the above running correlation can be approximated by

$$\widetilde{r} = \overline{r} + \overline{r}\frac{\Delta\widetilde{XY}}{\overline{XY}} - \overline{r}\frac{\Delta\widetilde{X^2}}{2\overline{X^2}} - \overline{r}\frac{\Delta\widetilde{Y^2}}{2\overline{Y^2}}\ , \quad (2)$$

where the first term on the right-hand side denotes the correlation during the entire time period, and the other three terms denote the contributions from the departure of the running covariance and variances. For details on this method, readers are referred to Geng et al. (2018).

3. The weakening relationship between ENSO and SCSSM onset

3.1. *Confirmation of the weakening relationship*

Figure 1 shows the 850-hPa zonal wind averaged over the central SCS for the period of 1979–2019. In late April (early June), the SCS is dominated by easterly (westerly) wind. May is the transition month of the Asian summer monsoon, during which the low-level zonal wind shifts from easterly to westerly. Following previous studies (Wang et al., 2004; Hu et al., 2018), the SCSSM onset is recognized as the firm establishment of the low-level westerly wind (black curve in Fig. 1), which can preclude the "bogus onset" triggered by intraseasonal oscillations. Details on the definition of SCSSM onset can be found in Hu et al. (2018).

To investigate the relationship between SCSSM onset and ENSO, Fig. 2a shows the time evolution of correlation between monsoon onset date and equatorial SST anomalies. Significant positive correlation appears over the central-eastern Pacific east of 180°E, while negative correlation appears

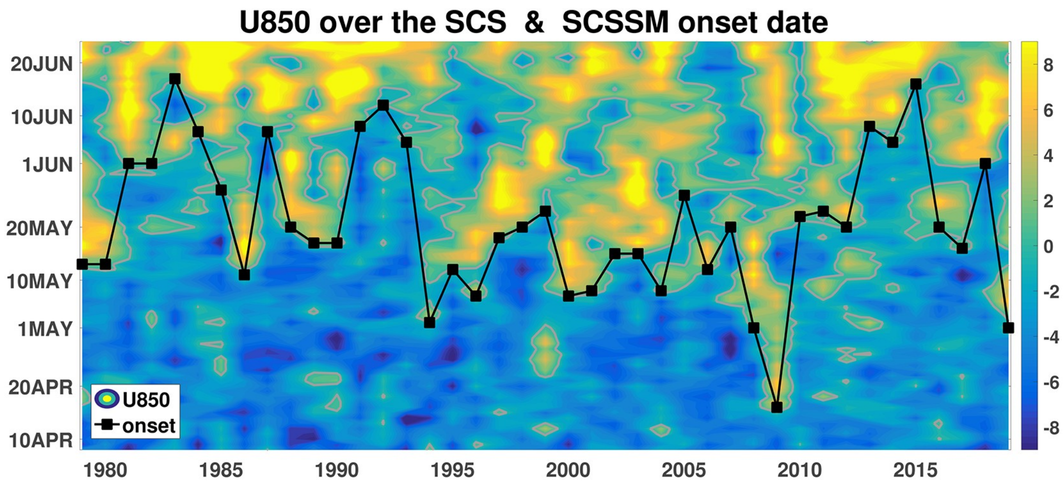

Fig. 1. 850-hPa zonal wind (shading, units in m s^{-1}) averaged over the central SCS (110°–120°E, 5°–15°N) for the period of 1979–2019. The gray contours denote the zero lines (i.e., easterly/westerly wind transition). The black curve denotes the SCSSM onset dates, which are recognized by the firm establishment of low-level westerly wind.

over the western Pacific around 120º–160ºE from January to May. Namely, a preceding El Niño event in the winter and spring tends to be followed by a delayed SCSSM onset, which is consistent with previous studies (e.g., Zhu and Li, 2017; Martin et al., 2019). The most significant SST anomalies in the equatorial central-eastern Pacific appear from preceding February to the simultaneous May, which bears resemblance to the decaying phase of El Niño (Fig. 2a). In the following, we focus on investigating the relationship between SST anomalies in the equatorial central-eastern Pacific in FMA (February–March–April-average) and the SCSSM onset. Note that the month of May is excluded since it cannot be used in the seasonal forecast of the SCSSM onset. The spatial pattern of correlation between SCSSM onset and FMA SST anomalies is shown in Fig. 2b and resembles the El Niño pattern. Corresponding to the delayed SCSSM onset, significantly positive SST anomalies appear over the equatorial central-eastern Pacific, and significantly negative SST anomalies appear over the western Pacific and extend in a horseshoe-like pattern to the subtropical North and South Pacific. Notice that the most significant correlations appear over the Niño-3.4 region (rectangle

