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ON A POSSIBLE MECHANISM FOR SOUTHERN ASIAN CONVECTION INFLUENCING THE SOUTH ASIAN HIGH ESTABLISHMENT DURING WINTER TO SUMMER TRANSITION

LIU Bo-qi (刘伯奇), HE Jin-hai (何金海), WANG Li-juan (王黎娟)

(Key Laboratory of Meteorological Disaster of Ministry of Education, College of Atmospheric Sciences, Nanjing University of Information Science & Technology, Nanjing 210044 China)

Abstract: The establishment of the South-Asian high (SAH) in April and May over the Indochina Peninsula (IP) is investigated based on the ERA-40 reanalysis data. The result shows that the SAH is generated and strengthened over the IP locally, rather than moving westward to the IP from the Western Pacific. After the SAH establishment the tropical upper tropospheric trough (TUTT) forms above the ocean to the east of the Philippines. We have found that the principal triggering factor of both the SAH construction and the TUTT formation is the variation in the Southern Asian atmospheric diabatic heating regime. In late April, both the climbing effect of Shan Plateau and the local surface sensible heating contribute to local rainfall over the IP. Then the local updraft and upper-air divergence are strengthened, being responsible for the SAH formed in the southern part of the IP. As convection moves northward along the Australian-Asian "maritime continent" and the Bay of Bengal (BoB) summer monsoon begins, the convection is intensified in May on the eastern BoB. The strong convection results in the SAH enhancing and expanding westward, accompanied by reinforced meridional flow to the east of SAH, where responses of the circulation to diabatic heating arrive at a quasi-steady state. Meanwhile, because of the positive geopotential vorticity advection resulting from upper equatorward flow, the local positive relative vorticity increases over the ocean to the east of the Philippines, making the tropical upper tropospheric trough (TUTT) form around 150°E.

Key words: South-Asian High; Indochina Peninsula; vertical heterogeneous heating; thermal adaptation

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1 INTRODUCTION

The South-Asian high (SAH) is the strongest and most stable circulation in the upper troposphere of Northern Hemisphere except the polar vortex[1]. The SAH is characterized by distinctly phased meridional shift in position and intensity from winter to summer, that is, in May and June it marches steadily westward and then northward from the South China Sea (SCS) to the Tibetan Plateau where it stays. At this time the atmospheric circulation over East Asia changes from the winter to the summer pattern. Such an evident seasonal change has direct impact on the atmosphere circulation pattern in Northern Hemisphere and thus on the weather/climate features in Asia as a whole. The circulation seasonal change also acts as an indicator for the seasonality of East Asian atmospheric circulations, South-Asian summer monsoon onset as well as the floods/droughts distribution over Eastern China[2, 3]. Studies show that the SAH is a thermal high-pressure system, whose formation depends on the distribution of heterogeneous diabatic heating effect over the Tibetan Plateau and whose seasonal evolution depends strongly on changes in atmospheric heating, marked by thermotaxis, or heat preference[4-8]. Cao et al.[9], for example, believed that the cause of abnormal location of the western Pacific subtropical high (WPSH) is the difference in early external thermal forcing, evoking different waveforms in the atmosphere. By investigating the 3D structure and dynamics of a surface Subtropical High over the North Pacific and those of the equivalent (Azores high) over the North Atlantic Ocean, Miyasaka and Nakamura[10] point out

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Biography: LIU Bo-qi, Ph.D. candidate, mainly undertaking research on monsoon dynamics.

