Article ID: 1006-8775(2011) 02-0147-09

A DIAGNOSTIC ANALYSIS OF THE WEAKENING OF WEST PACIFIC SUBTROPICAL ANTICYCLONE DURING THE PERIOD OF SOUTH CHINA SEA SUMMER MONSOON ONSET IN 1998

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Abstract: The onset of South China Sea summer monsoon in 1998 occurred on May 21st. Using the U.S. National Centers for Environmental Prediction reanalysis data, this paper examines the physical process of the weakening of a subtropical anticyclone in West Pacific during the onset period using the Zwack-Okossi vorticity equation. Results show that during the pre-onset period, the positive vorticity advection in front of an upper tropospheric trough was the most dominant physical mechanism for the increase of the cyclonic vorticity on the 850-hPa layer over the South China Sea and its nearby region. The secondary contribution to the increase of the cyclonic vorticity was the warm-air advection. After the onset, the magnitude of the latent-heat warming term rapidly increased and its effect on the increase of the cyclonic vorticity was about the same as the positive-vorticity advection. The adiabatic term and divergence term contributed negatively to the increase of the cyclonic vorticity most of the time. Thus, the positive vorticity advection is the most important physical mechanism for the weakening of the West Pacific subtropical anticyclone over the South China Sea during the onset period.

Key words: South China Sea Summer Monsoon; Zwack-Okossi vorticity equation; vorticity advection; West Pacific subtropical anticyclone

CLC number: P448 **Document code:** A **doi:** 10.3969/j.issn.1006-8775.2011.02.007

1 INTRODUCTION

China is located in the Asian monsoon region, which comprises of the Indian monsoon system and East Asian monsoon system, both independent of and interrelated with each other[1]. Being one of the important subsystems in the East Asian monsoon, the South China Sea monsoon exerts great impacts, via anomalous activity, on the general circulation and climate in East Asia and the whole globe[2, 3]. Since the 1990s, especially with the implementation of a South China Sea monsoon experiment (SCSMEX) in 1998, a lot of significant research results have been achieved on the South China Sea summer monsoon (SCSSM)[4]. A number of triggering mechanisms, such as low-frequency oscillations, sea surface temperature anomalies and trough-front systems intruding southward from mid-latitudes, have been put forward about the onset of the SCSSM. They point to the factors responsible for the onset of SCSSM from multiple viewpoints. Due to the complexity of monsoon onset, however, some of the results mentioned above are mostly obtained by qualitative synoptic analysis and few quantitative studies have been conducted on physical processes. Consequently, no consistent understanding has been achieved about the triggering mechanism of SCSSM as to date.

The determination of the SCSSM onset date is the basis of the study on its triggering mechanisms. Because of the complexity of the issue, no one single criterion for the date determination has been widely accepted. By comparing the dates identified with eight different approaches, Gao et al.[10] discovered that the number of identical dates determined by all of the eight methods takes up only one fifth of the overall samples (41 years). As 1998 is the year when the SCSMEX was undertaken, the onset of SCSSM aroused the most interest among researchers, who agreed on the onset date to be at pentad Five of May that year. Some studies have shown that the activity of

Received 2010-06-25; **Revised** 2011-02-20; **Accepted** 2011-04-15
Foundation item: Natural Science Foundation of China (40505015)
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the 1998 SCSSM is associated with the 30-60 day low-frequency oscillations[11, 12]. As it is well known, the process of SCSSM onset is completed within a short period of time[4]. Due to difference in time scale, these low-frequency oscillations cannot set off the 1998 SCSSM all by itself[13], making further analysis necessary. As shown in previous studies, associated with the onset of SCSSM, the most striking change in the large-scale tropospheric circulation is the rapid withdrawal from the South China Sea of the ridge of a West Pacific subtropical anticyclone formerly in control of the sea and the dominance of a southwesterly airflow there. Therefore, the study on the factors having impacts on the behavior of the subtropical anticyclone would conduce to reveal the mechanism reponsible for the onset of SCSSM. With analysis of the establishment of the 1998 SCSSM, Wu et al.[14] pointed out, though synoptically and quantitatively, that the eastward withdrawal of the West Pacific subtropical anticyclone ridge and the onset of SCSSM in the year were closely related with the development and southward advancement of an upper-level trough above the coast of southern China[14]. Making comments on the research achievements of East Asian summer monsoons, Ding et al.[13] also held that trough and front systems travelling south from the mid-latitudes, able to push the West Pacific subtropical high to retreat to the southeast, have not been studied for the physical processes and mechanisms therein. Using the Zwack-Okossi (Z-O) vorticity equation that explicitly incorporates the thermodynamic and dynamic factors of all air layers, Lupo et al.[15] and Walthorn et al.[16] were successful in probing the evolution of explosive cyclones. In this study, the Z-O vorticity equation is used to make diagnostic analysis of the physical factors and synoptic systems responsible for the weakening of the subtropical anticyclone ridge in the South China Sea during the onset of the 1998 SCSSM; the results are then used to make further attempts to study the triggering mechanism for the onset of the SCSSM.

