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DETERMINATION OF ONSET DATE OF THE SOUTH CHINA SEA SUMMER MONSOON IN 2006 USING LARGE-SCALE CIRCULATIONS

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Abstract: Since the South China Sea (SCS) summer monsoon (SCSSM) is pronouncedly featured by abruptly intensified southwesterly and obviously increased precipitation over the SCS, the lower-tropospheric winds and/or convection intensities are widely used to determine the SCSSM onset. The methods can be used successfully in most of the years but not in 2006. Due to the intrusion of Typhoon Chanchu (0601) that year, the usual method of determining SCSSM onset date by utilizing the SCS regional indices is less capable of pinpointing the real onset date. In order to solve the problem, larger-scale situations have to be taken into account. Zonal and meridional circulations would be better to determine the break-out date of SCSSM in 2006. The result indicates that its onset date is May 16. Moreover, similar onset dates for other years can be obtained using various methods, implying that large-scale zonal and meridional circulations can be used as an alternative method for determining the SCSSM onset date.

Key words: South China Sea summer monsoon (SCSSM); circulation; onset; typhoon

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1 INTRODUCTION

The South China Sea summer monsoon (SCSSM), with an onset date falling on the fourth pentad of May on average, is an important climatic system affecting the weather and climate of China. The lower-tropospheric (e.g., 850 hPa) winds and/or convection intensities are widely used to determine the SCSSM onset[1]. For example, Liang et al.[2] considered that an SCSSM onset should be represented by more than five persistent days of 850-hPa westerly average winds over the South China Sea (SCS) region (5−20° N, 110−120° E), which mainly originate from the tropics. Lam et al.[3] concluded that an SCSSM onset occurs when the SCSSM area index is more than 40%. The area index pertains to an area with southwesterly winds larger than 2 m/s and θ_{se} larger than 335 K in the SCS region (105−120° E, 5−20° N). On the other hand, He et al.[4] believed that an SCSSM onset is less than or equal to −8 K when the infrared (IR) temperature of black body (TBB) departure occurs. Li and Qu[5] used the divergence difference between the upper and lower troposphere to determine the SCSSM onset.

Essentially, differences in divergence represent convection as well as TBB or outgoing long-wave radiation so that the resultant onset dates only have a day of difference at most. Moreover, Xie et al.[6] and Zhang et al.[7] introduced the convection and winds to judge an SCSSM onset. Meanwhile, Yao and Qian[8] put forward a monsoon index that used a normalized regional average of 850 hPa with a moist potential vorticity based on the features of SCSSM onset, which indicates the onset of SCSSM when the index changes from negative to positive. The determinations above can be concluded from the emergence of convection or southwesterly winds over the SCS region, and the methods involved are generally effective in most years. Although air-sea or air-land fluxes demonstrate significant changes from pre- to post-SCSSM[9-11], the flux is still difficult to operate because of the absence of flux datasets. This explains why it is usually not used at present in determining the SCSSM onset dates in a course of several decades.

The present paper describes the evolution of the 2006 SCSSM onset and utilizes large-scale zonal and meridional circulations to determine its date. The datasets used in the present paper include horizontal winds, vertical p velocity, and geopotential height from the National Centers for Environmental Prediction (NCEP, U.S.A.)-2 reanalysis, with a resolution of 2.5° ×2.5° at 17 levels, and NCEP TBB with a resolution of 0.5° ×0.5° .

2 EVOLUTION OF 2006 SCSSM ONSET

Figure 1 shows the 850-hPa zonal wind, meridional wind, and TBB as averaged in the SCS region (5−20° N,

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105−120° E) in May, 2006. Based on the convection, it is known that the SCSSM reached the critical condition of onset (TBB<275 K) on May 13. The zonal and meridional winds met the critical condition on May 15. Therefore, the SCSSM onset date was May 15 (the third pentad) as determined from the convection and lower-tropospheric winds. Around the time, Typhoon Chanchu (0601) entered the SCS, subsequently causing uncertainty in determining the SCSSM onset. Tropical cyclones (TCs) are active prior to the SCSSM onset, a phenomenon that is not rare and occurs frequently in the past three decades.

