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CHARACTERISTICS OF ATMOSPHERIC HEAT SOURCE ASSOCIATED WITH THE SUMMER MONSOON ONSET OVER THE SOUTH CHINA SEA AND THE POSSIBLE MECHANISM RESPONSIBLE FOR ITS LATE OR EARLY ONSET

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ABSTRACT: The characteristics of atmospheric heat source associated with the summer monsoon onset in the South China Sea (SCS) are studied using ECMWF reanalysis data from 1979 to 1993. A criterion of the SCS summer monsoon onset is defined by the atmospheric heat source. Applying this criterion to the 15-year (1979 – 1993) mean field, the onset of the SCS summer monsoon is found to occur in the fourth pentad of May. And this criterion can also give reasonable results for the onset time of the SCS summer monsoon on a year-to-year basis. In addition, pretty high correlation has been found between the onset time of the SCS summer monsoon and the zonal mean vertically integrated heat source <*Q*1> at 40°S in April. The causes for the late or early onset of the SCS summer monsoon and the close relationship between the onset time and the zonal mean vertically integrated heat source <*Q*1> at 40 °S in April might be explained by the variations in intensity of the Hadley circulation.

Key words: onset of the SCS summer monsoon; atmospheric heat source; Hadley circulation

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1 INTRODUCTION

Connecting with the Indian Ocean and Pacific Ocean, the South China Sea (to be shortened as SCS) is an important region in which monsoon systems over South Asian and East Asia interact with each other. Some studies have shown that the onset of the SCS summer monsoon is the earliest signal that the general circulation changes from a winter pattern to a summer one and work on the onset has thus received much attention from a large number of experts and scholars. In recent years, a lot of fruitful achievements have been gained on the characteristics of the monsoon onset[1, 2]. Duan[3] analyzed the atmospheric heat sources and energy budgets for the monsoon region in SCS in 1979 and Ju et al.[4] investigated into the characteristics of atmospheric heat sources for the evolution of SCS summer monsoon. However, these attempts to reveal the relationship between the atmospheric heat sources and the SCS summer monsoon onset were mostly in connection with some specific years and used datasets of relatively short periods. To better reveal them, the current work uses a 15-year (1979 – 1993) ECMWF reanalysis data to probe further into the topics.

As an essential basic issue in the research, the onset date of the SCS summer monsoon is studied in comprehensive detail in [5] that builds on a number of works. From the dates set by He et al.[5] for the 41 years (1958 – 1998) as the time for the monsoon onset, we note that there are obvious interannual variations. The onset is early in some years but late in others. The earliest

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onset appears in the first pentad of May but the latest comes in the second pentad of June. What causes it to be what it is? What precursory factors can predict the onset dates? Some authors have worked on the questions. Xie et al.[6] point out that the onset of the SCS monsoon is usually late if a 850-hPa equatorial vortex is inactive near 105°E in April and May. Zhao et al.[7] conclude that a sustained warm (cool) SCS Warm Pool in winter and spring usually precedes a late (early) onset of the monsoon. In their study on the evolution and thermodynamics of the temperature fields over the south of China around the onset for 1993 and 1994, Jian et al.[8] show that temperature increased more significantly in mid-April to early May 1994 over the region than in the same period in 1993 and that led to an earlier reversal of north-south temperature gradients over the monsoon area in SCS and eventually an earlier onset of the monsoon itself. Relatively speaking, the reversal was later in 1993 than in 1994 and so was the monsoon onset. In addition, revelations are also reported about the linkage between the timing of the SCS summer monsoon onset and other physical factors[9]. In general, the precursory factors reviewed above do have some kind of association with the timing of the onset but not with particularly good correlation over longer periods. The current work, in view of it, attempts to isolate preceding factors that have better correlation with the onset timing and discusses causes and physical mechanisms responsible for it using heat sources in the atmosphere.