2 DATA AND METHODS

Take an air column with its pressure at the top and bottom denoted as P_t and P_b, respectively. Then, under static equilibrium conditions, the local change in geostrophic vorticity at a low-level isobaric surface (P_b) can be described using the following expression:

$$\frac{\partial \zeta_{gb}}{\partial t}=\underbrace{p_d\int_{p_t}^{p_b}-\vec{V}\cdot\nabla\zeta_a\,\mathrm{d}p}_{A}\underbrace{-p_d\int_{p_t}^{p_b}[\frac{R}{f}\int_{p}^{p_b}\nabla^2(-\vec{V}\cdot\nabla T}_{B}\underbrace{+\frac{\dot{Q}}{c_p}}_{C}\underbrace{+S\omega)\frac{dp}{p}]\mathrm{d}p}_{D}$$

$$\underbrace{+p_d\int_{p_t}^{p_b}\vec{k}\cdot\nabla\times\vec{F}\mathrm{d}p}_{E}\underbrace{-p_d\int_{p_t}^{p_b}\frac{\partial\zeta_{ag}}{\partial t}\mathrm{d}p}_{F}\underbrace{-p_d\int_{p_t}^{p_b}\omega\frac{\partial\zeta_a}{\partial p}\mathrm{d}p}_{G}\underbrace{-p_d\int_{p_t}^{p_b}(\frac{\partial\omega}{\partial x}\frac{\partial v}{\partial p}-\frac{\partial\omega}{\partial y}\frac{\partial u}{\partial p})\mathrm{d}p}_{H}$$

$$\underbrace{-p_d\int_{p_t}^{p_b}\zeta_a\nabla\cdot\vec{V}\,\mathrm{d}\,p}_{I} \qquad (1)$$

where $p_d=1/(p_b-p_t)$.

Eq. (1) is the so-called Z-O equation[15], which includes, theoretically, all physical processes resulting in the development of systems. As shown in Tsou et al.[17], G and H are both small terms as compared to the A, B, C and D terms[17], G and H can then be omitted in Eq. (1). Additionally, their calculation also shows that the local change in ageostrophic vorticity is also small on the synoptic time and space scale[17] and therefore the F term in Eq. (1) can be omitted as well. It is equivalent to taking approximation as in

$$\frac{\partial\zeta_g}{\partial t}\cong\frac{\partial\zeta}{\partial t}$$

On the other hand, flow field changes at the level of 850 hPa are usually used as representation in the discussion of the establishment of SCSSM circulation. In the calculation of this paper, 850 hPa is used as the isobaric surface of the lowest level (i.e. p_b=850 hPa). Besides, because 850 hPa is a level near the bottom of the free atmosphere, the friction term E in Eq. (1) can also be omitted. Then, Eq. (9) can be written approximately as:

$$\frac{\partial \zeta_{b}}{\partial t}=\underbrace{p_d\int_{p_t}^{p_b}-\vec{V}\cdot\nabla\zeta_a\,\mathrm{d}p}_{A}\underbrace{-p_d\int_{p_t}^{p_b}[\frac{R}{f}\int_{p}^{p_b}\nabla^2(-\vec{V}\cdot\nabla T}_{B}\underbrace{+\frac{\dot{Q}}{c_p}}_{C}\underbrace{+S\omega)\frac{dp}{p}]\mathrm{d}p}_{D}$$

$$\underbrace{-p_d\int_{p_t}^{p_b}\zeta_a\nabla\cdot\vec{V}\,\mathrm{d}\,p}_{E} \qquad (2)$$

where p_b=850 hPa, p_t=100 hPa.

Among the terms above, Term A shows the horizontal advection of absolute vorticity; Term B reflects the horizontal advection of temperature; Term C stands for the effect of diabatic heating (cooling), which includes longwave and shortwave radiation, latent-heat warming and sensible-heat warming, etc; latent-heat warming is prominent for movements on the synoptic scale[15, 16]; Term D refers to the adiabatic cooling (heating) associated with the vertical motion and Term E is the divergence (convergence).

It needs to be pointed out that all of these terms are averaged for almost all tropospheric layers. It can then be stated that this method takes into account the effect of almost all levels from the lower to upper troposphere during the generation and development of a system.

Using the U.S. National Centers for Environmental Prediction (NCEP) 2.5° ×2.5° longitude/latitude reanalysis, this work computes all terms of Eq. (2) for the South China Sea and adjacent areas. The duration of computation spans from 0000 Beijing Standard Time (BST) May 20th to 0000 BST May 22nd, 1998. A backward difference scheme was used for time difference and a time step was set at 6 hours long, while a central difference format was used for space difference, with a horizontal grid interval of

108 km. The O'Brien scheme[18] was used to correct ω. For the correction of divergence, Ding's simplified method[19] was adopted.

3 ONSET OF SCSSM

The 1998 SCSSM had its onset on May 21st[20], or to be more exact, at 1200 BST on May 21, 1998, the summer monsoon broke out on a full scale, according to Wu et al.[21] with an analysis of data at a 12-hour resolution. For the convenience of discussion below, the process of the 1998 SCSSM onset is briefly introduced next and related details are referred to in Li and Wu[20] and Wu et al.[21].