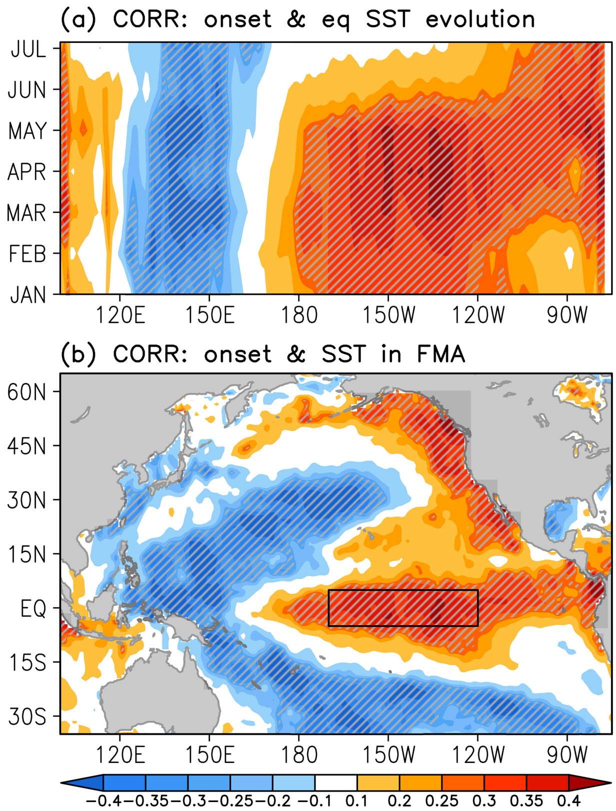

Fig. 2. (a) Monthly evolution of the correlation coefficients between the SCSSM onset date and SST anomalies in the equatorial Pacific (5°S–5°N-average) from preceding January to following July during 1979–2019. (b) Spatial pattern of the correlation coefficients between the SCSSM onset date and FMA-averaged SST anomalies during 1979–2019. The hatched areas denote the correlation coefficients that are significant at the 90% confidence level. The black rectangle in Fig. 2b highlights the Niño-3.4 region.

in Fig. 2b), which is widely employed to depict ENSO variability.

To further investigate the relationship between SCSSM onset and preceding ENSO, the normalized time series of monsoon onset date and Niño-3.4 index in FMA is shown in Fig. 3a. In the early period (e.g., before the early-2000s), the SCSSM onset shows coherent variability with the ENSO signal, which is in agreement with previous studies (e.g., Zhu and Li, 2017). However, in recent years the in-phase relationship between ENSO and SCSSM onset has significantly weakened. Moreover, out-of-phase variation even appears for 2018 and 2019 (Liu and Zhu, 2019, 2020; Deng et al., 2020; Lu et al., 2020; Hu et al., 2020a). To further investigate the interdecadal change in the ENSO–SCSSM onset relationship, the 19-year running correlation is calculated and shown in Fig. 3b. A significant in-phase relationship between preceding ENSO and monsoon onset only appears before the early-2000s, and this relationship weakens remarkably after that. According to Fig. 3b, the total analysis period of 1979–2019 is divided into two epochs: 1979–2001 when the ENSO–SCSSM onset relationship is strong, and 2002–19 when this relationship is very weak.

The time evolutions of equatorial SST anomalies that correlated with the SCSSM onset in these two epochs are further examined in Fig. 4. For the first epoch (1979–2001, Fig. 4a), the results are very similar to those derived from the total period (Fig. 2a). Namely, corresponding to the delayed SCSSM onset, significant warm (cold) SST anomalies appear in the equatorial central-eastern Pacific (western Pacific), indicating the robust in-phase ENSO–monsoon onset relationship. However, for the second epoch (2002–19, Fig. 4b), SST signals in the equatorial region are very weak and statistically insignificant. There appears to be no significant correlation east of the dateline, suggesting a weak contribution by ENSO to the SCSSM onset in recent decades, consistent with Hu et al. (2020a) and Jiang and Zhu (2021).

Spatial patterns of SST anomalies associated with the SCSSM onset during the two epochs are examined in Fig. 5. For the epoch of 1979–2001, significant SST anomalies associated with the SCSSM onset were mainly located in the tropical region (i.e., within 15°S and 15°N). Corresponding to a delayed SCSSM onset, significantly warm SST anomalies appear in the equatorial central-eastern Pacific while cold SST anomalies occur in the western Pacific. By contrast, for the epoch of 2002–19, SST anomalies associated with the SCSSM onset in the tropical Pacific are much weaker compared to those during 1979–2001. During this epoch, significant SST signals are mainly located in the extratropical region. Namely, a tripole SST anomaly pattern appears in the North Pacific Ocean, with two bands of positive SST anomalies extending from off California to the western Bering Sea and to the equatorial central Pacific, as well as a band of negative SST anomalies extending from the eastern coast of Asia to the central North Pacific. Thus, the weakening relationship between SCSSM onset and ENSO in recent