2 CALCULATION OF ATMOSPHERE HEAT SOURCES

With twice-daily ECMWF datasets of temperature, humidity, geopotential heights and wind fields on individual mandatory isobaric levels at 00GMT and 12GMT, which are with a resolution of 2.5°×2.5° over the years 1979 – 1993, $Q1$, the atmospheric heat source, and $<Q1>$, the vertical integration over the entire column of atmosphere, are calculated twice daily at 13 levels. They are then based to determine climatological values like the pentad mean and monthly mean. The 13 levels are distributed at 962.5 hPa, 887.5 hPa, 812.5 hPa, 737.5 hPa, 650 hPa, 550 hPa, 450 hPa, 350 hPa, 275 hPa, 225 hPa, 175 hPa, 125 hPa, and 85 hPa, respectively. The atmospheric heat source $Q1$ and moisture sink $Q2$ are calculated using the formula by Yanai et al. [10] Setting

$$Q11 = c_p \frac{\partial T}{\partial t} \tag{1}$$

$$Q12 = c_p \vec{V} \cdot \nabla T \tag{2}$$

$$Q13 = c_p \left(\frac{p}{p_0} \right)^k \omega \frac{\partial \theta}{\partial p} \tag{3}$$

then we have $Q1=Q11+Q12+Q13$, where T is the temperature, q is the specific humidity, θ is the potential temperature, ω is the p-vertical velocity, p_0 = 1000 hPa, $k=R/C_p$, R is the gas constant of the air, C_p is the specific heat pressure and $\vec{V}$ is the horizontal wind vector.

The vertically integrated atmospheric heat source $<Q1>$ is derived with the following expression[10]

$$\langle Q1 \rangle = \frac{1}{g} \int_{PT}^{Ps} (Q1) \, \mathrm{d}\, p \tag{4}$$

in which p_s refers to 1000 hPa and P_T 70 hPa.

3 CHARACTERISTICS OF THE ATMOSPHERIC HEAT SOURCE IN CONNECTION WITH SCS SUMMER MONSOON ONSET

There are three traits of typical evolutions[5]. (1) In the SCS region, the southwesterly prevails at the low level and the easterly at the upper level. The winds do not shift the direction simultaneously at the two levels. It is usually the case that the upper-level transformation is 1 – 2 pentads ahead of the lower-level one. At the time, the subtropical high recedes from the SCS to the western Pacific east of 120°E. (2) The lower-level southwesterly in the SCS originates in the low-latitude (tropical) areas of the Southern Hemisphere. (3) Abrupt changes take place in elements like the wind field, temperature, humidity, OLR, *TBB* and precipitation. Building on the research results by He et al.[5] on summarizing various work on the SCS onset dates, a schematic table is drawn here to show the dates for the onset of the monsoon from 1979 to 1993, which are extracted from a complete set for the 41 years from 1958 to 1998.

Tab.1 The onset dates of South China Sea summer monsoon from 1979 to 1993 (extracted from [5])

Year	1979	1980	1981	1982	1983	1984	1985	1986
Dates / pentads	27	28	27	31	27	28	30	27
Year	1987	1988	1989	1990	1991	1992	1993	
Dates / pentads	32	29	32	28	32	28	31	

To study the characteristics of the atmospheric heat source for the SCS summer monsoon onset, the dates listed in Tab.1 are taken as reference to conduct a composite analysis of the onset and 10 pentads before and 10 pentads after it, using the 15-year dataset. The composite analysis (figure omitted) shows how the circulation varies in the onset period. Prior to it, the southeasterly prevails at the level of 850 hPa over the SCS region to the southwest of an anti-cyclone over the western Pacific. The 588-hPa contour represents the subtropical high extending to the west of 112°E. About one pentad before the onset, a 200-hPa anti-cyclone center in the Northern Hemisphere is near Thailand and affects the region of SCS where the northwesterly prevails. In the very pentad in which the monsoon sets off, the 850-hPa anti-cyclone over the western Pacific weakens over the SCS region and recedes to the east, and the prevailing wind changes from the southeasterly to the southwesterly over the SCS, whose flows are formed when a SW flow from the Bay of Bengal area merges with a cross-equatorial flow between 100°E and 110°E. The 200-hPa anti-cyclone center moves northwards by about three latitudes in the Northern Hemisphere, and the SCS area is affected by it to change to be dominated by a NE flow. After the onset, the circulation generally maintains what it looks like at the onset except that the 200-hPa anti-cyclone center keeps moving north.

