



Climate shift of the South China Sea summer monsoon onset in 1993/1994 and its physical causes

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Abstract

The characteristics of anomalous circulations during spring associated with the climate shift of the South China Sea summer monsoon (SCSSM) onset in 1993/1994 and its physical causes are investigated. It is found that the interdecadal shift of SCSSM onset happened in 1993/1994 is related closely to the 850 hPa zonal wind anomalies over the area around Kalimantan Island. Easterly (westerly) anomalies over Kalimantan Island enhance (weaken) subtropical high over the western North Pacific, leading to the late (early) onset of SCSSM in 1979–1993 (1994–2013). The sea surface temperature anomalies (SSTAs) in the key region 140°–150° E, 5° S–2.5° N influence the interdecadal change of zonal winds over Kalimantan Island. The positive SSTAs over this key region in 1994–2013 force convergence toward the region at low-level and form significant westerly anomalies near Kalimantan Island located to the west of the key region. The negative anomalies of meridional gradient of zonal winds over the South China Sea region increase the atmospheric vorticity over there significantly and result in the weakening and retreating eastward of the subtropical high over the western North Pacific, which is conducive to the early onset of SCSSM.

Keywords The South China Sea summer monsoon (SCSSM) onset · Interdecadal shift · Change of 850 hPa zonal winds over the area around Kalimantan Island · SSTAs in the key region in equatorial western Pacific

1 Introduction

The South China Sea (SCS) summer monsoon (SCSSM) onset signifies the start of summer monsoon and rainy season in East Asian. The variation of the SCSSM onset time has a broad impact on the East Asian weather and climate in boreal summer (Nitta 1987; Lin et al. 2010) and the Indian Ocean climate variability (Kajikawa et al. 2003). The onset date of SCSSM varies within large extent, for example, the difference between the earliest onset and the latest onset is more than 50 days during the years of 1979–2013 (Lin et al. 2013, 2017). The mechanism about SCSSM onset appeals to a great deal of researchers. A number of studies (e.g. Ding

and Li 1999; Zhao et al. 2000; Mao et al. 2000; Ding et al. 2002; Liang et al. 2006; Huang et al. 2006; Lin et al. 2013; Liu et al. 2016) have proposed the close relationship between SCSSM onset and sea surface temperature (SST) anomalies (SSTAs). Feng and Hu (2014) deemed that the ocean heat content of upper 400 m layer in the region of (130°–150° E, 0–14° N) may be a predictor for SCSSM onset. Some studies showed that cold air originated from Southern Hemisphere through cross-equatorial flow impacts monsoon activity (Ramaswamy and Pareek 1978; Kuettner and Unninayar 1980; Sikka 1980; Rodwell 1996; He and Chen 1989; He et al. 1991; Li and Wu 2002; Gao and Xue 2006; Lin et al. 2017). The SCSSM onset exhibits significant interdecadal variation in addition to interannual variation. One common point from different studies is that there is an interdecadal shift in SCSSM onset date, and the transition took place in the middle of 1990s around 1993/1994 (Kajikawa and Wang 2012; Yuan and Chen 2013; Lin et al. 2013). Xiang and Wang (2013) proved further that the interdecadal transition of SCSSM onset appears in 1993/1994 from the view of regional mean of zonal winds in May. Even the relationship between the East Asian monsoon and the Northwest

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Pacific monsoon, both as the subsystems of the Asian monsoon, changed around 1993/1994 as well (Kwon et al. 2005). About the cause of the interdecadal transition of SCSSM onset, Kajikawa and Wang (2012) indicated that the earlier onset of SCSSM during 1994–2008 is triggered by the enhanced intraseasonal variation (ISV) and tropical cyclone (TC) activity over SCS and the Philippine Sea during the period from mid-April to mid-May, which are ascribed to a significant increase of SST in equatorial western Pacific. Analyses from synoptic scale by Yuan and Chen (2013) showed that the earlier onset of the SCSSM is a result of earlier retreat of the subtropical high over the western North Pacific, which is because of the strengthening in intraseasonal oscillations of tropical convections in tropical western Pacific. The enhanced convections mentioned by Kajikawa and Wang (2012) may be the effect of interdecadal warming in the tropical western Pacific. So the La Nina-like change of the tropical Pacific SSTs is likely to be the cause of the shift of SCSSM onset (Yuan and Chen 2013).