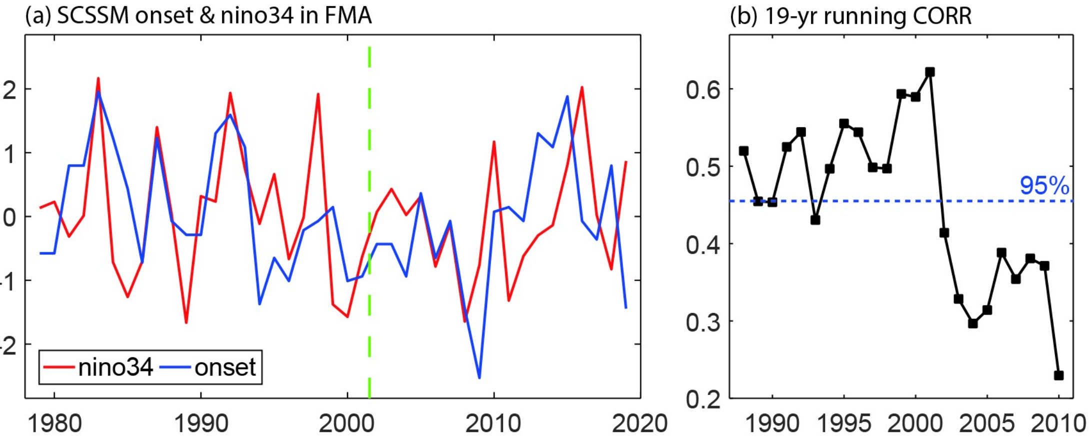

Fig. 3. (a) The normalized time series of SCSSM onset date (blue curve) and Niño-3.4 index averaged in preceding FMA (red curve). (b) The 19-year running correlation coefficients between the SCSSM onset date and the Niño-3.4 index in FMA. The horizontal dashed line in (b) denotes the correlation being significant at the 95% confidence level.

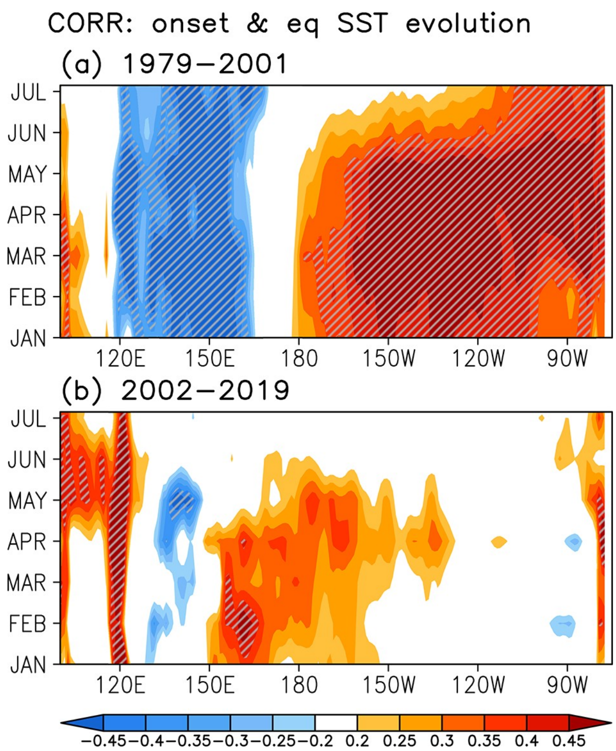

Fig. 4. Monthly evolution of the correlation coefficients between the SCSSM onset date (blue curve in Fig. 3a) and SST anomalies in the equatorial Pacific (5°S–5°N-average) during (a) 1979–2001 and (b) 2002–19. The hatched areas denote the correlation coefficients that are significant at the 90% confidence level.

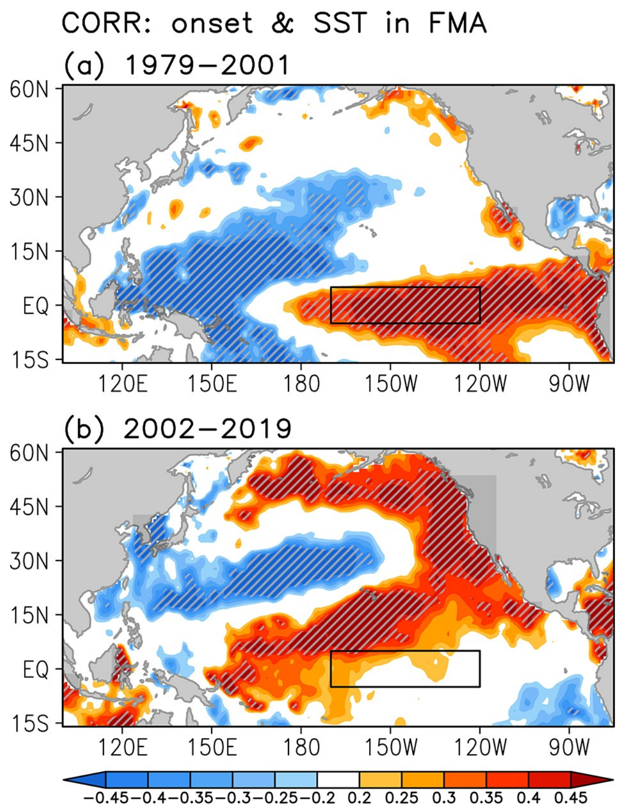

Fig. 5. Spatial pattern of the correlation coefficients between the SCSSM onset date (blue curve in Fig. 3a) and SST anomalies in preceding FMA during (a) 1979–2001 and (b) 2002–19. The hatched areas denote the correlation coefficients that are significant at the 90% confidence level. Black rectangles highlight the Niño-3.4 region.

years is again confirmed by Fig. 5.

3.2. *The ENSO perspective: change of ENSO teleconnection*

In the above section, the weakening relationship between SCSSM onset and preceding ENSO after the early-2000s is revealed. A question that needs to be further addressed is: what are the plausible factors contributing to the interdecadal change of the ENSO–SCSSM onset relationship? Following Geng et al. (2018) and as shown in Fig. 6, the 19-year running correlation of the SCSSM onset and ENSO can be decomposed into four terms: correlation during the entire time period, and the contributions from the departure of the running covariance and variances of ENSO and SCSSM onset. The total correlation between ENSO and monsoon onset during 1979–2019 is 0.374 (blue curve) and is significant at the 95% confidence level. Meanwhile, the departure of the running variances of ENSO (magenta curve) and SCSSM onset (green curve) contributes little to the interdecadal change of the ENSO–SCSSM onset relationship. The dominant term that contributes to the weakening relationship is the departure of the running covariance term (red curve). Namely, the variance of ENSO or SCSSM onset has not changed much during the two epochs, as confirmed by the F-test of equal variance. It is the co-variability between ENSO and monsoon onset that mainly contributes to this interdecadal change toward weakening in their relationship.