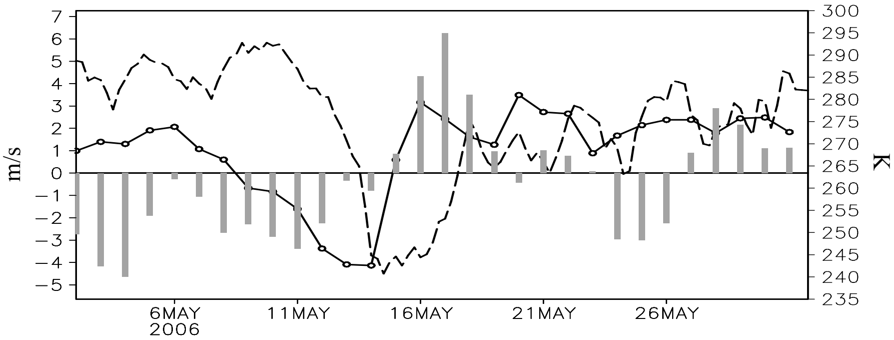

Fig. 1. Time series of the daily zonal wind (bar, m/s), meridional wind (open-cycle line, m/s), and TBB (dashed line, K) as averaged over the SCS region (5–20° N, 105–120° E) in May 2006. Winds and TBB correspond to the left and right *y*-coordinates, respectively.

Through an analysis of circulation characteristics prior to the 2003 SCSSM onset [13], Liang et al.[12] noted the presence of a weak cyclone that emerged over the 10−15° N region of SCS before the SCSSM onset. Table 1 shows the statistics on TCs before the SCSSM onset based on the NCEP-2 reanalysis. Furthermore, the table shows a number of years in which TCs occurred before the SCSSM onset, especially in the recent decade. The TC-induced precipitation and lower-tropospheric southwesterly winds are naturally not represented by the SCSSM onset when the large-scale monsoon circulation is not established. Thus, determining the SCSSM onset using large-scale circulations is important to some extent.

Table 1. Years with and without TCs appearing one pentad before the SCSSM onset date since 1979 (based on NCEP-2 reanalysis)

With TCs over the SCS	1985, 1989, 1999, 2000, 2001, 2003, 2004, 2006
With TCs east of the Philippines	1979, 1980, 1986, 1990
Without TCs	1981, 1982, 1983, 1984, 1987, 1988, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 2002, 2005

Severe typhoon (STY) Chanchu (0601) developed gradually from a tropical depression (TD) near the Palau Islands in the western Pacific. It strengthened and became a tropical storm (TS) at 2000 Beijing Standard Time (BST) May 9. It subsequently developed into a severe TS (STS) at 1400 BST May 10. Thereafter, the STS moved northwestward and passed the central part of the Philippines on May 12. At 0800 BST May 13, the STS traveled over the SCS and developed into a typhoon (TY). TY Chanchu then met the cold air in the SCS and moved westward along 14° N, which eventually became a super TY at 0800 BST May 15 and simultaneously turned exactly right to shift northward. On May 16, Chanchu entered the north SCS. From the night of May 17 until before dawn of May 18, the super TY successively traveled over the surrounding waters of Jieyang, Shantou and Nan'ao Island in Guangdong and then made landfall in Raoping-Chenghai at 02:15 May 18.

From May 13 to 16, TY Chanchu was active in the SCS region. Its convection further strengthened beginning from May 13. This explains the difficulty in whether the enhanced convection should be attributable to the TY activity or the SCSSM onset. Moreover, Figs. 2c and 2d indicate that the southwesterly winds over the SCS resulted to a great extent from the flows to the south of TY on May 15 and 16, which means that the increased southwesterly winds in Fig. 1 may not originate from tropical westerly winds.

3 USING LARGE-SCALE CIRCULATION TO DETERMINE SCSSM ONSET DATE

As described above, the SCSSM onset date is difficult to be determined using local convection and lower-tropospheric winds due to TY activity in the SCS. Thus, it is essential to identify other ways to deal with this particular situation. Zonal circulation is normally more important than the others for the Indian monsoon, whereas meridional circulation is as important as the zonal one for the SCSSM. Yang et al.[14] explored the establishment of weak and strong SCSSM using the

Hadley cell diagnostic equations. Since the establishment of circulation is a large-scale feature that shows the onset of SCSSM and TY is a synoptic-scale system, we can determine the SCSSM onset through large-scale zonal and meridional circulations.