At 1200 BST on May 20, 1998, the center of a South Asia high was located near (14° N, 94° E) and a trough was to its northeast over the east coast of continental China, extending from the south of the Korean Peninsula to Taiwan Island (Fig. 1a). Beneath the trough, cyclonic disturbance developed at the level of 850 hPa over the Bashi Channel, with the center near the southern tip of the Taiwan Island (Fig. 2a). The ridge of the subtropical high, already in the South China Sea by that time, was near 14° N and the central South China Sea was still dominated by an easterly wind (Fig. 2a). At 1200 BST on May 21st, the center of the 200-hPa South Asia high jumped northward to 21° N while a trough over the coastal area of eastern and southern China deepened rapidly, with the bottom of the trough intruding southward to the central part of the South China Sea (Fig. 1b). At the same time, a subtropical vortex near the Bashi Channel in front of an upper-level trough at 850 hPa developed further and moved to the southeast, with its cyclonic circulation migrating into the central and northern Philippines which was formerly controlled by the subtropical high; the ridge of the West Pacific subtropical high weakened rapidly and withdrew eastward from the South China Sea. Consequently, a southwesterly airflow, expanding eastward from tropical Indian Ocean to the South China Sea via Indo-china, merged with a 110° E cross-equatorial airflow over the central South China Sea, making the westerly a dominant wind in that part of the sea and thus leading to the onset of the SCSSM (Fig. 2b). After May 21st, with the eastward expansion of the bulk of the South Asia high at 200 hPa, the trough in front of the ridge kept developing and moving to the southeast; correspondingly, the 850-hPa subtropical vortex disturbance also expanded and the subtropical high continued to shrink with it (figure omitted).

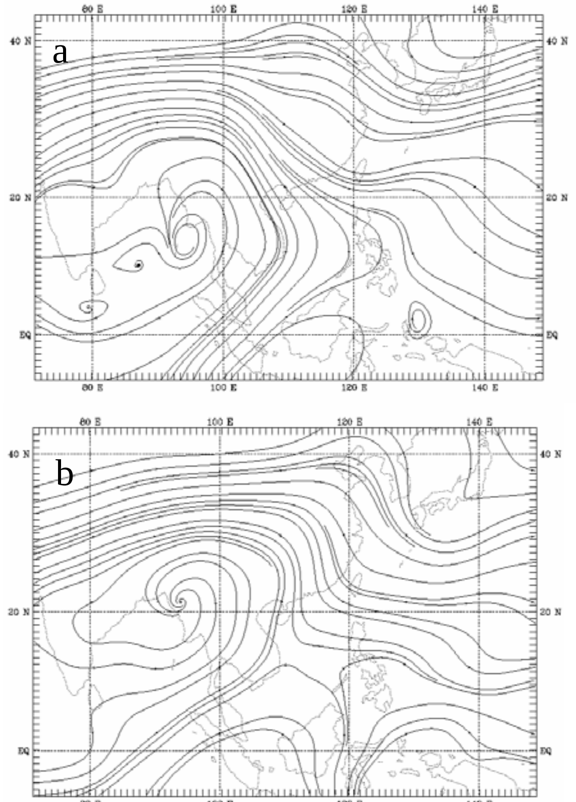


Fig. 1. 200-hPa flow field of the South China Sea and adjacent areas for 1200 BST May 20th (a) and 1200 BST May 20th (b), 1998

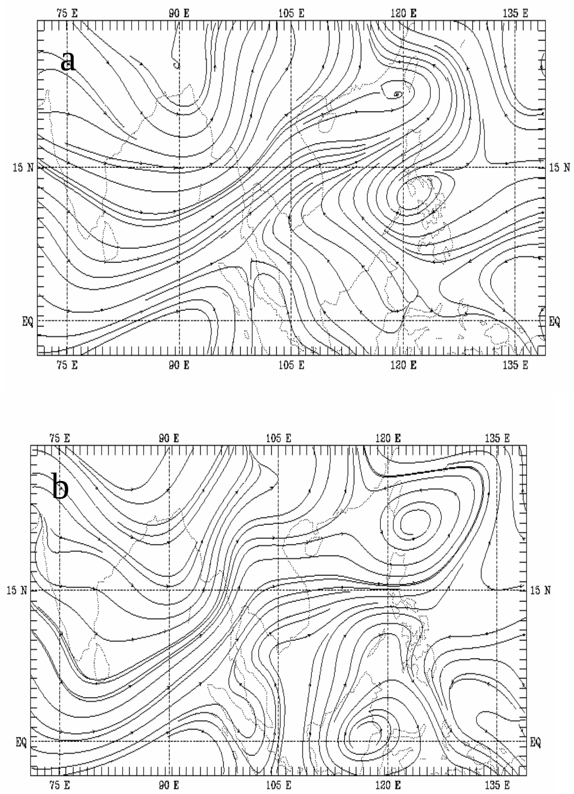


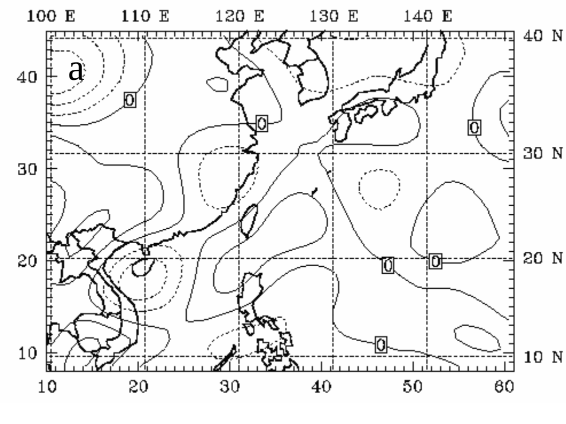
Fig. 2. Same as Fig. 1 but for the 850-hPa flow field

4 850-hPa VORTICITY CHANGES IN THE SOUTH CHINA SEA MONSOON AREA

The simplified version of the Z-O equation, as in Eq. (2) derived above, is used to calculate the changes in 850-hPa vorticity in the South China Sea monsoon area. The results and their analysis are given as follows.