As mentioned in the Introduction, ENSO can modulate the SCSSM onset via several different pathways (e.g., the anomalous Walker circulation, Philippine Sea anticyclone, South Asian high, Tibetan plateau snow depth, and Bay of Bengal summer monsoon onset). Among these pathways, the Walker circulation (e.g., Kumar, 1999; McPhaden et al., 2021) is the most straightforward mechanism that directly links the SST anomalies over the equatorial central-eastern Pacific to the SCSSM onset. Thus, changes in the Walker circulation (i.e., upper-level velocity potential) during the two epochs are examined and shown in Fig. 7. For the first epoch (1979–2001), corresponding to the anomalously warm SST in the equatorial central-eastern Pacific, significant upper-level divergence is induced and is accompanied by remarkable upper-troposphere convergence over East Asia, the SCS, and the WNP. Such upper-level convergence hinders the development of monsoonal convection, thus, resulting in delayed SCSSM onset. However, for the second epoch (2002–19), the upper-level divergence over the tropical central-eastern Pacific becomes much weaker and is significant only around the dateline. Meanwhile, the upper-level convergence also becomes much weaker and is significant only over the Philippine Sea. Note that the upper-level convergence fails to pass the significance test over the SCS, thus, the ENSO signal in the second epoch cannot be delivered to the SCSSM onset via the Walker circulation. As such, one possible explanation for the weakening relationship between ENSO and monsoon onset is the change of the ENSO teleconnection (i.e., Walker circulation).

The change in the Walker circulation may be associated with the change in ENSO pattern. Figure 8 shows the correlation pattern between Niño-3.4 index in FMA and the SST anomalies in the following May. For the first epoch (1979–2001), significantly warm SST anomalies appear over the equatorial central-eastern Pacific, and cold SST anomalies appear over the WNP, which is consistent with the robust Walker circulation shown in Fig. 7a. However, for the second epoch (2002–19), significantly warm SST anomalies were mainly located over the equatorial central Pacific, and the warm SST anomalies over the equatorial east-

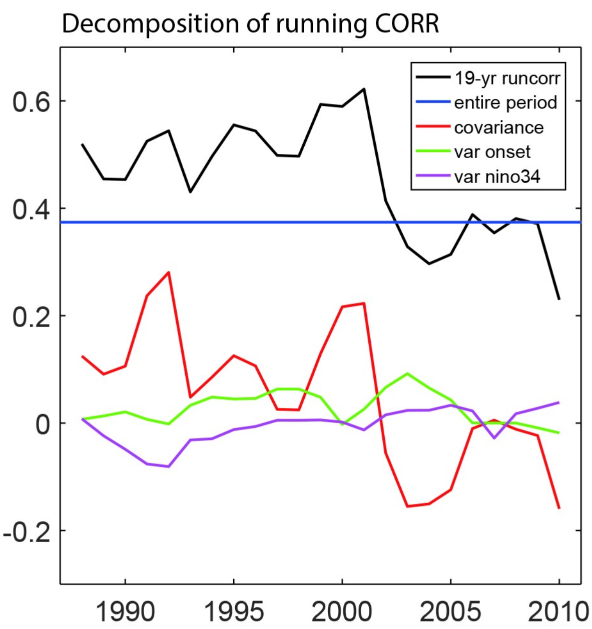

Fig. 6. The decomposition of the 19-year running correlation between SCSSM onset and ENSO (black curve): correlation during the entire period (blue curve), contribution from the departure of running covariance (red curve), running variance of SCSSM onset (green curve), and running variance of ENSO (magenta curve).

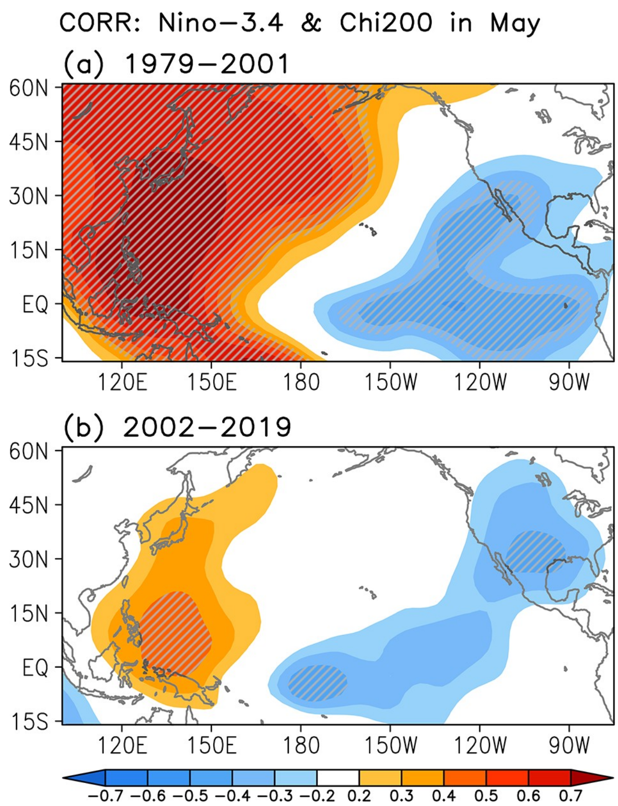

Fig. 7. The spatial pattern of correlation coefficients between the Niño-3.4 index in FMA (red curve in Fig. 3a) and the velocity potential at 200 hPa in May during (a) 1979–2001 and (b) 2002–19.