Up to now, many studies attributed the interdecadal shift of SCSSM onset to the interdecadal variation of La Nina-like type SSTAs in tropical Pacific (Kajikawa and Wang 2012; Yuan and Chen 2013; Xiang and Wang, 2013). However, the interdecadal transition of large-scale SSTAs in tropical Pacific appeared in the late 1990s (Yang et al. 2004; Burgman et al. 2008; Chen et al. 2010; Feng et al. 2010; Meehl and Arblaster 2012; Dai 2013). Analysis of the global SST data from 1867 to 2005 documented that the global SST field after 1998 became a new interdecadal background (Xiao and Li 2007). It is evident that the interdecadal transition of SCSSM onset is not consistent with the transition of the tropical Pacific interdecadal variation. The interdecadal transition of tropical large-scale SSTAs to a La Nina-like type occurred later than the interdecadal shift of SCSSM onset by about five years. Therefore, it is unreasonable to attribute the interdecadal shift of SCSSM onset to the interdecadal transition of large-scale tropical Pacific SST to a La Nina-like type. Moreover, for the characteristics of the circulations associated with the interdecadal transition of SCSSM onset, current studies focused mainly on the evolution of the circulations on the subseasonal timescale near the onset of SCSSM (Kajikawa and Wang 2012; Yuan and Chen 2013). However, the key process in the change of atmospheric circulations on interdecadal timescale, which is responsible for the shift of SCSSM onset around 1993/1994, is still unclear. In this study, we will examine the characteristics of anomalous atmospheric circulations during spring associated with the climate shift of SCSSM onset and investigate the related physical processes.

In the rest of this paper, data and method used in this study will be described in Sect. 2. In Sect. 3 the atmospheric circulation anomalies associated with the climate shift of SCSSM onset are checked. The possible physical mechanism

responsible for the climate shift is proposed in Sect. 4. In Sect. 5 the conclusions and discussions are presented.

2 Data and method

It is known that the reanalysis product of the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) is currently available for a period starting January 1948 (Kalnay et al. 1996). However, the data quality over Asia in NCEP–NCAR analysis may be low prior to 1968, especially at the lower troposphere (Yang et al. 2002). Therefore, the daily and monthly mean meteorological data from National Center for Environmental Prediction/Department of Energy (NCEP–DOE) Reanalysis II (Kanamitsu et al. 2002) during the period of 1979–2013, with a global coverage at a $2.5^\circ \times 2.5^\circ$ resolution, are used in the present study. The monthly sea surface temperature (SST) at a $2^\circ \times 2^\circ$ resolution during the same 35-year period is from NOAA ERSST.v2 (Smith and Reynolds 2004).

The definition of the SCSSM onset from Lin et al. (2013, 2017) is referred to. The SCSSM onset date is defined as the first day when the steady westerly winds at 850 hPa establish over the South China Sea region (105° – 120° E, 5° – 20° N). The climatological onset date of SCSSM averaged in the period of 1979–2013 is May 16st according to this index (Lin et al. 2017).

3 Atmospheric circulations associated with the interdecadal shift of SCSSM onset

Figure 1 gives the time evolution of SCSSM onset date in the past 35 years from 1979 to 2013 and its 9-year moving Student's *t* test. It can be seen that the SCSSM onset is later during first period from 1979 to 1993 and earlier during second period from 1994 to 2013. And an extreme of the 9-year moving T-test appears in 1993. The mean onset dates during 1979–1993 and 1994–2013 are May 21st and May 12th, respectively. The mean difference of SCSSM onset date between two periods is 9 day, which is statistically significant exceeding 95% confidence level according to the Student's *t* test. It is indicated that the interdecadal variation of SCSSM onset date is obvious. An interdecadal climate shift of SCSSM onset took place in 1993/1994.

Figure 2 shows the difference between the periods of 1994–2013 and 1979–1993 in each month during spring (March–May) for 850 hPa winds. The retreating eastward of the subtropical high over western North Pacific and the extending eastward of tropical westerlies are a primary changes feature of in atmospheric circulation associated with the SCSSM onset (Ding et al. 2004; Huang et al. 2006; Kajikawa and Wang 2012; Yuan and Chen 2013; Lin et al. 2017).