Zonal circulation is first examined in Fig. 3. Meanwhile, Fig. 3a shows that summer monsoon circulation formed over the Bay of Bengal and Indo-China Peninsula east of 100° E on May 13, whereas weak westerlies formed in the lower troposphere in the SCS region. On May 13, summer monsoon circulation was not established in the SCS. The westerlies were not linked to those of the Indo-China Peninsula on May 15 when a transition period appeared to have occurred. On May 16, the tropics-originated westerlies prevailed, confirming that the summer monsoon zonal circulation had been established.

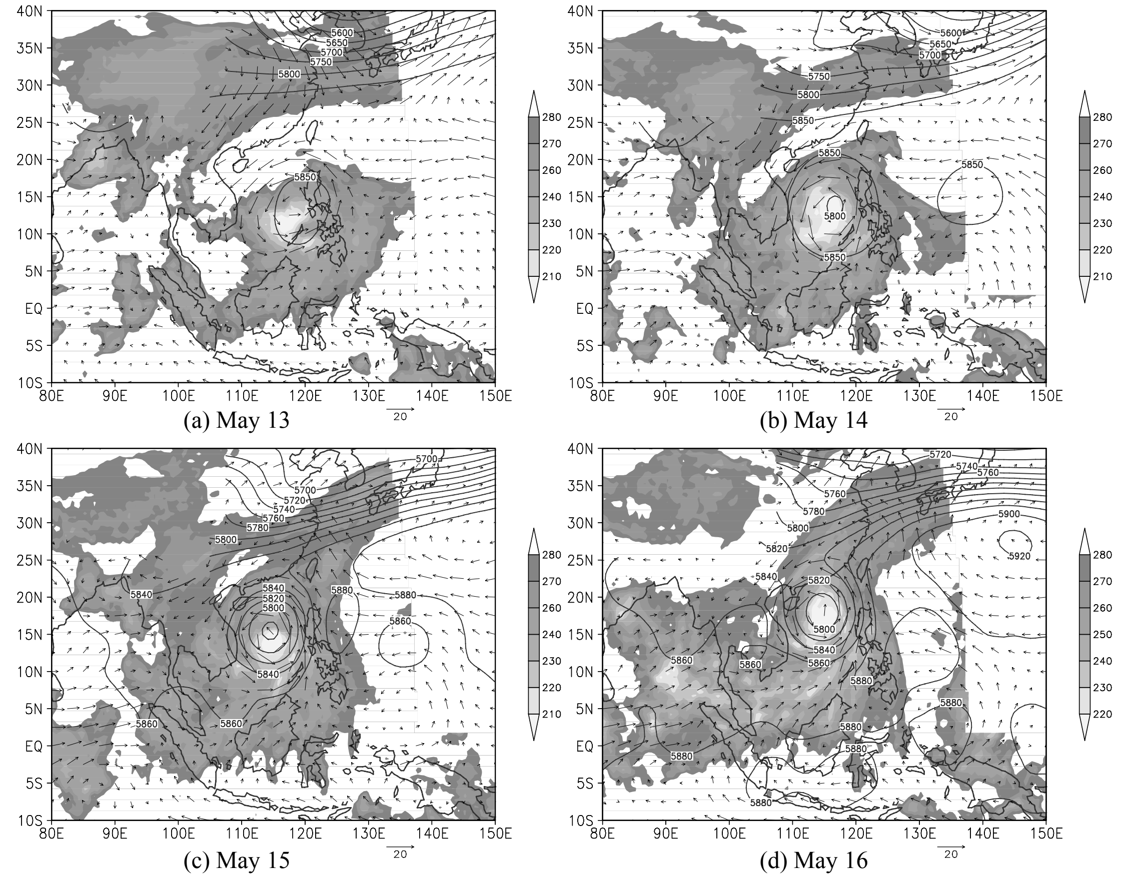

Fig. 2. 850-hPa winds (vector, m/s), geopotential height (isoline, geopotential meter), and TBB (shadow, K) for May 13 (a), May 14 (b), May 15 (c), and May 16 (d), 2006.

The SCSSM system is also composed of meridional circulation[15]. Fig. 4 shows the presence of meridional circulations from May 13 to 16. Meanwhile, the Hadley cell controlled the SCS region on May 13 and 14 (Figs. 4a and 4b), indicating the presence of northerlies in the lower troposphere. The ascending branch of Hadley cell shifted to approximately 15° N on May 15 and moved northward near 18° N on May 16. At that time, the summer monsoon meridional circulation formed over the SCS.