A large number of studies have been devoted on the circulation around the onset[11 – 14]. By comparing these studies and analyses, we note that the composite we made is able to capture some of the typical circulation features about the SCS summer monsoon onset. On the basis of it, the atmospheric heat source before, during and after the onset is analyzed in more detail. Fig.1 gives the evolution of the vertically integrated $\langle Q1 \rangle$ around the onset point. It shows that the main center of the heat source formerly near the equator before the onset has now moved north to the area between 10°N and 22°N after the onset. Careful analysis shows that in the 10th pentad before the onset (figure omitted), an atmospheric heating source distributes over the tropical area between 15°S and 10°N. An area of weak atmospheric heat source is found between 25°N and 40°N while an extensive area of heat sink is observed between 10°N and 25°N. In the 4th pentad before the onset, however, the two zones of heat sources connect over the Indochina – equator region. In the first pentad before the onset, the atmospheric heating center between 60°E and 100°E moves obviously to the north and begins to stay between 10°N and 22°N both at and after the onset. One of the centers is just next to the west coast of the Indian Peninsula and the other is right neighboring that of the Indochina Peninsula. Another prominent characteristic of the evolution of the $\langle Q1 \rangle$ field is that the part of the SCS at 10°N – 20°N, 110°E – 120°E has been an area that serves as a heat sink of the atmosphere until the onset of the monsoon; it acts as a heat source right in and after the pentad when the onset occurs. It makes it possible that the heat

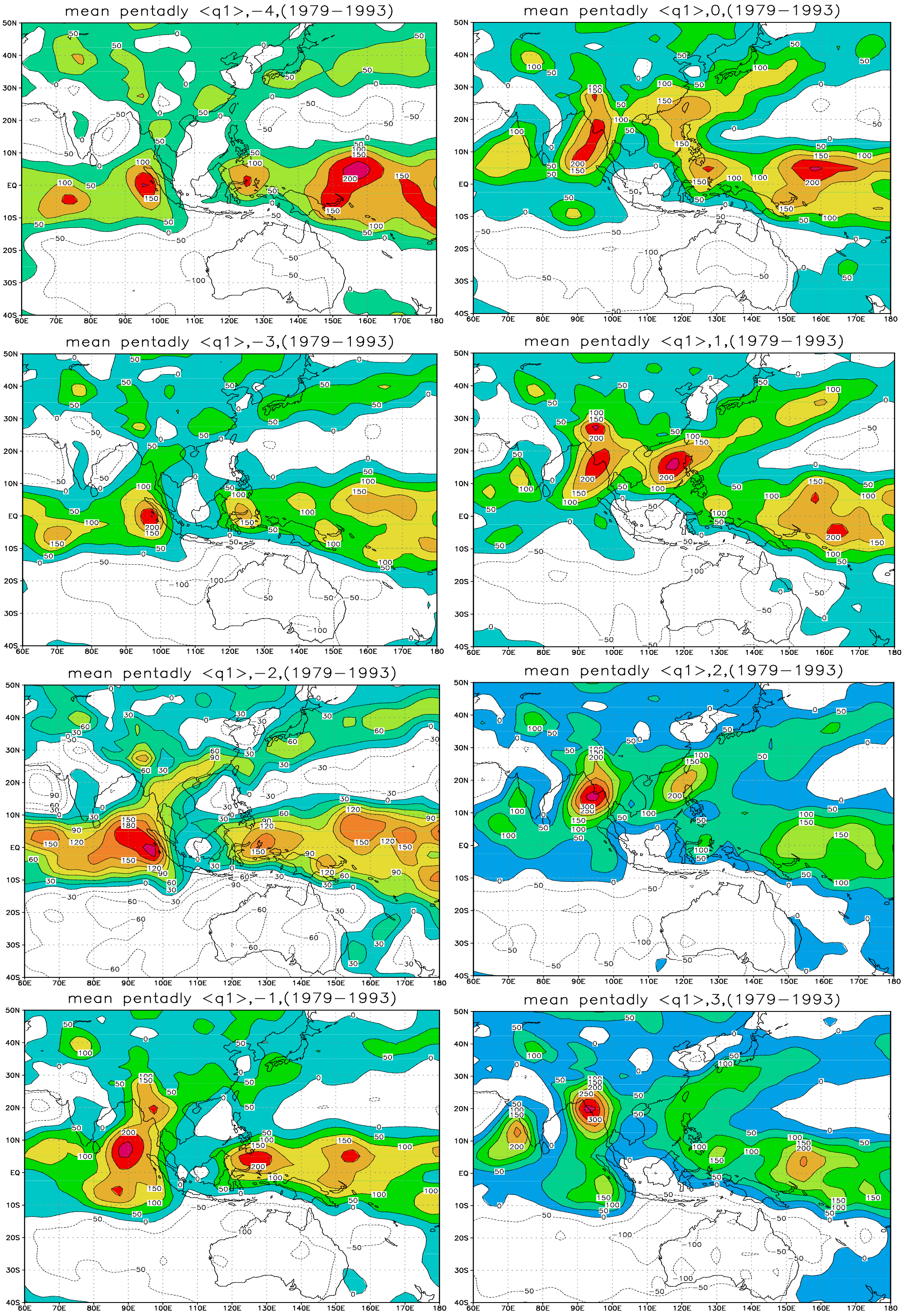
mean pentadly <q1>,−4,(1979−1993)
mean pentadly <q1>,0,(1979−1993)
mean pentadly <q1>,−3,(1979−1993)
mean pentadly <q1>,1,(1979−1993)
mean pentadly <q1>,−2,(1979−1993)
mean pentadly <q1>,2,(1979−1993)
mean pentadly <q1>,−1,(1979−1993)
mean pentadly <q1>,3,(1979−1993)