Corresponding author: HE Jin-hai, e-mail: hejhnew@jsmail.com.cn

that the leading direct forcing is the land-ocean thermal contrast due to land sensible heating and ocean radiation cooling. Wu and Liu [11, 12] and Liu et al.[13, 14] put forward the subtropical LOSECOD quadruplet heating in summertime in order to explain the formation of the Subtropical High. The LOSECOD denotes that the ocean region to the west is characterized by strong longwave radiative cooling (LO); the western and eastern portions of the continent are dominated by sensible heating (SE) and condensation heating (CO) respectively; and the ocean region to the east is characterized by double dominant heating (D). Wu et al.[15] stressed the connotation of the subtropical LOSECOD heating distribution in summer, and further investigated the modulation of land-sea distribution on the air-sea interaction and used it to interpret the formation of the heating quadruple. They also explore the contribution of the mosaic of LOSECOD quadruplet heating to the formation and distribution of summertime subtropical anticyclone. On the other hand, the WPSH exhibits interannual changes[16-22]. Wu and Zhou[23] indicated that the annual and interannual variability of the WPSH is associated with the "maritime continent" and the equatorial mid- and eastern-Pacific SST forcing. The annual variability of WPSH is also remarkable. The proposed factors include the monsoon diabatic heating[24-27], land-sea heating [10, 12, 13], diabatic amplification in terms of the cloud-reduced radiative cooling[28], and air-sea interaction[29]. Because of the intimate linkage between the SAH and the Subtropical High, it is attempted here to explain the SAH establishment in April and May over the Indochina Peninsula (IP) in terms of the change in atmospheric diabatic heating regime. As noted by He et al.[30], through the splitting and reconstruction of the anticyclone center over the IP as seasonal shift in April and May, the SAH moves fast from the waters into the IP—the shift may be attributed to the rapid northward migration of Sumatra convection and the initiation of convection in the IP. Up to this point, we would like to ask what the signatures of the SAH establishment are and what the mechanism is. This work makes an attempt to deal with the above problems preliminarily.

2 DATA AND METHODS

Two sets of data are used in this study: (1) the ERA-40 daily averaged pressure-level data from European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis dataset[31] and (2) the Outgoing Longwave Radiation (OLR) daily averaged data from National Oceanic and Atmospheric Administration-Cooperative Institute for Research in Environmental Sciences/Climate Diagnostics Center satellite observations[32]. Both datasets span the years from 1979 to 2001 and have a horizontal grid resolution of 2.5°×2.5°. The OLR data are commonly used as a proxy to represent large-scale convective activities over the tropical and subtropical areas. The long-term daily mean and pentad mean are obtained by arithmetically averaging the 23-year (1979 to 2001) dataset, hereafter referred to as the climatology.

The 150 hPa streamline field is used to describe SAH activity and we define the zonal zero wind isoline along with anticyclonic zonal wind shear ($\partial u/\partial y > 0$) as the SAH ridge line at 150 hPa. To further gain insight into the SAH primary properties, vertical decomposition is made of the atmospheric circulation, according to Peixoto and Oort scheme[33], arriving at

$$\text{Barotropic mode}\quad \begin{cases} \bar{u} = \dfrac{1}{p_s - p_t}\displaystyle\int_{p_t}^{p_s} u\,\mathrm{d}p, \\ \bar{v} = \dfrac{1}{p_s - p_t}\displaystyle\int_{p_t}^{p_s} v\,\mathrm{d}p, \end{cases} \tag{1}$$

$$\text{Baroclinic mode}\quad \begin{cases} u' = u - \bar{u}, \\ v' = v - \bar{v}, \end{cases} \tag{2}$$

where p_s and p_t denote, respectively, pressure at surface and the tropospheric top (at 100 hPa). Here the barotropic mode refers to the wind field averaged over the whole-depth troposphere and the residual is called the baroclinic mode, in which the boundary layer frictional effect is neglected. The barotropic mode is indicative of the general trend of whole-extent air motion whereas the baroclinic counterpart denotes the wind vector difference between the actual flow field and the mean at 150 hPa, or the barotropic mode. Also the baroclinic mode represents roughly the baroclinicity between the layers, which bears a close relation to the thermal effect. Yet the dynamic effect is represented by the barotropic mode respectively. As a result, it is possible to use the baroclinic mode to depict the role played by the thermal factor approximately.