4.1 *Term of local changes of vorticity*

At 1200 BST May 20th, a stretch of positive local change of vorticity ($\frac{\partial\zeta}{\partial t}>0$) existed within a trough area under and in front of an upper-level trough near the east coast of the continent and north of the 850-hPa subtropical high. This positive-value area extended from the south of Japan to the southwest to reach the central South China Sea via the Bashi Channel (Fig. 3a). The subtropical vortex as shown in Fig. 2 formed and developed right near the center of the positive-value area over the channel. Afterwards, with the development and southward progression of the coastal upper-level trough, the axis of the positive-value band of the aforementioned $\frac{\partial\zeta}{\partial t}>0$ also pushed to the south and by 1200 BST May 21st, the centers of three large-value areas were located in the central South China Sea, northern Philippines and the Philippine Sea, respectively (Fig. 3b). It can then be known that the distribution and evolution of the local change term for the 850-hPa vorticity generally reflect the development of the subtropical vortex near the Bashi Channel and the weakening and eastward retreat of the subtropical anticyclone ridge in the West Pacific.



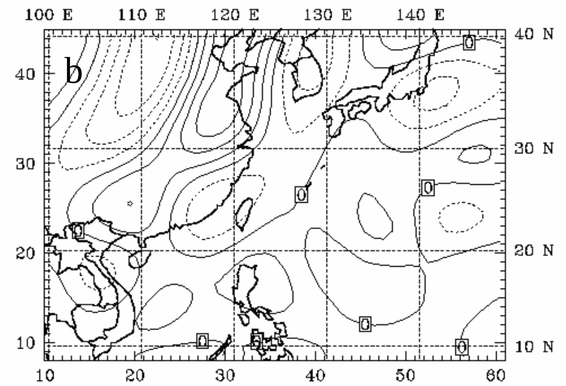


Fig. 3. Horizontal distribution of the local variation of 850-hPa vorticity for May 1998. a: 1200 BST May 20th; b: 1200 BST May 21st. The dashed line is for negative values and solid line for zero or positive values. The contour is at intervals of 2. The unit is 10^{-9} s^{-2}. The same captions follow in the figures below.

4.2 *Term of horizontal advection of vorticity*

Figure 4 gives the horizontal distribution of the term of horizontal advection of vorticity. On May 20th, a band of positive-vorticity advection, oriented nearly northeast-southwest, extended from the south of the Sea of Japan to the east of South China Sea (Fig. 4a), which was just in front of a 200-hPa upper-level trough (Fig. 1a). With the deepening and southeastward movement of the upper-level trough over the coast of southern China on May 21st, the width of the advection band expanded further, comprising the subtropical West Pacific west of 140° E and most of the South China Sea, with the center of the largest positive-value area located over the ocean south of Japan. At the same time, another band of positive-vorticity advection, secondary in value and aligned nearly east-west, was present over the northern South China Sea through the Philippine Sea off northern Philippines (Fig. 4b). At that time, the ridge of the subtropical anticyclone receded from the South China Sea and the SCSSM broke out (Fig. 2b). With the southeastward movement of the upper-level trough, the center of the positive-vorticity advection north of the Philippines strengthened further and moved southward to central Philippines at 0000 BST May 22nd (figure omitted). As shown in the result of the analysis above, with the deepening and southeastward movement of the upper-level trough over the coast of southern China, the area of positive-vorticity advection ahead of the trough gradually progressed to Hainan Island and the subtropical West Pacific region that were earlier controlled by the subtropical high, increasing the positive vorticity there ($\frac{\partial\zeta}{\partial t}>0$) and then further weakening the subtropical high.