Fig.1 The vertically integrated field of <*Q*1> of the atmospheric heat source around the onset of SCS summer monsoon. –1, 0 and 1 stand for the pentad before, during and after the onset, and other numerals follow the same pattern.

source between 110°E and 130°E over the equatorial western Pacific connects with that over the south of China. In the first pentad after the pentad, a strong heating center appears between 10°N and 20°N over the SCS. The moisture sink <*Q*2> evolves in much the same way as the atmospheric heat source <*Q*1>. It is actually a reflection that frontal rain bands merge with tropical rain bands over the SCS after the monsoon onset. For the particular area of the SCS at 10°N – 20°N, 110°E – 120°E, it has been a moisture source before the onset; right in and after the onset period, however, it changes to a moisture sink. The atmospheric heat source <*Q*1> is comparable with the moisture sink <*Q*2> in magnitude right in the pentad of onset and during several pentads after it, suggesting that heating in the SCS is mainly attributable to condensation.

Following the characteristics of the atmospheric heat source as described above, the following simple standard can be used to define the onset of the SCS summer monsoon. When the regional mean <*Q*1> is greater than 38.4 W/m^2 over the SCS area at 10°N – 20°N, 110°E – 120°E, the SCS summer monsoon is said to begin. Here, 38.4 W/m^2 is the annual mean of the climatological <*Q*1> averaged over that area and the 15 years. As shown in the composite analysis, that part of the sea has been an atmospheric heat sink before the onset but turns into a heat source right in and after the pentad when the onset takes place. It is then made a regional mean. Performing an abrupt changes test of element fields averaged over the 40 years in the SCS region, He et al.[5] isolate a region with abrupt changes that is consistent with the one selected in the current work. When onset dates are determined using such standard of atmospheric heat sources, we note that the onset dates defined for 1983, 1992 and 1993 are later than those set in Tab.1 but those defined for 1984 and 1989 are earlier than those set in Tab.1. The dates for other years are the same.

For pentad-to-pentad evolution of <*Q*1>, the vertically integrated atmospheric heat source averaged over 15 years, the above standard is used to define the onset, with the finding that the onset of the SCS summer monsoon takes place on average in the 28th pentad (the 4th pentad of May) for the period from 1979 to 1993. An analysis of the 15-year mean flow field also points to the same pentad (figure omitted). Following the pentad-to-pentad evolution of the atmospheric heat source averaged over the 15 years, a more detailed analysis is made of its vertical structure (figure omitted). It can be seen that it is in the 28th pentad that the <*Q*1>, the regional mean for the SCS, first surpasses the annual mean; before the 28th pentad, the atmospheric heating rate <*Q*1> is nearly always smaller than or equal to zero throughout the whole troposphere; after the 28th pentad until the 65th pentad, it is nearly always positive, with the maximum heating center between 600 hPa and 300 hPa. In the analysis of *Q*11, *Q*12 and *Q*13, the three components of *Q*1, no obvious changes are observed in *Q*11 or *Q*12 before and after the onset and *Q*13 becomes the main source for the variation of *Q*1 in the SCS area, indicating that, as far as the SCS region is concerned, very significant changes have taken place in the condition of convection of the entire trospospheric atmosphere, before and after the monsoon onset.

4 PRECEDING FACTORS FOR ONSET TIMING OF SCS SUMMER MONSOON

From the onset dates as determined in Tab.1, it is seen that the earliest onset of the summer monsoon occurred in the 27th pentad (the 3rd pentad of May) and the latest one in the 32nd pentad (the 2nd pentad of June) over the period from 1979 to 1993. They have a difference of five pentads, or nearly a month. Are there any preceding factors that can be used with better results to determine the timing of onset?