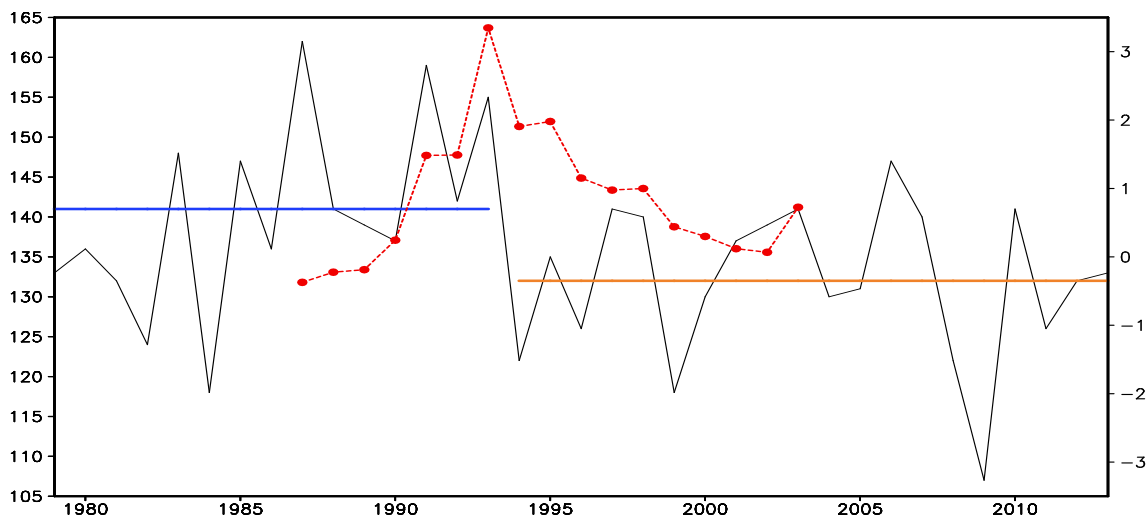


Fig. 1 Time evolution of South China Sea summer monsoon onset day during 1979–2013. The left Y-axis is the sequence number of day for monsoon onset date from 1 January for each year (Unit: day).

Blue and orange lines are the mean onset date in 1979–1993 and 1994–2013, respectively. Red dashed curve is the t value of 9-year moving Student's t test (right Y-axis)

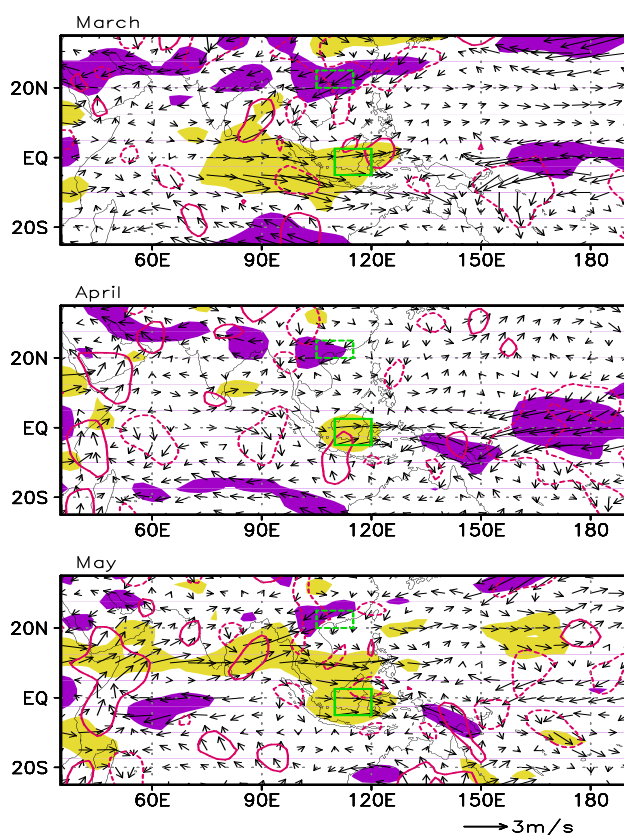


Fig. 2 Difference of 850 hPa winds between the periods of 1994–2013 and 1979–1993 in each month from March to May. Shadings and contours represent zonal and meridional winds, respectively, which pass 95% confidence level. Solid (dashed) line box is the area of positive (negative) zonal wind anomalies around Kalimantan Island (north-west South China Sea and Western South China)

It is shown from Fig. 2, that the cyclonic circulation anomaly of the difference between two periods exists over South China Sea and Western Pacific which means the weakening and retreating eastward (enhancing and extending westward) of the subtropical high over western North Pacific during the second (first) period. So the SCSM onset is earlier (later) during the second (first) period and later in the first period. It can be seen that significant anomalies last three months from March to May over two areas: one is over the area around Kalimantan Island which is located to the south of the South China Sea, and the other over the area from north-western South China Sea to western South China. Persistent westerly anomalies exist over the area around Kalimantan Island and easterly anomalies over the area from north-western South China Sea to western South China. Because SCSM onset took place mainly in April and May for past 35-year (Lin et al. 2016, 2017), here we focus on the variation of winds in April and May averaged over above two areas. Figure 3 shows the time evolution of zonal wind anomalies averaged over the area around Kalimantan Island (110°E , 5°S – 2.5°N). It is clear that the interdecadal variations of zonal winds for both monthly mean and 2-month mean are evident. The zonal wind anomalies are basically negative except for few years during first period (1979–1993), and positive during second period (1994–2013). The difference of zonal winds in either April or May between two periods are statistically significant and exceeds 99% confidence level. The mean value of zonal wind anomalies averaged in April and May is -1.1 m/s and 0.8 m/s during first and second period, respectively. Their difference reaches about 1.5 times of the absolute value of climatological mean (-1.3 m/s).