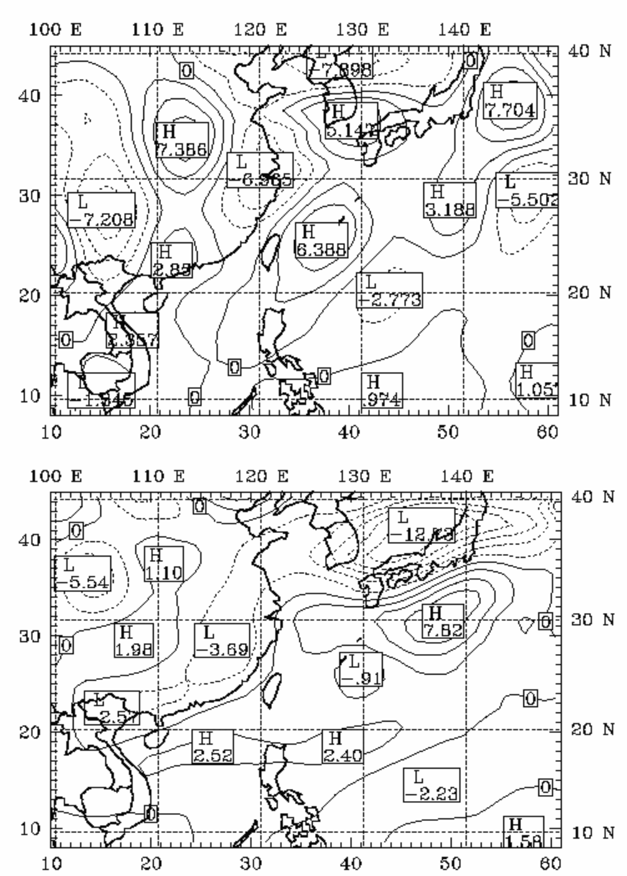


Fig. 4. Horizontal distribution of the term of horizontal advection of absolute vorticity. Upper panel: 1200 BST May 20th; lower panel: 1200 BST May 21th. Other captions are the same as those in Fig. 3.

4.3 *Term of divergence*

It is known from Eq. (2) that if the whole air column P_b through P_t is net convergent, $\frac{\partial \zeta}{\partial t} > 0$; if the air column is net divergent, however, $\frac{\partial \zeta_b}{\partial t} < 0$. Fig. 5 gives the horizontal distribution of the divergence term. On May 20th, a (negative) band of net divergence extended southwest from the ocean south of Japan to central South China Sea via the Bashi Channel; two of the negative centers were located in the south of Japan and Bashi Channel, respectively (Fig. 5a). Afterwards, the divergence band gradually advanced to the southeast with its coverage increasing rapidly; by May 21st, the zero isoline at the southern edge had moved southward to central Philippines near Manila with a much strengthened center (Fig. 5b). The negative band described above was ahead of an upper-level trough and the negative area of the divergence term was corresponding to the ascending motion in front of the trough (figure omitted). Inevitably, changes in $\frac{\partial \zeta}{\partial t}$, resulting from divergence (convergence), are made up for by other physical processes (such as the term of latent-heat warming, to be discussed later in this work) associated with divergence (convergence) and related with vertical motion.

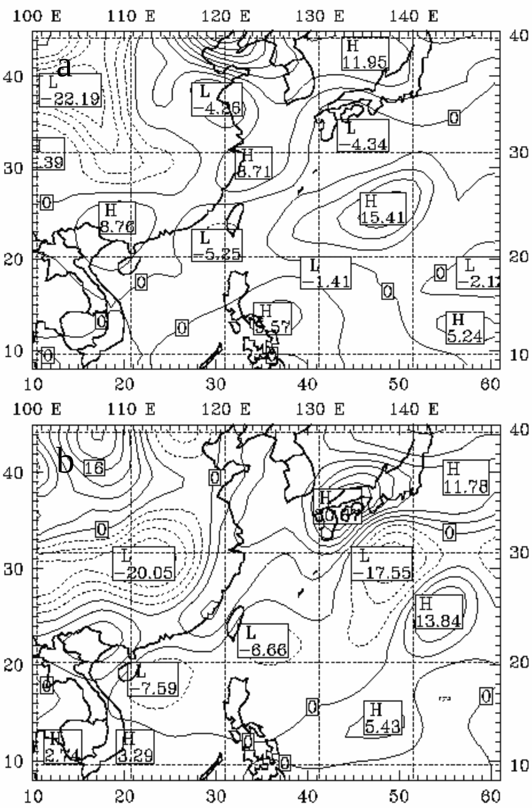


Fig. 5. Same as Fig. 3 but for the horizontal distribution of the divergence term

4.4 *Term of temperature advection*

The role of the temperature advection in Eq. (2) is equivalent to that of the Laplacian term for the horizontal advection of temperature. When there is warm-air advection ($-\vec{V}\cdot\nabla T > 0$), advection of temperature contributes positively to the local change of low-level vorticity where maximum warm-air advection appears ($\nabla^2(-\vec{V}\cdot\nabla T) < 0$). On the contrary, advection of temperature contributes negatively to the local change of low-level vorticity where maximum cold advection occurs ($\nabla^2(-\vec{V}\cdot\nabla T) > 0$).

Figure 6 gives the horizontal distribution of the term of temperature advection. It shows that prior to May 22nd there was an extensive zone of positive values ($\frac{\partial \zeta}{\partial t} > 0$) in central and northern South China Sea and northern Philippines. Meanwhile, the values of the term of temperature advection are quite small relative to the term of vorticity advection, as shown by comparing Fig. 6 with Fig. 3.

4.5 *Term of adiabatic heating*

Under the conditions of stable air column ($S > 0$), $\nabla^2(S\omega) > 0$ where the ascending motion is maximum and the term of stability for that area contributes negatively to the local change of vorticity ($\frac{\partial \zeta}{\partial t}$) at 850 hPa; by contrast, $\frac{\partial \zeta}{\partial t} > 0$ where descending motion is maximum.