The atmospheric diabatic heating regime is designated by the apparent heat source calculated with the inverse calculation scheme deduced by Yanai et al. [34], which takes the form

$$Q_1 = C_p \cdot \left[\frac{\partial \bar{T}}{\partial t} + \bar{\vec{V}} \cdot \nabla_p \bar{T} + \left(\frac{p}{p_0}\right)^{\frac{R}{C_p}} \cdot \bar{\varpi} \frac{\partial \bar{\theta}}{\partial p} \right]. \tag{3}$$

By integration with respect to the whole-depth air column we have

$$< Q_1 > = \frac{1}{g}\int_{p_t}^{p_s} Q_1 dp \approx LP + S + < Q_R >, \tag{4}$$

wherein p_t (p_s) stands for the upper (lower) limit at 100 hPa (surface), L for the term of the rate of latent heat released via condensation, P for rainfall, LP for the vertically-integrated condensation heating, S for the surface sensible heating flux term, and $\langle Q_R \rangle$ for the vertically-integrated radiative heating term.

To diagnose the interactions between heating and stream (vorticity) fields, we utilize the complete form of vertical vorticity equation[35, 36], in which the effects of frictional dissipation and Slantwise Vorticity Development (SVD) are ignored except the effect of external heat sources, leading to

$$\frac{\partial \zeta}{\partial t}+\vec{V}\cdot\nabla\zeta+\beta v=(f+\zeta_z)(1-\kappa)\frac{\omega}{P}+\frac{f+\zeta_z}{\theta_z}\frac{\partial Q_1}{\partial z}-\frac{1}{\theta_z}\frac{\partial v}{\partial z}\frac{\partial Q_1}{\partial x}+\frac{1}{\theta_z}\frac{\partial u}{\partial z}\frac{\partial Q_1}{\partial y} \quad (5)$$

in which the non-adiabatic heating term is in the form

$$\frac{f+\zeta}{\theta_z}\frac{\partial Q_1}{\partial z}-\frac{1}{\theta_z}\frac{\partial v}{\partial z}\frac{\partial Q_1}{\partial x}+\frac{1}{\theta_z}\frac{\partial u}{\partial z}\frac{\partial Q_1}{\partial y},\theta_z\neq 0\,. \quad (6)$$

Recalling that the SAH is a synoptic-scale system in the upper troposphere, we set its horizontal dimension to 10^6 m and following the barometric formula we obtain the depth of the layer where the SAH is situated is about 15 km (1.5×10^4 m) and therefore we take 10^4 m as the vertical scale. From scale analysis, the horizontal heating difference scale (10^{-11} to 10^{-12} s^{-2}) is much smaller compared to the vertical equivalent (10^{-10} s^{-2}), indicating that the effect of horizontal heating difference is considerably weaker than that of the vertical counterpart. This means that the latter is dominant, and so the equation is simplified to

$$\frac{\partial \zeta}{\partial t}+\vec{V}\cdot\nabla\zeta+\beta v\approx\frac{f+\zeta}{\theta_z}\cdot\frac{\partial Q_1}{\partial z}\,. \quad (7)$$

The three terms on the left hand side of Eq. (7) are those of relative vorticity advection, geostrophic vorticity advection and vertical difference of diabatic heating, in order. It should be noted that the relative vorticity advection term consists of local mean and transient variability. As a consequence, Yuan et al.[37] have derived a diagnostic equation for meridional circulation from local zonal average. But since our study concentrates on climatological regime, the contribution of transient change of horizontal advection is ignored in calculation. On the other hand, due to the weak zonal wind near the SAH ridge line in the subtropical area, the effect of relative vorticity advection can be neglected, thus leading to (7) in the form

$$\frac{\partial \zeta}{\partial t}+\beta v\approx\frac{f+\zeta}{\theta_z}\cdot\frac{\partial Q_1}{\partial z}\,. \quad (8)$$

The characteristics of SAH establishment over the IP are provided in Section 3. A possible mechanism is described in Section 4. Section 5 is about the summary and discussion.