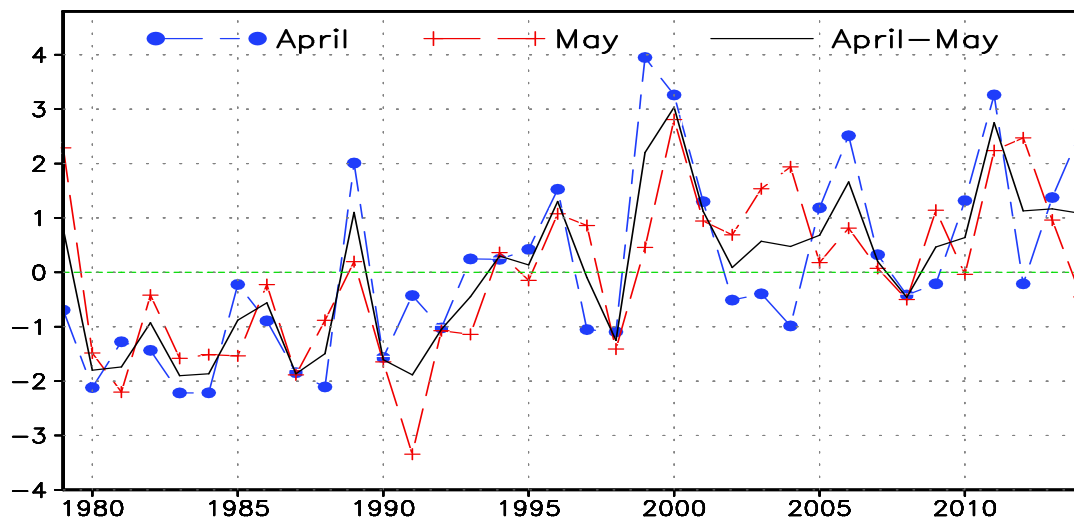


Fig. 3 Time evolutions of 850 hPa zonal wind anomalies averaged in the area around Kalimantan Island (110° – 120° E, 5° S– 2.5° N) in April (blue), May (red) and mean of April and May (black) (Unit: m/s)

In Fig. 4 we show the variation of mean zonal wind anomalies in April and May averaged over the area from north-western South China Sea to western South China (105° – 115° E, 20° N– 25° N). The interdecadal transition from positive to negative exists in 1995/1996, which is later than the transition of SCSSM onset. Another point worth mentioning is that the interdecadal transition of SSTAs over tropical western Pacific from negative to positive, which is also shown in Fig. 4. Kajikawa and Wang (2012) regarded the transition of SSTAs as a possible reason for the enhanced intraseasonal oscillation over the South China Sea and the Philippine Sea, and the increase of tropical cyclone over tropical western Pacific. However, it can be seen clearly that the transition of SSTAs existed in 1998/1999, which is much later than the transition of SCSSM onset as well.

From above analyses we can see that the interdecadal turning point of SCSSM onset is closely related to the interdecadal transition of 850 hPa zonal wind anomalies over the

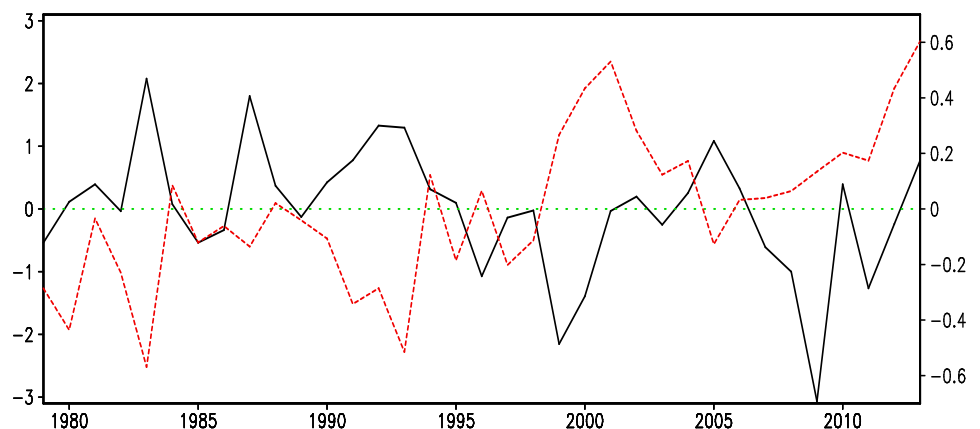
area around Kalimantan Island. The physical reason for the anomalous winds over this region as well as their link with the SCSSM onset will be investigated in the next section.