ern Pacific and the cold SST anomalies over the Philippine Sea are absent. This suggests that the zonal SST gradient is much weaker during 2002–19 compared to that during 1979–2001, consistent with the weaker anomalous Walker circulation in the second epoch shown in Fig. 7b. Such a change in ENSO pattern may be linked to the ENSO properties (e.g., Hu et al., 2020c and references therein; Capotondi et al., 2020; Jiang and Zhu, 2021). For example, the variance of SST was significantly reduced in the eastern tropical Pacific, which is in agreement with the more frequent appearance of central Pacific ENSO events after 2000 (Hu et al., 2020c). Meanwhile, the peak period of the Niño-3.4 index also becomes shorter, indicating ENSO frequency has increased since 1999/2000 (Hu et al., 2020c). In addition, Jiang and Zhu (2021) argued that the occurrences of "cold tongue" La Niña events (Jiang and Zhu, 2020; Hu et al., 2020c), which are different from classical La Niña events, could contribute to the weakening relationship between ENSO and SCSSM onset. However, investigating the changes in ENSO diversity is beyond the scope of the current study.

3.3. *The SCSSM onset perspective: the interference of Victoria mode*

In addition to the ENSO perspective explained in section 3.2, another way to understand the weakening ENSO–SCSSM onset relationship is from the monsoon onset perspective. As stated earlier in Fig. 5, for the first (second) epoch, the significant SST anomalies correlated with the SCSSM onset were mainly located in the tropical (extratropical) region. For the epoch of 2002–19 (Fig. 5b), a tripole pattern of SST anomalies appears over the North Pacific, with significantly cold SST anomalies around 15°–35°N sandwiched by warm SST anomalies to its north (roughly 45°–60°N) and south (roughly 5°–20°N). Such a pattern resembles the Victoria mode, which is the second EOF mode of the SST anomalies over the extratropical North Pacific (Bond et al., 2003; Ding et al., 2015). For comparison, Fig. 9 shows the anomalous SST and low-level (850-hPa) wind associated with the Victoria mode. A dipole pattern of SST anomalies appears over the extratropical North Pacific, with warm SST anomalies extending from the western Bering Sea to off California and cold SST anomalies extending from the central North Pacific to subtropical East Asia. Corresponding to the dipole SST anomalies in the extratropics, an anomalous low-level cyclone appears over the Bering Sea and an anomalous anticyclone appears to the north of Hawaii. Such a pattern is associated with the out-of-phase variation of the Aleutian Low and Hawaii High, namely, the North Pacific Oscillation (e.g., Linkin and Nigam, 2008; Chen and Wu, 2018). In addition, anomalously warm SST and southwesterly wind appear, extending from off California to the equatorial central Pacific, indicating the impacts of the Victoria mode on the tropical region (e.g., Vimont et al., 2001, 2003; Ding et al., 2015). It should also be noted that the SST anomalies over the Niño-3.4 region are insignificant, and the simultaneous correlation between Victoria mode index and Niño-3.4 index in FMA is only 0.123, indicating the Victoria mode is largely independent of simultaneous ENSO.

Figures 5b and 9 suggest that the Victoria mode may be a prominent factor affecting the SCSSM onset, and its import-

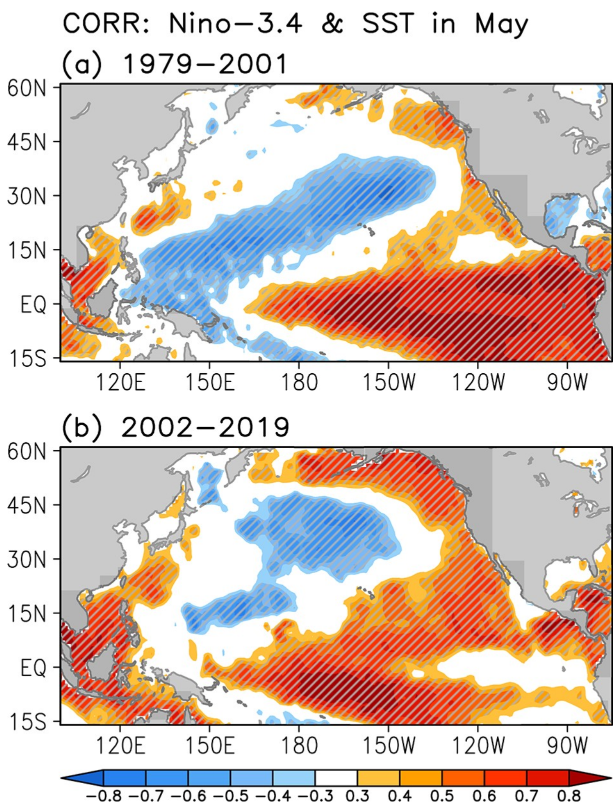

Fig. 8. Spatial pattern of the correlation coefficients between the Niño-3.4 index in FMA (red curve in Fig. 3a) and SST anomalies in May during (a) 1979–2001 and (b) 2002–19. The hatched areas denote the correlation coefficients that are significant at the 90% confidence level.