3 PROCESS FOR SAH ESTABLISHMENT OVER THE INDOCHINA PENINSULA

The pentad evolution of climatological (mean over April and May 1979–2001) 150 hPa flow field is presented in Figure 1. It is shown that early in April, there is no evident anticyclone center except that a high pressure region emerges around 150°E to the east of the Philippines, with the ridge close to 7.5°N (Figure 1a). Subsequently, a local high pressure with a close anticyclone center (SAH) exists over IP at pentad 24 (Figure 1c), with little or no change in either the position of the ridge line or the appreciable northward trend of the main body. Meanwhile the upper streamline field changes little over the ocean to the east of the Philippines, The structure maintains itself till pentad 27 (Figure 1e), during which the ridge migrates northward from 7.5°N to 12.5°N, illustrating the initial formation of SAH over the IP. And then the SAH stays motionless and continues to get enhanced over the IP and consequently, the tropical tropospheric trough (TUTT) strengthens gradually on the West Pacific (Figure 1f, g). With the South China Sea (SCS) summer monsoon building up at pentad 29 (Figure 1h), the TUTT stays around 150°E and the geopotential height decreases remarkably.

When the SAH is entirely established over the IP, its ridge line is displaced rapidly north from 12.5°N to 17.5°N, indicating the dominance of zonal (meridional) motion of the high-pressure main body before (after) the SAH establishment. In addition, the daily climatological streamline field at 150 hPa (not shown) represents similar conclusion. Based on the climatological pentad evolution of 150 hPa flow fields, the SAH establishment over the IP is divided into three phases according to the SAH strength and position: 1) the SAH pre-establishment phase in pentads 19 to 22 with no anticyclone's main body situated over the IP; 2) the SAH initial formation phase in pentads 23 to 25, when the SAH forms and is located over the IP; 3) the SAH complete construction phase (pentads 26 to 28), during which the SAH strengthens and shifts northward and the TUTT builds up and develops over the ocean. Besides, Figure 1 depicts that after the SAH establishment the TUTT forms in mid-May and the TUTT formation seems to be the result of the SAH establishment. The reason will be discussed in the next section.

Figure 2 clearly depicts 150 hPa stream and divergence fields in the various phases of the SAH establishment, indicating that there is always a zone of strong upper divergence to the east of the Philippines, in association with convection over the western Pacific "warm pool". During the SAH initial formation stage, divergence is intensified over the IP, with another stronger divergent core over the southern Bay of Bengal (BoB) for the onset of summer monsoon there, but at this time the TUTT cannot be observed. In the SAH complete construction phase the divergence is reinforced over the IP, accompanied by enhanced upper-air divergence over the southern SCS, ushering in the onset of summer monsoon over there. At this time the TUTT forms to the east of the Philippines, implying the start of establishing a summer circulation situation.