4 Physical processes

4.1 Interdecadal change of circulation anomalies

The SCSSM onset corresponds to the retreating eastward of the subtropical high over the western North Pacific and the extending eastward of tropical westerlies (Ding et al. 2004; Huang et al. 2006; Kajikawa and Wang 2012; Yuan and Chen 2013; Lin et al. 2017). Lin et al. (2017) indicated that the SCSSM onset is related closely to the intensity of subtropical high over the South China Sea at 850 hPa, which is characterized by negative vorticity over this region. An early (late) onset of SCSSM is accompanied with a high

Fig. 4 Time evolutions of 850 hPa zonal wind anomalies averaged over the area from north-west South China Sea to Western South China (105° – 115° E, 20° N– 25° N) (black solid curve) and SSTAs averaged over the area of tropical Western Pacific (120° – 150° E, 0° – 15° N) in April and May (red dashed curve)



(low) vorticity value (Lin et al. 2017). We calculated the vorticities in the first period (1979–1993) and second period (1994–2013) (Figure omitted) and the results show that the vorticity over the South China Sea from March to May during second period is higher obviously than that during first period. The vorticity difference between second period and first period is 1.1, 0.7 and 1.6 (unit: 10^{-6} s^{-1}) in March, April and May, respectively. Figure 5 gives the time evolution of vorticity anomalies averaged over the South China Sea (105° – 120° E, 5° – 20° N) averaged in April and May. It is clear that the vorticity anomaly changes from negative to positive before and after 1993/1994. The averaged values during 1979–1993 and 1994–2013 are -0.65 and 0.45 , respectively. The difference of the vorticities between the two periods is statistically significant and exceeds 99% confidence level. It is indicated that the subtropical high over the western North Pacific weakens and retreats eastward, resulting in the interdecadal advanced SCSSM onset after 1993/1994.

The vorticity contains two terms: the negative value of meridional gradient of zonal winds ($-\partial u/\partial y$) and the zonal gradient of meridional winds ($\partial v/\partial x$). In Fig. 5 the two terms of the vorticity anomalies averaged over the South China Sea are also shown. Comparing the three curves in Fig. 5, it is obvious that the term $-\partial u/\partial y$ plays an important role in the variation of mean vorticity anomalies over the South China Sea. The westerly anomalies around Kalimantan Island make the increase of the term $-\partial u/\partial y$, resulting in the increase of total vorticity anomalies and weakened subtropical high over the South China Sea. To prove the effect of the westerly anomalies around Kalimantan Island on the term $-\partial u/\partial y$ over South China Sea, the correlation between the zonal winds around Kalimantan Island and the negative value of meridional gradient of zonal winds ($-\partial u/\partial y$) over South China Sea is examined. The correlation coefficient

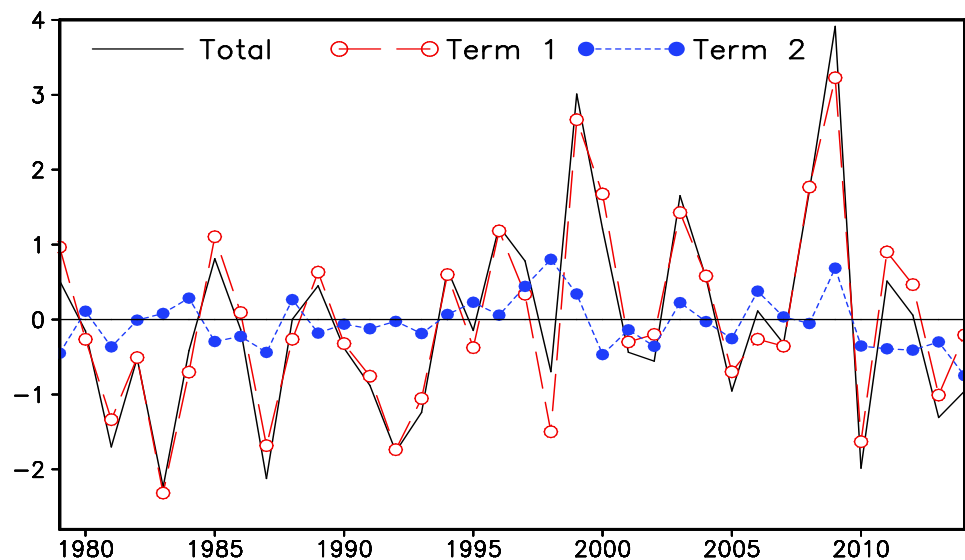
between them is 0.5610, which is statistically significant passing the 99% confidence level. The significant positive correlation indicates that an increased westerly around Kalimantan Island corresponds to an enhanced $-\partial u/\partial y$ over South China Sea. The difference between 1994–2013 and 1979–1993 of the term $-\partial u/\partial y$ accounts for 88% of the interdecadal increment of the total vorticity over the South China Sea. In Fig. 5 we can see the amplitude of the term $\partial v/\partial x$ is very small. The difference between 1994–2013 and 1979–1993 of this term is not significant. Therefore, it is the westerly anomalies over the area around Kalimantan Island that increase the total vorticity anomalies through the term $-\partial u/\partial y$, which makes the subtropical high weakens and retreats eastward. All these processes are favorable for the advanced SCSSM onset.