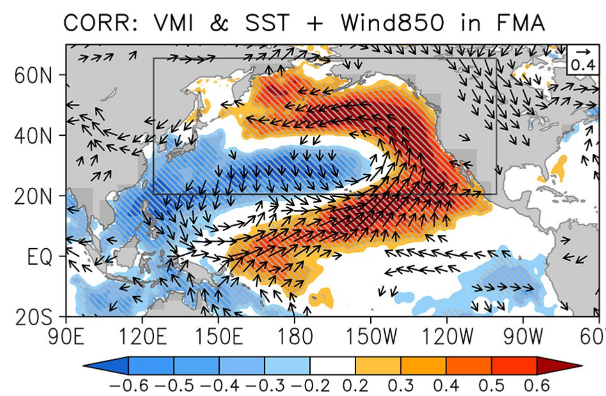

Fig. 9. Spatial pattern of the correlation coefficients between the Victoria mode index in FMA (red curve in Fig. 10) and SST (shading, hatched areas denote the correlations are significant at the 90% confidence level) and wind at 850 hPa (vectors, only those significant at 90% confidence level are shown) in the simultaneous FMA. The rectangle highlights the extratropical North Pacific region (124.5°–259.5°E, 20.5°–65.5°N) where the EOF analysis is performed.

ance may have increased in recent years. To confirm this statement, Fig. 10 shows the normalized time series of monsoon onset date and the Victoria mode index. In the beginning, the relationship between SCSSM onset and the Victoria mode is very poor and insignificant. However, in recent decades, there appears to be coherent variability between the Victoria mode and monsoon onset date, which exhibit significant in-phase variation. While the preceding La Niña in 2017/18 and El Niño in 2018/19 cannot explain the abnormal SCSSM onset in 2018 and 2019 (Fig. 3a), the Victoria mode index is positive for 2018 and negative for 2019 and is consistent with the SCSSM onset (Fig. 10a). The 19-year running correlations also confirm the strengthening relationship between SCSSM onset and preceding Victoria mode in recent years, especially after the late-2000s.

In addition to the statistical relationship revealed in Fig. 10, it is also necessary to explain the dynamical linkage between the SCSSM onset and Victoria mode. Figure 11a shows the correlation between the Victoria mode in FMA and the SST and low-level winds in May, which largely resemble those in FMA (Fig. 9). Moreover, anomalously warm SST and southwesterly wind in the tropical region exhibit equatorward shifts and are consistent with previous studies (Vimont et al., 2001, 2003; Chen and Wu, 2018). As explained in Hu et al. (2021), such equatorward displacement is mainly due to the positive wind–evaporation–SST feedback mechanism. Figure 11b shows the upper-level velocity potential anomalies in May, which exhibit significant divergence over the tropical central Pacific and convergence over the SCS and Maritime continent. As such, the signal of the Victoria mode in FMA can persist into May (Fig. 10a), and the tropical warm SST anomalies could also modulate the SCSSM onset via the large-scale divergent circulation (Fig. 10b). Thus, another possible explanation for the weakening ENSO–SCSSM onset relationship is the interference of the Victoria mode, which is largely independent of simultaneous ENSO. Namely, in recent years, the SCSSM onset has been mainly affected by the Victoria mode, thus its linkage to the preceding ENSO becomes weaker and insignificant. Hence, variation of the Victoria mode should be better accounted for when predicting the SCSSM onset in recent decades.

3.4. *The internal atmospheric processes: role of quasi-biweekly oscillation*

In the above sections, two possible perspectives are proposed to explain the recent weakening relationship between ENSO and SCSSM onset. However, the above two explanations (change of ENSO teleconnection and interference of the Victoria mode) focus on interannual factors. The direct triggers for the SCSSM onset are intraseasonal oscillations and synoptic-scale systems (Hu et al., 2020a and references therein). The recent study by Liu and Zhu (2021) investigated the important role of the quasi-biweekly oscillation in modulating SCSSM onset and the monsoon onset –ENSO linkage. They decomposed the SCSSM onset process into the slow-varying seasonal cycle part (the annual mean and first three Fourier harmonics) and the transient subseasonal part (associated with intraseasonal oscillations). While ENSO mainly modulates the slow-varying seasonal march of the SCSSM, the vigorous quasi-biweekly oscillation can disrupt the monsoon onset from this slow-varying seasonal march (Liu and Zhu, 2021). Namely, when the quasi-biweekly oscillation is active and vigorous, the SCSSM onset date may be greatly different from the transition time of the slow-varying seasonal march modulated by ENSO, thus resulting in the weakening relationship between ENSO and monsoon onset. As shown in Fig. 12a, the standard deviation of the 10–25-day filtered 850-hPa zonal wind anomalies over the SCS increased remarkably in recent decades. This indicates that the quasi-biweekly oscillation is more vigorous after the early-2000s, while the intensities of the 30–60-day oscillation or synoptic-scale systems have not changed much (Figures not shown). Figure 12b further shows the composited quasi-biweekly oscillation with respect to the SCSSM onset date in the two epochs. The