We determined that May 16 (the fourth pentad) is the 2006 SCSSM onset date in terms of both the zonal and meridional circulations. The result, according to Zhang et al.[16], reveals a critical condition of 850-hPa southwesterly winds that were larger than 3 m/s on May 16. The criterion of Zhang et al. included both the lower southwesterly and upper northeasterly winds, highlighting the importance of circulations.

Table 1 shows the years with TCs appearing one pentad before the SCSSM onset since 1979. It must be noted, however, that the SCSSM onset dates in 1985 and 1989 are in dispute. Using the averaged zonal winds in the SCS (5−15° N, 105−120° E), Xie and Dai[6] have determined that the 1985 SCSSM onset date was in the fifth pentad of April. Zhang et al.[7] established the date in the sixth pentad of May through winds and convection, with more than a month of difference against that of Xie and Dai [6]. Xie and Dai[6] and Zhang et al.[7] argued that the 1989 SCSSM began in the fourth pentad of May. However, based on the 850-hPa warm moist southwesterly winds in the SCS, Fong et al.[17] documented that the 1989 SCSSM began in the second pentad of June, which has a difference of approximately 20 days relative to the date proposed by Xie and Dai[6] and Zhang et al.[7]. Thus, we attempted to determine the SCSSM onset dates in these two years by using large-scale circulations.

The large-scale zonal and meridional circulations in the fifth pentad of April and sixth pentad of May 1985 are illustrated in Fig. 5. Furthermore, we can observe from Fig. 5a that in the fifth pentad of April, zonal circulation was situated west of 100° E, and the mid- and upper-troposphere over the SCS was in the control of the westerly. In the sixth pentad of May (Fig. 5b), the summer monsoon zonal circulation, though somewhat weak, was formed with the easterly shear between the upper and lower zonal winds. On the other hand, the meridional circulation located south of 12.5° N in the fifth pentad of April (Fig. 5c) obviously dominated the SCS region in the sixth pentad of May (Fig. 5d). Thus, according to the circulations, the 1985 SCSSM onset date was in the sixth pentad of May, which is consistent with the result presented by He et al.[18].