Certainly, the easterly anomalies over the area from north-western South China Sea to western South China as seen in Fig. 2 can also reduce the meridional gradient of zonal winds, and contribute to the positive increase of vorticity over the South China Sea. But the transition time of the easterly anomalies over above region lags behind the transition of SCSSM onset. It can be seen in Fig. 5 that the vorticity anomalies over the South China Sea increase further in the end of 1990s. This may be related to the joint effect of anomalous winds both over the area around Kalimantan Island and that from northwest South China Sea to western South China.

4.2 Role of SSTAs

Kajikawa and Wang (2012) proposed that the decadal change of SCSSM onset may be associated with the decadal change of large-scale SSTAs in tropical Pacific. They pointed out that a significant increase in SST over the western tropical Pacific enhanced the ISV and TC activity over SCS and the

Fig. 5 Time evolutions of vorticity anomalies averaged over South China Sea (105° – 120° E, 5° – 20° N) in April and May (black solid curve), meridional gradient of zonal wind (Term 1 = $-\partial u/\partial y$) anomalies (red long dashed curve), and zonal gradient of meridional wind (Term 2 = $\partial v/\partial x$) anomalies (blue short dashed curve) (Unit: 10^{-6} s^{-1})



Philippine Sea, which favored the earlier onset of SCSSM. However, the interdecadal shift of SSTAs in tropical western Pacific (120° – 150° E, 0° – 15° N) from negative to positive appeared around 1998/1999 (Fig. 4), which is not consistent with the shifts of the westerly anomalies over the area around Kalimantan Island and the onset of SCSSM. Therefore, why did the interdecadal shift of anomalous zonal winds over the area around Kalimantan Island occur in 1993/1994? Which area of SSTAs affects the zonal winds over there?

Considering the westerly anomalies over the area around Kalimantan Island are located near equator and the zonal winds near equator are related primarily to SSTAs near equator, we focus the influence of SSTAs near the equator. Figure 6 gives the longitudinal distribution of correlation coefficients between zonal winds over Kalimantan Island and SST in the same latitudes. It can be seen that in the equatorial western Pacific (140° – 150° E) the significant correlation lasts for three months from March to May. We calculated the T value of the Student's t test for the difference of SST between two periods and its distribution is shown in Fig. 7. It is obvious that the largest T value centers are around the equatorial western Pacific which last for three months from March to May. The area with largest T value is almost in the same location as that the significant correlation between SST and zonal winds over Kalimantan located at (Fig. 6). To check when the interdecadal shift of SSTAs in this area appear, the time evolution of mean SSTAs averaged over the domain (140° – 150° E, 5° S– 2.5° N) in spring is given in Fig. 8. It is shown that the interdecadal variation is obvious and the shift existed in 1993/1994. The difference of SST between the two periods of 1994–2013 and 1979–1993 reaches 0.44° C and passes 99% confidence level. The interdecadal shift of SSTAs in this key domain is consistent with the interdecadal shifts of both anomalous zonal winds over the area around Kalimantan Island and SCSSM onset. It is indicated that the interdecadal shift of SSTAs in the key domain of equatorial western Pacific is earlier than that of the large-scale SSTAs in tropical Pacific which occurred in the late 1990s. The forcing of the SSTAs in this Key region should be related with the interdecadal shift of SCSSM

Fig. 6 Zonal distribution of correlation coefficients between the 850 hPa zonal winds over the area around Kalimantan Island (110° – 120° E, 5° S– 2.5° N) and SST in the same latitudes (5° S– 2.5° N) in spring (March–May). The pecked lines indicate the threshold of 99% confidence level