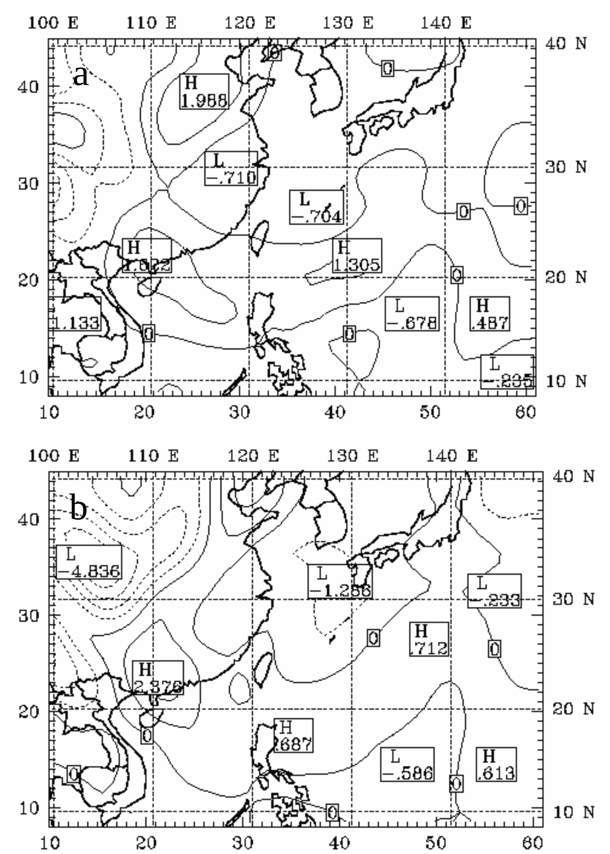


Fig. 6. Same as Fig. 3 but for the horizontal distribution of the term of temperature advection

Figure 7 gives the horizontal distribution of the term of adiabatic heating. On May 20th, a northeast-southwest negative-value area covered the subtropical West Pacific west of 130° E and most of the central and northern South China Sea (Fig. 7a). Then, with the development and southeast movement of the upper-level trough over the coast of southern China, this negative-value area, together with the area of positive-vorticity advection (as shown in Fig. 4), was also moving slowly to the southeast. At the same time, a negative-value center appeared near the centre of the subtropical vortex mentioned above (Fig. 7b). It can then be known that the term of adiabatic heating is not conducive to the development of the subtropical vortex and the weakening of the subtropical high in West Pacific.

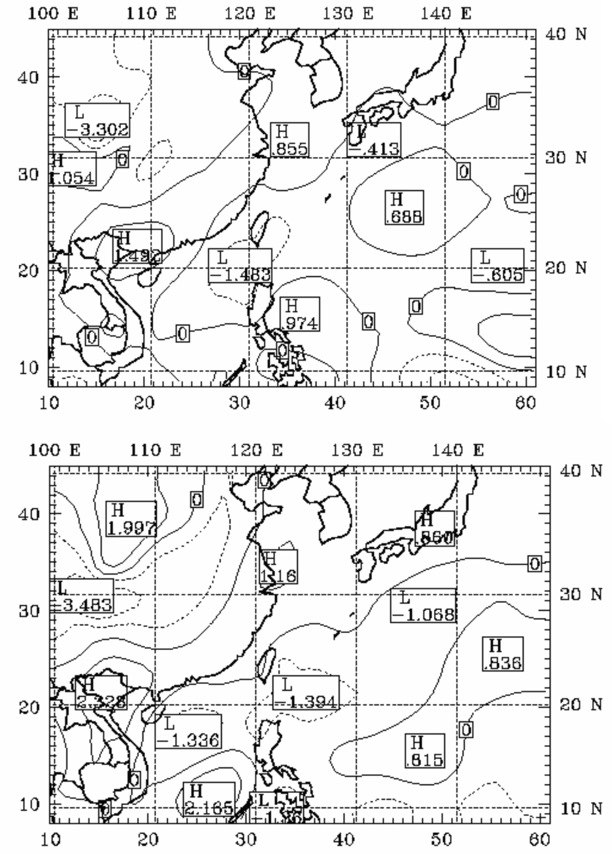


Fig. 7. Same as Fig. 3 but for the horizontal distribution of the term of adiabatic heating

4.6 *Term of diabatic heating*

The term of diabatic heating in Eq. (2) is determined through the method of residual, i.e., let

$$Z \equiv -p_d \int_{p_t}^{p_b} [\frac{R}{f} \int_{p}^{p_b} \nabla^2 (\frac{\dot{Q}}{c_p}) \frac{\mathrm{d}\,p}{p}] \mathrm{d}\,p$$

Then, from Eq. (10), Z can be obtained by

$$Z = \frac{\partial \zeta_{850}}{\partial t}$$

$$-p_d \int_{p_t}^{p_b} -\vec{V} \cdot \nabla \zeta_a \,\mathrm{d}\,p + p_d \int_{p_t}^{p_b} [\frac{R}{f} \int_{p}^{p_b} \nabla^2 (-\vec{V} \cdot \nabla T + S\omega) \frac{\mathrm{d}\,p}{p}] \mathrm{d}\,p$$

$$+ p_d \int_{p_t}^{p_b} \zeta_a \nabla \cdot \vec{V} \,\mathrm{d}\,p \qquad (3)$$

Substituting the results computed from each of the aforementioned terms into Eq. (3) yields the horizontal distribution of Z, the term of diabatic heating.