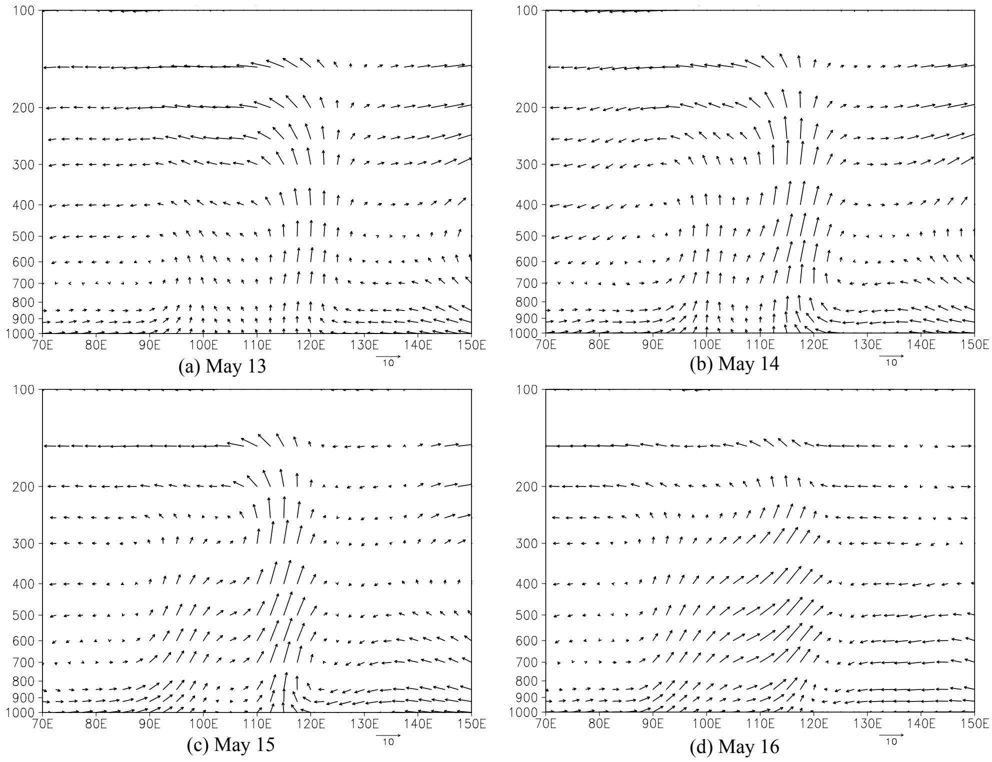

Fig. 3. 5−20° N averaged zonal circulation for May 13 (a), May 14 (b), May 15 (c), and May 16 (d), 2006. A 20-longitude smoothing has been performed, and the vertical *p* velocity has been magnified 50 times and assigned with an opposite sign.

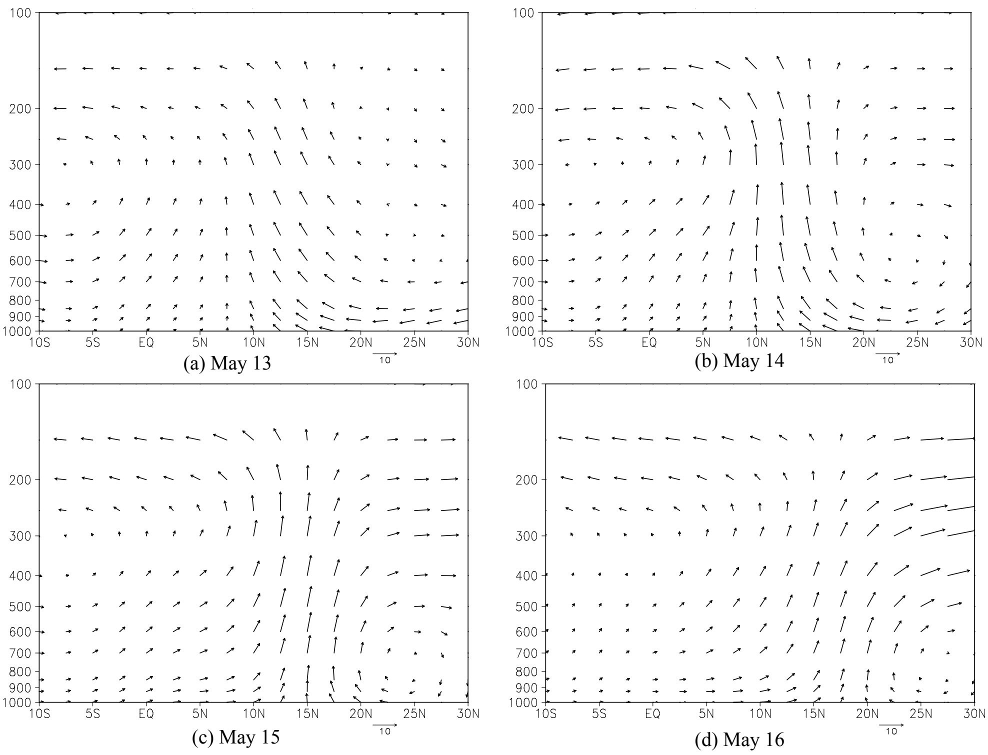

Fig. 4. Same as Fig. 3 but for 105−120° E averaged meridional circulation.