The center of the heat source moves north significantly after the monsoon onset, which is indicated in the 3rd section of the current work. Fig.2 gives the month-to-month variation of <*Q*1> averaged over the entire zonal circle and the 15 years between 90°S and 90°N, which shows significant seasonal migration of major zones of heat sources. Analyzing it on a yearly basis (figure omitted), things are different from one year to another. Obvious interannual variations also exist in the month-to-month variations of <*Q*1> averaged over the zonal circle. Does such planetary-scale interannual variations have a role to play in the timing of onset of the SCS summer monsoon? For this purpose, the yearly distribution of correlation between the month-to-month onset dates and month-to-month variations of <*Q*1> averaged over the zonal circle between 90°S and 90°N is derived (Fig.3). As the correlation coefficient with the maximum negative value (–0.86) appears at 40°S in April, the annual anomalous variations of <*Q*1> averaged over the zonal circle at 40°S for April are plotted in Fig.4, with the onset dates on a yearly basis and their corresponding numerals listed in Tab.2.

It is shown in Fig.4 that the SCS summer monsoon will have late (early) onsets if the zonally averaged <*Q*1> decreases (increases) at 40°S in April and it is 100% true for the 15 years that have been studied. Analyzing Tab.2 indicates that years with anomalously late (early) onsets are, without exception, with large negative (positive) anomalies of <*Q*1>. –19W/m^2 is the 15-year mean of the zonally averaged <*Q*1> at 40°S in April, whose anomalous value to be denoted with "*C*". The study above is then used to determine preceding determination indexes for the onset timing of the SCS summer monsoon: when $5 \le C < 10$, the onset happens in the 27th pentad; when $0 \le C < 5$, it occurs in the 28th pentad; when $-5 \le C < 0$, it takes place in the 29th, 30th or 31st pentad; when $C < -5$, it is in the 32nd pentad.

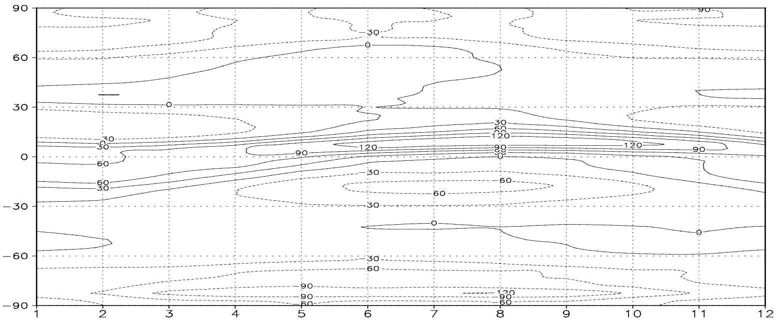

Fig.2 Month-to-month evolution of <*Q*1> zonally averaged (annual mean over 1979 – 1993).

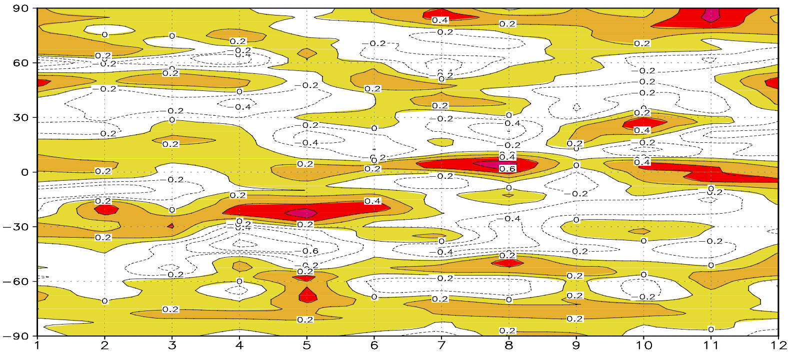

Fig.3 The distribution of correlation between SCS summer monsoon onset dates and month-to-month variation of zonally averaged <*Q*1>.

Applying the index in determining the onset dates of the SCS summer monsoon from 1979 to 1993, we find that the fitting rate is 87% except for two years, 1979 and 1993, when the determination disagrees with the reality. C is –0.9 for 1985 and the onset occurred in the 30th pentad; it is –3.6 for 1982 and the onset appeared in the 31st pentad; it is –4.1 for 1988 and the onset should have been in the 31st pentad, too, but in fact it fell in the 29th pentad. In view of the fact that only one or two years had their onset dates in the 29th, 30th or 31st pentad among the 15-year period. determinations given with the indexes are fuzzy and thus open to discussion for the years with such pentads of onset.