As described above, diabatic heating includes longwave and shortwave radiation, sensible-heat warming from the underlying surface and latent-heat warming from condensation associated with ascending motion. For short processes on a time scale of a few days, diabatic heating is mainly controlled by latent-heat warming from condensation[16]. For the ease of discussion, it is also called a term of latent-heat warming. It is known from its expression that in the region of maximum latent-heat warming, $\nabla^2(\frac{\dot{Q}}{c_p}) < 0$, then $Z>0$. In other words, the latent-heat warming term contributes positively to the development of low-level positive vorticity.

Figure 8 gives the horizontal distribution of the latent-heat warming term. Comparing Fig. 8 with Fig. 5 shows that the horizontal distribution of the latent-heat warming term (including the orientation of isolines and the position of large-value centers) is quite similar to that of the divergence term except for an opposite phase. This indicates that the latent-heat warming, associated with ascending motion, contributes positively to the development of the subtropical vortex and the weakening of the subtropical high in West Pacific; the positive contribution is offset, to some extent, by the negative contribution of the divergence term.

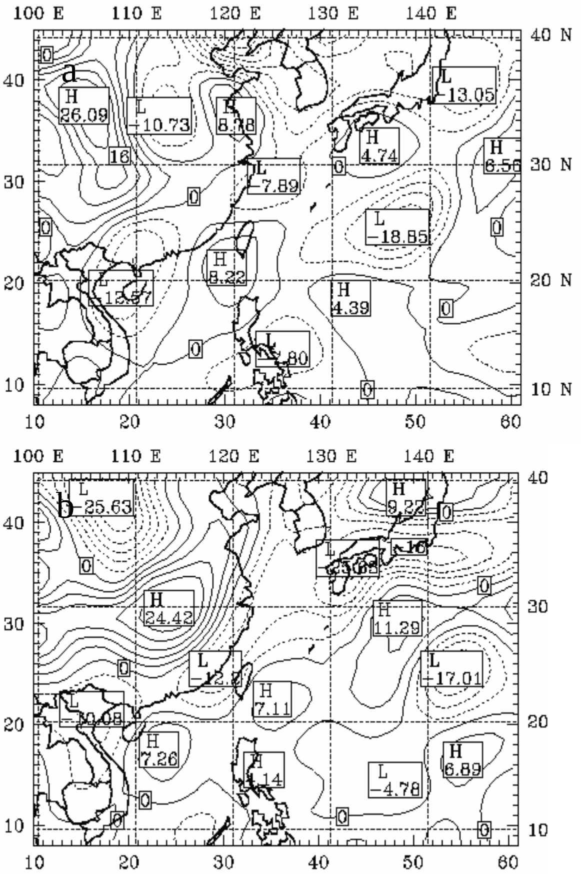


Fig. 8. Same as Fig. 3 but for the horizontal distribution of the term of diabatic heating

4.7 *Results of regional averaging*

To have better knowledge of the roles of individual terms in Eq. (2) in the weakening of the subtropical anticyclone ridge over the South China Sea and West Pacific, regional averaging is taken for all the terms in Eq. (2) over an area of 10–20° N, 110–135° E. Called the subtropical high area in short, this is an area controlled by the ridge of the subtropical high in West Pacific prior to the monsoon onset. Results of the regional averaging are presented in Fig. 9.

It is shown in Fig. 9 that the average cyclonic vorticity began to increase in the subtropical high region from 1800 UTC May 20th, especially between 0600 and 1200 UTC May 21st when the variability rate increased rapidly while the subtropical anticyclone ridge reduced rapidly over the South China Sea (Fig. 2). Though being mild in magnitude at 1800 UTC May 20th, the warm-air advection was the only factor responsible for the increase of cyclonic vorticity. Afterwards, the magnitude of the vorticity advection term rapidly grew. In the time leading up to the monsoon onset, i.e., 0000–1200 UTC May 21st, the most crucial factor for the increased cyclonic vorticity was the vorticity advection, followed by the warm-air advection. Prior to the onset (or before 1200 UTC May 21st), the divergence term was slightly positive or negative but increased rapidly in its absolute value after the monsoon set off till it became the largest term of negative contribution, indicating the presence of intense divergence in front of the upper-level trough. Prior to the monsoon onset, the term of diabatic heating was negative or positive close to zero; after the onset (1200 UTC May 21st through 0000 UTC May 22nd), the term grew rapidly till it was comparable in magnitude to the term of positive-vorticity advection. These two terms, namely the positive-vorticity advection and latent-heat warming, are the principal physical factors causing the increase of regionally averaged cyclonic vorticity, followed by the warm-air advection. By contrast, the adiabatic term has little contribution to the change in regionally averaged vorticity during the time prior to or after the monsoon onset.

It indicates then, based on the calculated results above, that the advection of positive vorticity is the most important physical factor for the rapid weakening of the ridge of the West Pacific subtropical high around May 21st.