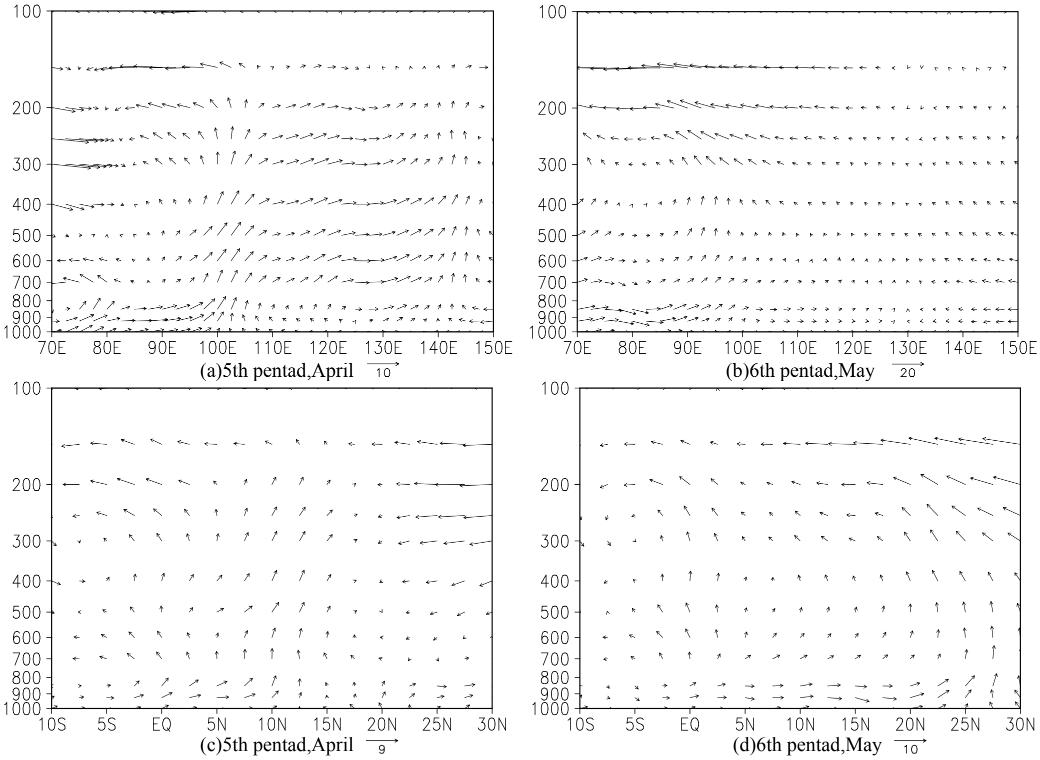

Fig. 5. 5−20° N averaged zonal circulation in the fifth pentad of April (a) and sixth pentad of May (b), 1985; 105−120° E averaged meridional circulation in the fifth pentad of April (c) and sixth pentad of May (d), 1985. A 20-longitude smoothing has been performed, and vertical *p* velocity has been magnified 50 times and assigned with an opposite sign.

Figure 6 shows the averaged large-scale circulations in the fourth pentad of May and second pentad of June 1989. Both zonal circulations in the two pentads (Figs. 6a & 6b) have achieved the critical condition of the SCSSM onset. The difference in the meridional circulations is determined (Figs. 6c and 6d). The monsoon circulation was south of 12.5° N. There was a Hadley cell in the fourth pentad of May, indicating that the SCSSM meridional circulation was formed incompletely. By the second pentad of June, the monsoon meridional circulation had been established over the SCS. Meanwhile, the 1989 SCSSM began in the second pentad of June, which is on the same date indicated in He et al.[18]