Tab.2 The anomaly of <Q1> zonally averaged at 40°S for April and onset dates of SCS summer monsoon

Year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993
Dates / pentads	27	28	27	31	27	28	30	27	32	29	32	28	32	28	31
Anomaly	3.4	2.1	5.1	-3.6	6.7	3.8	-0.9	7.7	-8.9	-4.1	-15.6	4.5	-5.6	4.5	0.6

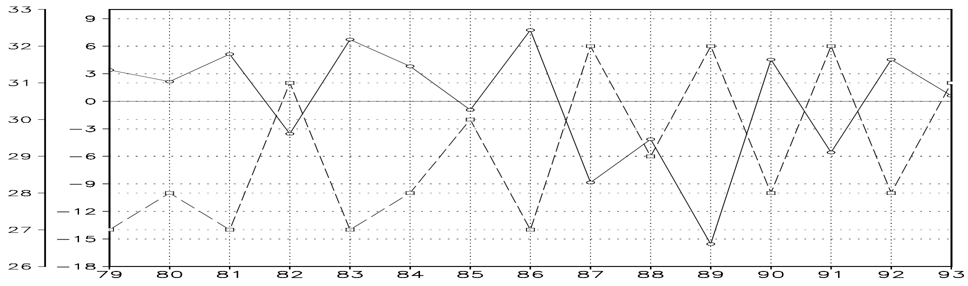

Fig.4 Annual anomalous variation of <Q1> averaged over the entire zonal circle at 40°S in April (the solid line) and annual onset dates of the SCS summer monsoon (the dashed line).

5 CAUSES OF ONSET TIMING OF SCS SUMMER MONSOON

Why does the timing of monsoon onset have such close relationship with the zonally averaged <Q1> at 40°S?

Let’s first examine the climatological-scale background for the summer monsoon onset in the SCS. Fig.5a – 5c are the 15-year-mean April – June vertical profiles of the zonally averaged atmospheric heat source Q1 (with the shaded area indicating Q1>0) and zonally averaged meridional circulation. It shows that the ascending branch of the Hadley cell corresponds to the atmospheric source region of the entire troposphere and the descending branch corresponds to the heat sink region at most of the trospospheric levels. The ascending branch and its associated column of heat source display obvious northwards movement in April – June, during which changes are observed in the area between 10°N and 25°N. There is strong descending flow over it in April with negative atmospheric heating rate at most of the tropospheric levels. When it comes to May, the flow greatly reduces over the area and ascending flow begins to appear below the level of 600 hPa near 15°N. In June, the ascending flow strengthens over the area and the atmospheric heating rate turns to positive at most of the tropospheric levels.

To account for the linkage between the onset timing and the zonal mean <Q1> at 40°S, Averages are taken over the years with anomalously weak <Q1> (1987, 1989 and 1991) and the years with anomalously strong <Q1> (1981, 1983 and 1986) respectively. Then, the results of the anomalously weak years are used to subtract those of the anomalously strong years to obtain the vertical profile of the difference field of the zonally averaged *Q*1 for April (Fig.6a). Likewise, the vertical profile of the difference field of the meridional circulation that is zonally averaged for April is also determined (Fig.6b). Fig.6c is the vertical profile of the difference field of the meridional circulation that is zonally averaged for May.