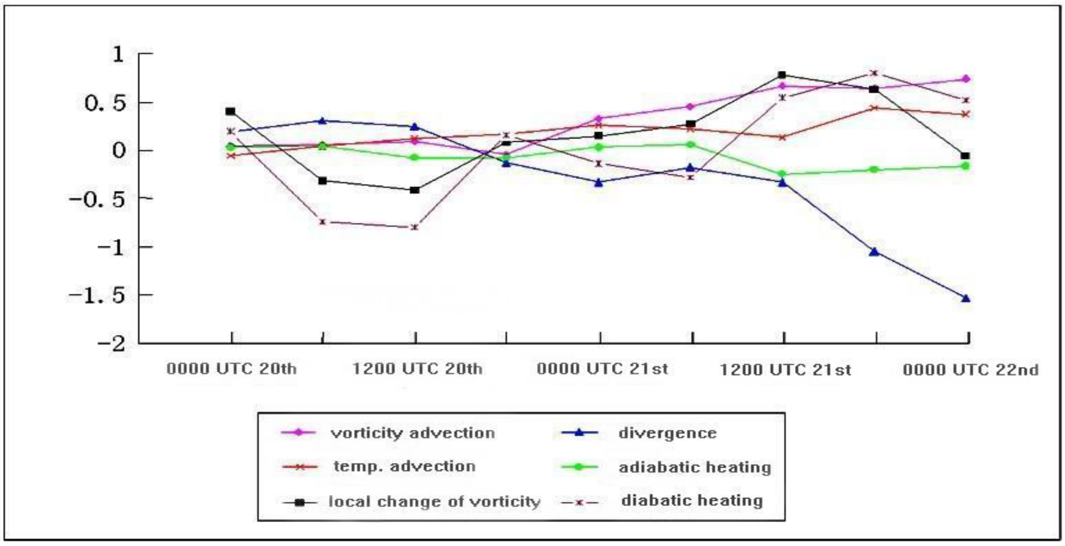


Fig. 9. Temporal variations of regional averages of main terms of the Z-O equation for the subtropical high area (Captions are presented in the text.)

5 CONCLUSIONS AND DISCUSSION

(1) Prior to the onset of the 1998 summer monsoon, positive-vorticity advection in front of the upper-level trough over the coast of South China, which was moving southeast while developing, gradually progressed to the South China Sea and tropical West Pacific; the advection of positive vorticity was the most important physical factor, followed by the warm-air advection, for the increase of cyclonic vorticity at 850 hPa in these regions.

(2) After the onset of summer monsoon, the impact of the divergence term, an essential physical factor for the decrease of the regionally averaged cyclonic vorticity, was increasing rapidly. The adiabatic term had relatively small contribution to the variation of the regionally averaged vorticity either prior to or after the monsoon onset.

(3) After the monsoon onset, the role of latent-heat warming increased rapidly till it was comparable in magnitude with the term of positive-vorticity advection. The advection of positive vorticity and latent-heat warming are two major physical factors responsible for the increase of the regionally averaged cyclonic vorticity; together with the warm-air advection term, they offset the negative contribution from the terms of divergence and diabatic heating, enabling the maintenance and development of cyclonic vorticity (or the cyclonic circulation) in the monsoon region.

As what Wu et al. once pointed out, prior to the onset of the 1998 summer monsoon, heating from condensation within a monsoon low in the Bay of Bengal produced a powerful warm center in the middle- and upper-troposphere in the northern part of the bay. The warm center superimposed in phase with a warm ridge moving eastward in middle latitudes to form a powerful warm ridge that extended northeast from the northern Bay of Bengal to northern China; the warming it had resulted in caused the horizontal meridional gradient of the mid- and upper-tropospheric temperature to change from a winter pattern to a summer one over South Asia east of 90° E. Such a change in the temperature gradient resulted in a rapid northward jump of the center of South Asia high on May 21st, with the northwesterly airflow ahead of the ridge speeding up the deepening and southeastward advancement of a trough over the east coast of China[14, 22]. In this sense, therefore, the establishment of the 1998 summer monsoon is the result of interactions of circulation systems between the middle and lower latitudes[22]. Seasonal evolution of land-sea thermal contrast, sea surface temperature and low-frequency oscillation of the atmosphere provide background conditions for the interactions. As shown in the computation results of this study, the advection of positive vorticity in front of the trough, which was moving toward the South China Sea and tropical West Pacific during the interactions, was the most important physical factor for the rapid weakening around May 21st of the subtropical West Pacific anticyclone ridge that originally controlled the South China Sea. It is then clear that the development and southward advancement of the coastal trough over the coast of southern China was the immediate trigger of the onset of the 1998 summer monsoon in the South China Sea.

Having calculated 40-year (1961–2001) longitudinal propagation with time of the 850-hPa vorticity averaged over the region 110–120° E during the onset of South China Sea summer monsoon, Choi discovered that about 70% of the onset processes are related with positive vorticity being propagated from north to south across 25° N, which is the category the year 1998 belongs to[23]. Some of the case studies, like those for the years 1987[23], 1994[9], and 1998, have shown that this type of propagation of positive vorticity is connected with a trough-front system moving southward. Therefore, the trough-front system may be the most common trigger of the SCSSM onset, which awaits verification with more case studies.

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Citation: HUANG Chen-jie, LAN Guang-dong, CHOI Man-cheng et al. A diagnostic analysis of the weakening of West Pacific subtropical anticyclone during the period of South China Sea summer monsoon onset in 1998. *J. Trop. Meteor.*, 2011, 17(2): 147-155.