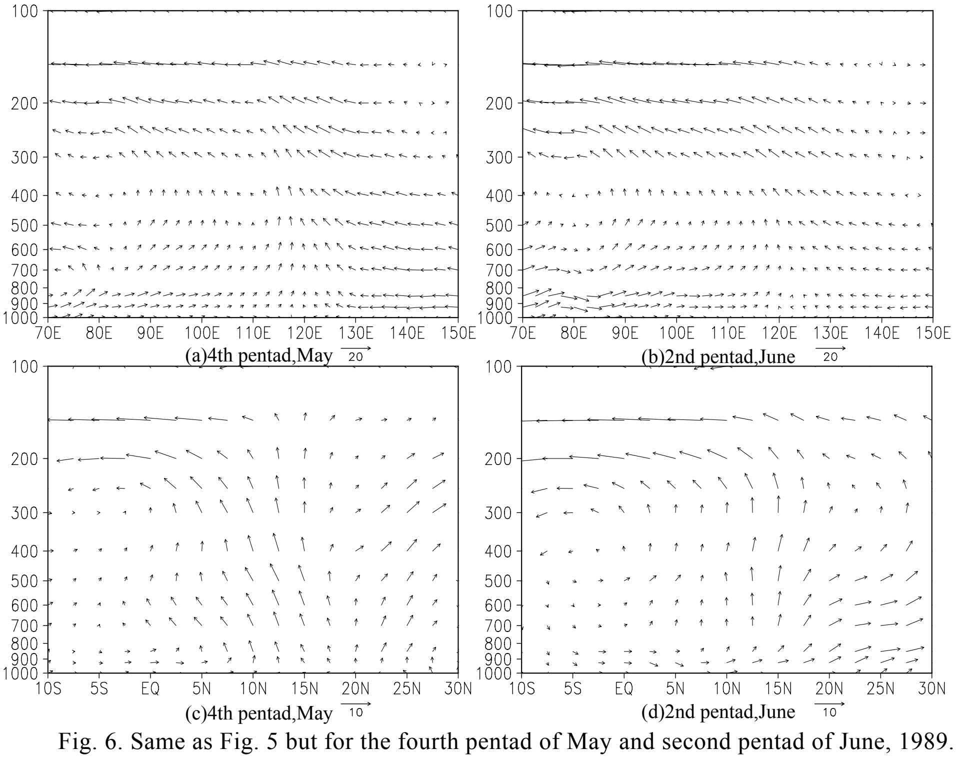

Fig. 6. Same as Fig. 5 but for the fourth pentad of May and second pentad of June, 1989.

We presented a definition for the SCSSM onset date. First, large-scale smoothing was applied using anomalous circulation grid numbers that were less than 6 (from 70−120° E for the zonal, and from 10° S−17.5° N for the meridional) and vertical *p* velocity that was less than -0.01 Pa/s in specified locations (17.5° N for the meridional and 120° E for the zonal) throughout at least one pentad. Table 2 lists the SCSSM onset dates from 1979 to 2005 by means of large-scale circulations that are almost in accordance with the dates in He et al.[18] For the years with TC activities before the SCSSM, as shown in Table 1, the dates in Table 2 are quite consistent with those in He et al.[18] Therefore, large-scale circulation is an effective index to determine the SCSSM onset date. There is an advantage of specifying the SCSSM onset date when TCs are active.

Table 2. SCSSM onset dates for 1979−2006 which are determined by means of large-scale circulations. Dates inconsistent with He et al.[18] are highlighted in bold italic.

Years	Onset dates (month.pentad)	Years	Onset dates (month.pentad)	years	Onset dates (month.pentad)	Years	Onset dates (month.pentad)
1979	5.3	1986	5.3	1993	5.6	2000	5.3
1980	5.3	1987	6.2	1994	5.1	2001	5.4
1981	5.3	1988	5.5	1995	5.3	2002	5.4
1982	5.6	1989	6.2	1996	5.2	2003	5.5
1983	5.5	1990	5.4	1997	5.4	2004	5.4
1984	***5.4***	1991	6.2	1998	5.5	2005	5.6
1985	5.6	1992	***5.6***	1999	4.5	2006	5.4

4 SUMMARY AND DISCUSSION

(1) In general, clear physical concepts on the indices of monsoon onset available at present can clearly describe the features of SCSSM (e.g., abrupt changes of winds, moisture and convection, etc.). It is uncertain whether the changes result from the monsoon onset since TYs are active and bring similar influences. In view of the characteristic synoptic scale of the TY, we can use larger scale zonal and meridional circulations to determine the monsoon onset date.

(2) The 2006 SCSSM onset was disturbed by TY Chanchu (0601) that caused abrupt changes in the lower-level southwesterly winds and/or rainfall over the SCS region. Thus, we determined that the 2006 SCSSM was established on May 16 (the fourth pentad of May) when the SCSSM meridional and zonal circulations were established.

(3) For the controversial onset dates of 1985 and 1989 SCSSM, the results from the large-scale zonal and meridional circulations are consistent with He et al.[18] Moreover, SCSSM onset dates from 1979 to 2006 are similar to He et al.[18], which implies that the method is applicable except for some particular cases.

Figure 2d indicates that certain local influence is still exerted by the Western Pacific High (WPH, represented with 5880 isoline), though it almost moved off the SCS on May 16 and the WPH completely shifted out of the SCS on May 17 (figure omitted). Consequently, the onset date is considered to fall on May 17 if we determine it based on the figure[19]. Fig. 4d shows that the ascending branch of meridional circulation was located on 18° N around the Hadley cell, which was in control of the SCS region on May 16. Provided that the SCSSM did not form until the ascending branch of meridional circulation was exactly situated at 20°N or north of it, then the 2006 SCSSM meridional circulation would be formed on May 16 as well (figure omitted). A small difference in the critical conditions would lead to one or two days of discrepancy on the SCSSM onset date, but they are of the same onset period in the fourth pentad of May in terms of the pentad-mean.

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