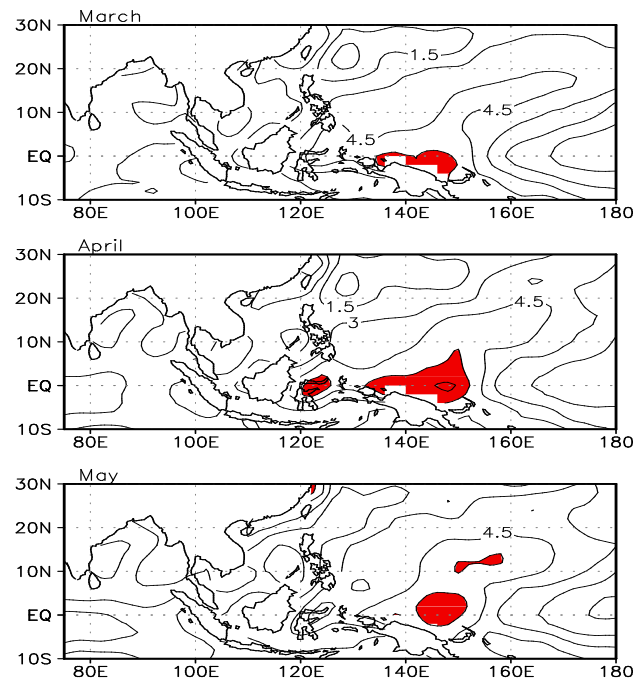
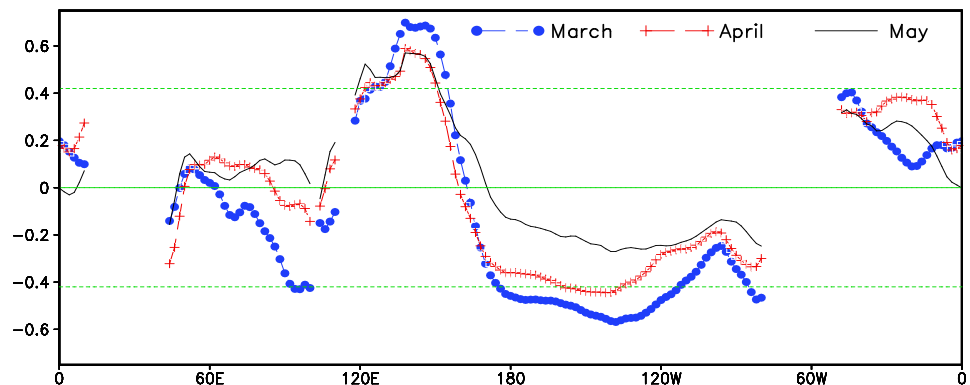


Fig. 7 T value distribution of the Student's t test for the SST difference between the periods of 1994–2013 and 1979–1993 in spring months from March to May. Red shadings represent anomalies equal or greater than 6

onset, considering that the shift occurred earlier than that of the large-scale SSTAs in tropical Pacific.

According to the analyses above, the physical process for the shift of the averaged onset date before and after 1993/1994 can be proposed as below (Fig. 9). The increase of SST in the key domain in equatorial western Pacific heats the atmosphere and convergence occurs toward the region at low-level. Easterly and westerly anomalies are produced in the east and west to this heating region, respectively. The Kalimantan Island is located to the west of the heating region. Then, as shown in Fig. 2, significant westerly anomalies occur over the area around Kalimantan Island and negative anomalies in meridional gradient of zonal winds ($\partial u/\partial y$) are produced over the South China

Fig. 8 Time evolution of SSTAs averaged over equatorial western Pacific (140°–150° E, 5° S–2.5° N). The unit of Y-axis is °C

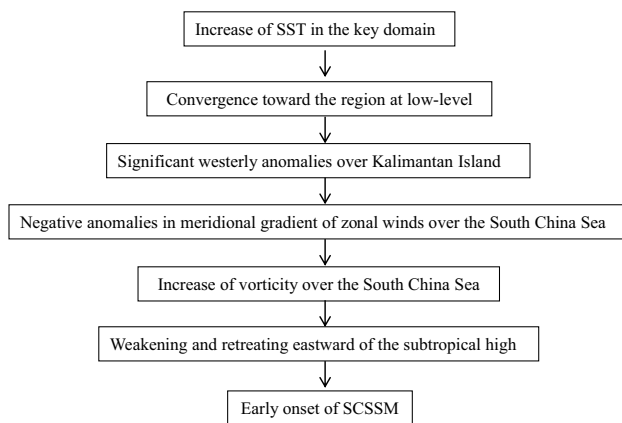
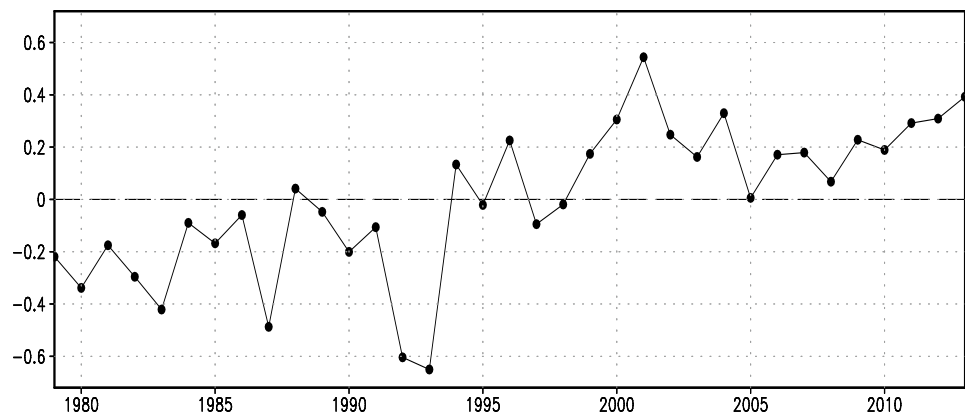