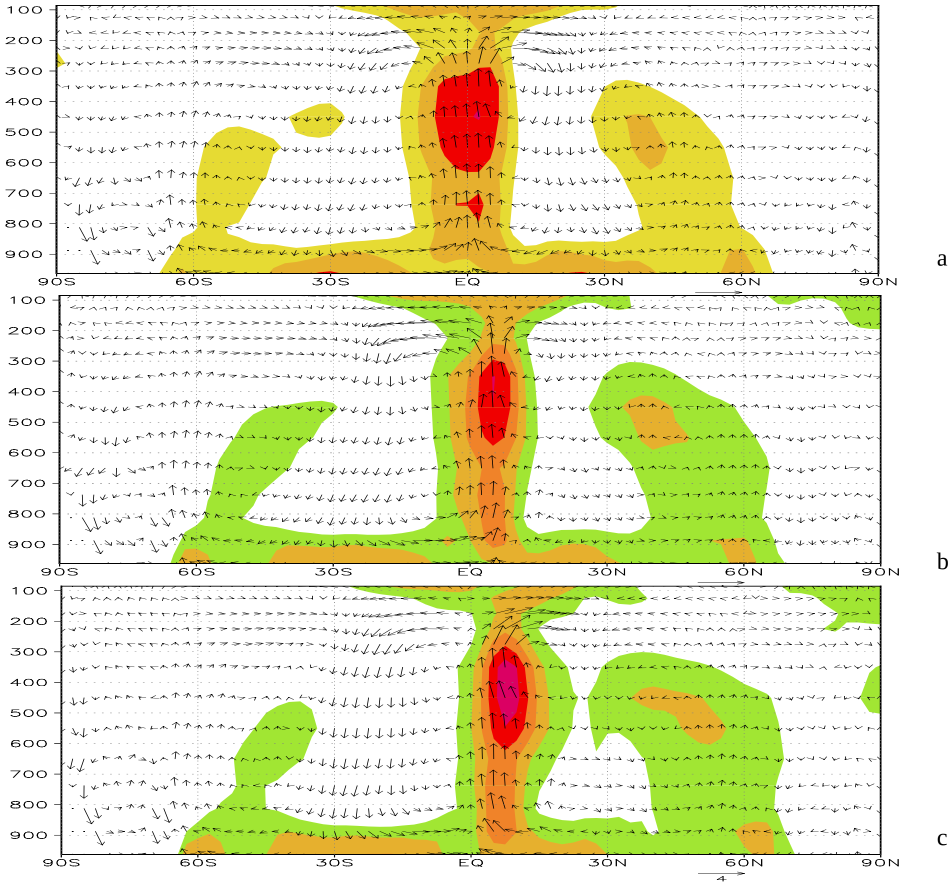

Fig.5 Vertical profiles of the zonal mean atmospheric heat source *Q*1(shaded area indicates *Q*1>0) and the zonal mean meridional circulation in April – June (a – c).

It is known from Fig.6a that the *Q*1 difference near 40°S in April is negative for the whole troposphere and negative *Q*1 difference is also observed at most of the tropospheric levels between 15°N and 40°N, while it is positive in the area between the two negative zones. Corresponding to such difference field of heat sources, strong descending flows appear near 40°S and between 15°N and 28°N. To keep an equilibrium state, a strong ascending flow is required between 0° and 10°N (Fig.6b). In May, the difference pattern is generally maintained with strong descending flow near 40°S but strong descending motion between 10°N and 25°N (Fig.6c). It is then seen that if the zonal mean <*Q*1> at 40°S in April is weak, the corresponding Hadley cells in both the Northern and Southern Hemispheres would be strong. The situation is basically maintained in May so that a strong descending flow is persistent between 10°N and 25°N. Such climatic background is unfavorable for the early onset of the SCS summer monsoon and a late onset may be expected.