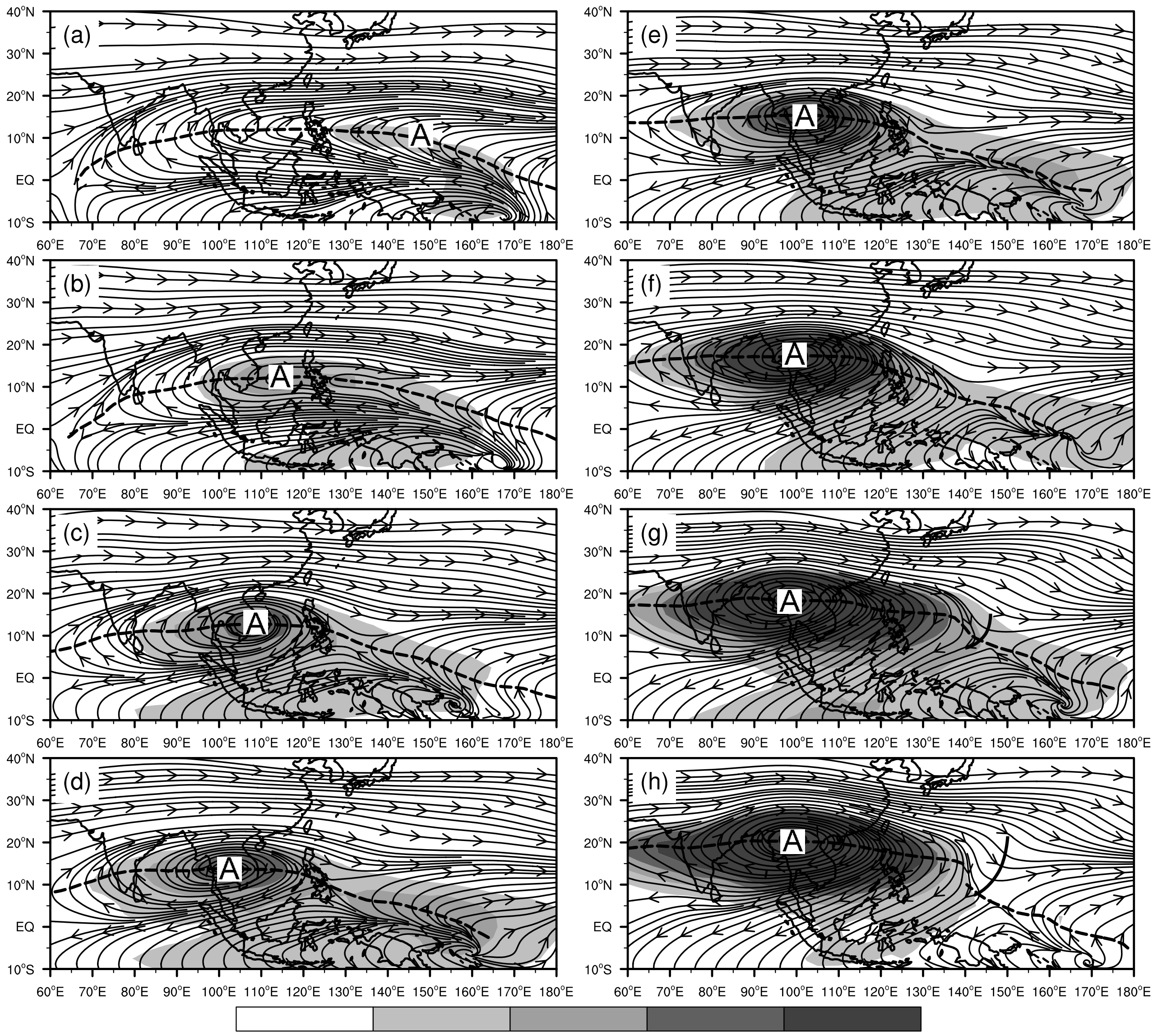

Figure 1. 1979 to 2001 April-May averaged pentad flow and geopotential height (shaded, units: dagpm) fields at 150 hPa, with (a) to (h) denoting pentads 22 to 29, in order, where the trough (TUTT) is labeled by the dashed (solid) line.

In order to confirm the importance of dynamic effect and thermal factor in the SAH establishment, the vertical decomposition of atmospheric circulation has been induced and the results are shown in Figure 3. It is seen therefrom that the high-value center of baroclinic relative vorticity (BRV, see the shading of Figure 3) corresponds to the anticyclone's core. As the BRV is enhanced (reduced) over the IP (Western Pacific), the SAH forms and intensifies over the IP while the TUTT develops above the ocean. Comparison of Figures 2 to 3 shows that for the baroclinic mode and actual stream field their patterns are highly similar except slight difference in intensity, illustrating that the SAH establishment is mainly under the control of atmospheric thermal factor.

Barotropic modes (Figures 3a to 3c) are the mean flow fields across the whole-depth troposphere during the SAH establishment and also represent the breaking of the Subtropical High Belt. As the SAH makes its initial appearance the barotropic mode of the flow field (Figure 3b) manifests itself as an inverse trough around the eastern Indian Peninsula. In the phase of SAH complete construction, a closed Sri Lanka vortex emerges and the main body of Subtropical High withdraws eastward (Figure 3c). In the SAH initial formation phase, the anticyclone is weak at high levels and so is the meridional flow, leading to weak geostropic vorticity advection, thus illustrating that the circulation response to the latent heating fails to reach a stationary state. But as the SAH constructs completely, the upper-air anticyclone is vigorous and so is the meridional air, leading to enhanced geostrophic vorticity advection, so that the response of circulation to latent heating arrives at a stationary state. In what follows detailed discussion is made of the impact of different responses to the latent heating upon the SAH establishment over the IP.