Fig. 9 Schematic diagram of the physical process for the shift of the SCSSM onset time after 1993/1994

Sea region to the north of Kalimantan Island. The negative anomalies in meridional gradient of zonal winds ($\partial u/\partial y$) over the South China Sea lead to the positive anomalies of vorticity through the term $-\partial u/\partial y$ and increase the vorticity over the South China Sea. The increased vorticity results in the weakening and retreating eastward of the subtropical high over the western North Pacific. Therefore, the higher SST in the heating region during the period of 1994–2013 is conducive to an early onset of SCSSM.

On the other hand, according to Gill (1980) the increased SST in the equatorial western Pacific can stimulate atmospheric Rossby wave response in the west side of the heating region and a pair of anomalous cyclones appear. Such a pair of cyclones can be clearly seen in Fig. 2, which are located in the both sides of the westerlies around Kalimantan Island. The cyclone over the region of western Pacific and South China Sea can weaken the subtropical high over the western North Pacific and retreats it eastward, which is favorable to the onset of SCSSM. Moreover, the equatorial western Pacific is an important source region of the intraseasonal oscillation. The increasing of

SST in this region is conducive to the enhancement of ISV activity and therefore favor the SCSSM onset.

5 Conclusions and discussions

The characteristics of atmospheric circulation anomalies during spring associated with the interdecadal shift of SCSSM onset around 1993/1994 and its forming mechanisms are investigated through data diagnoses. The main conclusions are as follows.

The interdecadal shift of the averaged SCSSM onset date before and after 1993/1994 is related closely to the zonal wind anomalies at 850 hPa over the area around Kalimantan Island (110°–120° E, 5° S–2.5° N) in spring. During the periods of 1979–1993 and 1994–2013, easterly and westerly anomalies over Kalimantan Island correspond to the late and early onset of SCSSM, respectively.

The impact of zonal winds at 850 hPa over the area around Kalimantan Island on the SCSSM onset is through affecting the subtropical high over the western North Pacific during spring. The interdecadal increment of the regional vorticity over the South China Sea during the period of 1994–2013 was mainly due to the vorticity component of the meridional gradient of zonal winds ($-\partial u/\partial y$), which accounts for 88% of the total interdecadal vorticity variation. The westerly anomalies over the area around Kalimantan Island decreased the meridional gradient of zonal winds ($\partial u/\partial y$) over the South China Sea and increased the vorticity. The increased vorticity over the South China Sea weakened the subtropical high and made it retreat eastward, which was beneficial to the earlier onset of SCSSM in 1994–2013.

The interdecadal variation of 850 hPa zonal winds over the area around Kalimantan Island in spring is a response to the forcing by the SSTAs in the key area of equatorial western Pacific (140°–150° E, 5° S–2.5° N). During 1979–1993, the mean SSTAs in the key area were negative and easterly anomalies appeared over Kalimantan Island; During 1994–2013, the mean SSTAs in the key area were positive

and westerly anomalies appeared over the area around Kalimantan Island.

The interdecadal transition of SSTAs in the key area in equatorial western Pacific around 1993/1994 was the root cause of the interdecadal transition of SCSSM onset. The related physical processes are as below. The positive SSTAs in the key domain during the period of 1994–2013 forced the convergence toward the region at low-level. Significant westerly anomalies occurred over the area around Kalimantan Island located to the west of the key domain, which made negative anomalies in meridional gradient of zonal winds ($\partial u/\partial y$) over South China Sea region to the north of Kalimantan Island. The negative anomalies in meridional gradient of zonal winds increased the vorticity over the South China Sea significantly. The increased vorticity, together with the atmospheric Rossby wave response to the SSTAs in the key region, resulted in the weakening and retreating eastward of the subtropical high over the western North Pacific, which were conducive to the earlier onset of SCSSM during the second period of 1994–2013.

The interdecadal transition of SSTAs in the above key region appeared around 1993/1994, which is earlier than the interdecadal transition of large-scale SSTAs in tropical Pacific occurred in 1998/1999. It seems that the SSTAs in the key region are a crucial reason for the interdecadal shift of SCSSM onset. The question that this paper attempts to answer is why the interdecadal shift of SCSSM onset occurred before the large-scale interdecadal transition in tropical Pacific. As for why the interdecadal transition of large-scale SST in tropical Pacific occurred first in the western equatorial Pacific, further investigation is needed for future study. Additionally, the change of zonal winds over Kalimantan Island was successive during 1991–1996 (Fig. 3), but a sharp increase occurred in 1993–1994 for the monsoon onset time (Fig. 1). To find out the physical reason for such difference is another future research topic.

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