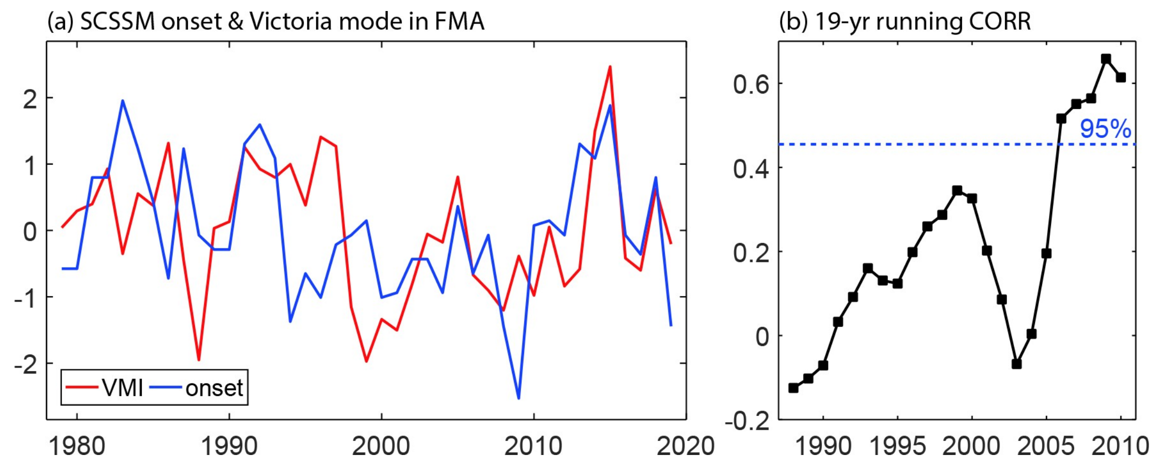

Fig. 10. (a) The normalized time series of SCSSM onset date (blue curve) and Victoria mode index averaged in FMA (red curve). (b) The 19-year running correlation between SCSSM onset date and Victoria mode index, the horizontal dashed line denotes the 95% confidence level.

quasi-biweekly oscillation is remarkably amplified in the second epoch (2002–19) compared to the first epoch (1979–2001), thus is more important for the SCSSM onset. Although in Fig. 12b the amplified quasi-biweekly oscillation mainly occurs after the onset day (for example, day +3), this does not mean the quasi-biweekly oscillation is enhanced after the SCSSM onset. Actually, the positive phase of the quasi-biweekly oscillation after the onset day is an integral part of the SCSSM onset, which contributes to the firm establishment of the low-level monsoonal westerly winds (e.g., Kajikawa and Wang 2012; Hu et al., 2018). As such, in addition to the interannual factors like the Victoria mode, the vigorous quasi-biweekly oscillation in recent years may also contribute to the weakening relationship between ENSO and SCSSM onset.

4. Summary and discussion

The SCSSM onset has received extensive research attention due to its significant socioeconomic impacts (Hu et al., 2020a). Skill in predicting an early or late SCSSM onset is important for agriculture practice in East and Southeast Asia. Although ENSO has always been regarded as the most important predictor for SCSSM onset, their relationship has broken down in recent years. The recent case in 2018 and 2019 drives us to investigate the weakening ENSO–SCSSM onset relationship from a statistical point of view. Three possible perspectives have been put forward to explain the interdecadal change in the linkage between ENSO and SCSSM onset.

The first perspective is the change in the ENSO teleconnection. By comparing the epochs of 1979–2001 and 2002–19, it is found that in the latter epoch the anomalous Walker circulation induced by ENSO is much weaker and the upper-level convergence is not significant over the SCS. Thus, the anomalously weak Walker circulation in recent years cannot deliver the ENSO signal to the SCSSM onset. The second perspective is the interference of other interannual factors such as the Victoria mode. Recently, the SCSSM onset has been closely linked to the Victoria mode, which is largely independent of ENSO and can also modulate the monsoon onset via large-scale divergent circulation. The strengthening relationship between the Victoria mode and SCSSM onset may interfere with the linkage between ENSO and monsoon onset. The third perspective is the internal atmospheric disturbances like the quasi-biweekly oscillation. The vigorous quasi-biweekly oscillation can disrupt the SCSSM onset from the slow-varying seasonal