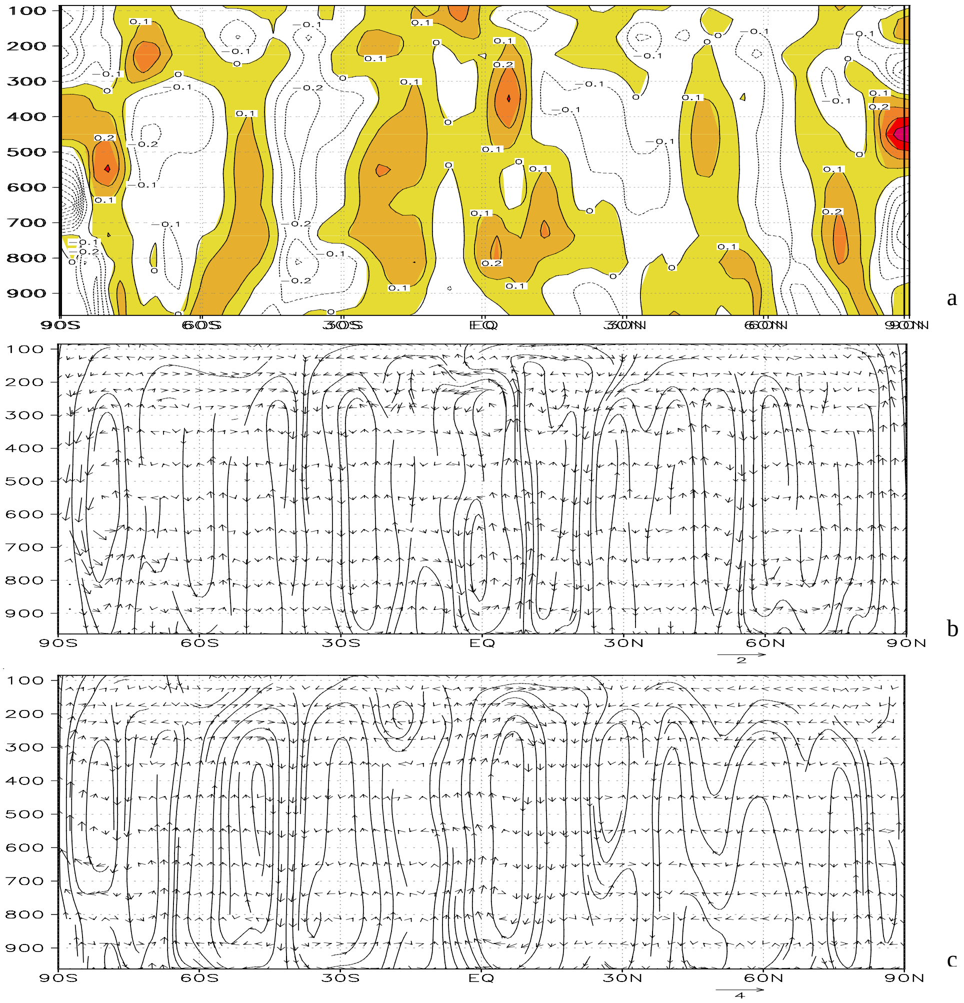

Fig.6 The vertical profiles of the difference fields of the zonal mean <*Q*1> and the zonal mean meridional circulation at 40°S between the years of anomalously weak <*Q*1> and the years of anomalously strong <*Q*1>. (a) zonal mean <*Q*1> difference in April, (b) zonal mean meridional circulation difference in April, and (c) zonal mean meridional circulation difference in May.

6 CONCLUDING REMARKS

a. Setting as reference onset dates as determined in [5] for each of the years, the atmospheric heat source field is studied with composite analysis for 10 pentads each before and after the onset of the SCS summer monsoon over a period from 1979 to 1993. It is found that obvious northward shifting of the heat source center is observed after the monsoon onset; the area of 10°N – 20°N, 110°E – 120°E over the SCS has been a heat sink before the onset but it changes to a heat source right in and after the onset, connecting the heat source in the equatorial western Pacific at 110°E – 130°E with that over the south of China; In the first pentad after the onset, a strong heating center appears between 10°N and 20°N over the SCS.

b. Before the monsoon onset (the 28th pentad), the atmospheric heating rate $Q1$ over the SCS is nearly less than or equal to zero for the whole troposphere but it is positive throughout almost all of the troposphere from the 28th to 65th pentad, with the maximum heating center located between 600 hPa and 300 hPa. Of the three components of $Q1$, $Q11$ and $Q12$ do not change significantly around the onset and the changes in $Q1$ in the region of the SCS are mainly contributed by $Q13$.

c. The timing of the monsoon onset is closely related with $<Q1>$ zonally averaged at 40°S in April, with a –0.86 correlation coefficient. When $<Q1>$ increases (decreases) as compared to the previous year, the onset will be late (early), which is 100% true for the 15-year period analyzed. Following such a pattern, the anomalies of $<Q1>$ zonally averaged at 40°S in April are used to obtain preceding determining indexes for the onset dates (pentads) of the SCS summer monsoon. From the application for the years 1979 – 1993, we note that determinations for 1979 and 1993 are the only two exceptions that disagree with the observation, resulting in a fitting rate of 87%.

d. If the zonal mean $<Q1>$ at 40°S is relatively weak in April, the Hadley cell in both the Northern and Southern Hemispheres will be relatively strong and persist through May, constituting to strong descending air flows between 10° and 25°N. It is a climatic background that delays the onset dates of the SCS summer monsoon.

For the 15-year period studied, the earliest onset took place in the 27th pentad. Longer time series are needed to locate quantitative preceding determination indexes for monsoons that have even earlier onset. With a 40-year (1958 – 1997) NCEP dataset, Wang et al.[15] suggest that the interdecadal variations be great of the climatological characteristics concerning the onset of the SCS summer monsoon — the onset tended to be late in the first 20 years of the period but early in the late 20 years. What such restraints of interdecadal background will have on the determination of annual dates of summer monsoon onset is also an issue to be dealt with using longer time series.

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