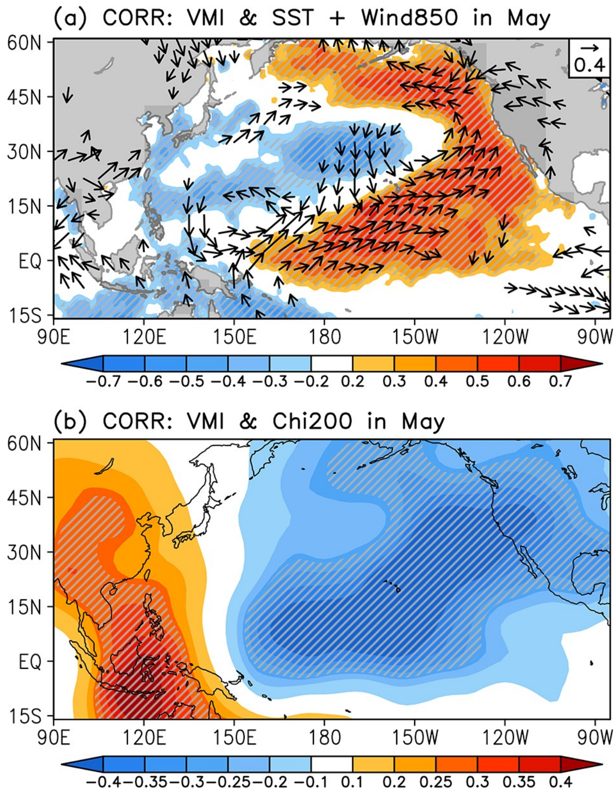

Fig. 11. (a) As in Fig. 9, but for the SST (shading, hatched areas denote the correlations are significant at the 90% confidence level) and wind at 850 hPa (vectors, only those significant at 90% confidence level are shown) in May. (b) As in (a), but for the velocity potential at 200 hPa in May.

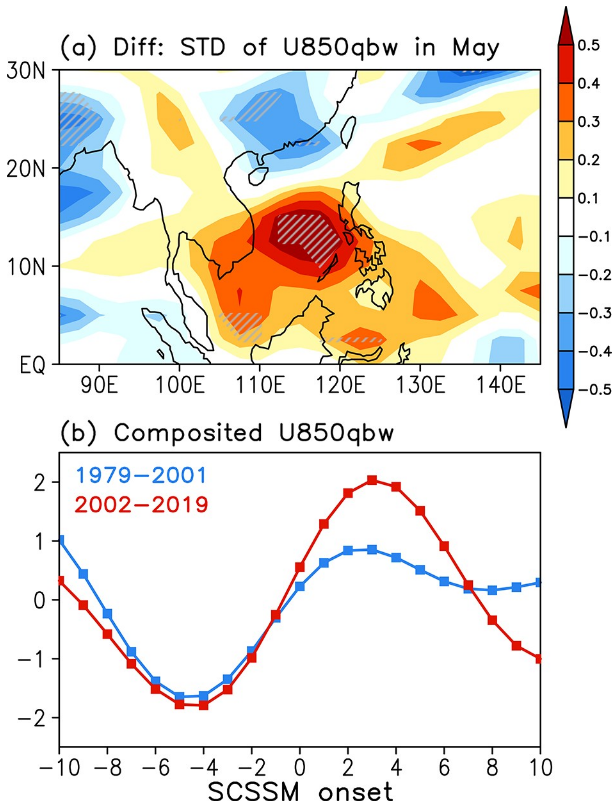

Fig. 12. (a) The epochal difference (2002–19 minus 1979–2001) in the standard deviation of 10–25-day filtered 850-hPa zonal wind anomalies in May. Hatched areas denote the differences being significant at the 90% confidence level. (b) The composited 10–25-day filtered 850-hPa zonal wind averaged over the SCS for the epochs of 1979–2001 (blue curve) and 2002–19 (red curve). Date "0" indicates the SCSSM onset day. Signs of "+" and "−" denote the dates after and before the monsoon onset, respectively.

march modulated by ENSO. Thus, the amplified quasi-biweekly oscillation in recent decades may also contribute to the weakening relationship between ENSO and monsoon onset.

Given the fact that the linkage between ENSO and SCSSM onset breaks down in recent years, it seems impossible to make seasonal prediction mainly based on tropical Pacific SST anomalies. New predictors originating from the extratropics (Liu and Zhu, 2019; Liu et al., 2020; Deng et al., 2020), for example the Victoria mode (Ding et al., 2015, 2018) or Arctic Oscillation (Hu et al., 2021), could be introduced to make skillful predictions. Besides, the increasing importance of the quasi-biweekly oscillation in recent decades suggests that more attention should be paid to the extended-range forecast (Zhu and Li, 2017; Liu and Zhu, 2021). Thus, the empirical (Zhu and Li, 2017) and dynamical (Martin et al., 2019) predictions of SCSSM onset should be revisited and updated (e.g., Geen, 2021).

While this study proposed three possible perspectives to explain the weakening relationship between ENSO and SCSSM onset, their relative contributions and interactions deserve further investigation. For example, the recent study of Wang et al. (2021) revealed that the northeastward movement of intraseasonal oscillation is related to the Victoria mode and Pacific Meridional Mode. Although the quasi-biweekly oscillation is regarded as an internal atmospheric disturbance (e.g., Chen and Sui, 2010; Zhang et al., 2020), it can be modulated by SST anomalies in the Pacific Ocean (Wu and Cao, 2017; Wang et al., 2021). In addition, this study primarily focused on the SST anomalies in the Pacific Ocean, and the possible roles of SST in the Indian Ocean and Atlantic Ocean in modulating the ENSO–SCSSM onset relation (e.g., Chen et al., 2019; Liu and Zhu, 2019; Lu et al., 2020; Mohapatra et al., 2020) deserves further investigation.

The change in ENSO teleconnection may be related to ENSO properties (e.g., Capotondi et al., 2020; Hu et al., 2020c; Jiang and Zhu, 2021), and this important issue should be further investigated. It would also be meaningful to check whether the ENSO–SCSSM onset relationship changes in the twentieth century reanalysis data, as well as the possible modulation of interdecadal background oscillations like the Pacific Decadal Oscillation (Wu and Mao, 2019) or Atlantic Multidecadal Oscillation (Fan et al., 2018).

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