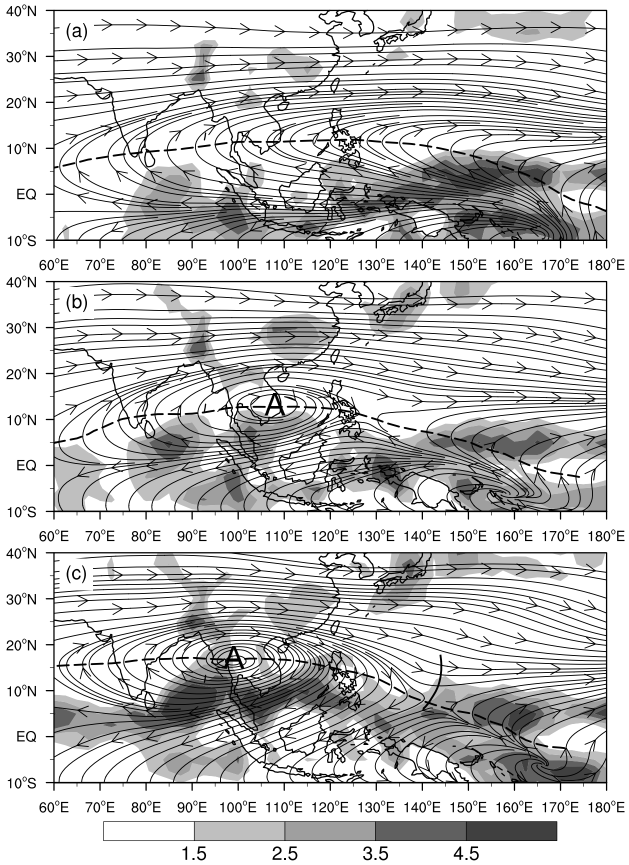

Figure 2. Spatial distribution of 150 hPa stream and divergence fields for the phased stream fields relating to the SAH establishment over the Indochina Peninsula, with pre-establishment in (a), initial formation in (b) and complete construction in (c). The heavy solid line denotes the trough line, the shading represents the divergence and the red dash line is the ridge.

To sum up, the SAH establishment over the IP in April and May is featured as follows: 1) the establishment is accomplished from late April to mid-May and during the onset the most noticeable characteristic is that the SAH establishes over the IP locally and then the TUTT builds up on the ocean to the east of the Philippines; 2) the SAH establishment is in effect a process by which the SAH is formed and enhanced over the IP locally instead of the anticyclone moving west from waters east of the Philippines onto the IP, which is the result of changes in the atmospheric thermal factor; 3) after the SAH initial formation period, the summer monsoon is established over the eastern BoB. However, the SCS summer monsoon begins only when the SAH is completely constructed over the IP. This indicates that the SAH establishment over the IP is closely associated with the development and migration of East Asian summer monsoon.

He et al.[38] has noted that the IP convection begins first in mid-April, and the diabatic heating difference between the Indochina and Indian peninsulas is the key of the Subtropical High Belt breaking over the BoB. Then, is the SAH establishment in April and May associated with the initiation of convection over the IP? If so, how does the convection affect the process? Wang et al.[39] showed that the convection initiated over the IP is related to the convection migrating there along the Asian-Australian maritime continent. We shall analyze the evolution of calculated strength of atmospheric apparent heat source, whereby a possible linkage is revealed between the convection and the SAH establishment over the IP. As shown above, the SAH establishment over the IP is accompanied with the TUTT formation above the ocean, and both of them are due to the mode of response to the latent heating that varies in the different phases of the SAH establishment. The linkage between them will be discussed in the following.

4 POSSIBLE MECHANISM

As noted clearly above, the SAH establishment over the IP is the result of changes in the atmospheric thermal factor. Figure 4 depicts the evolution of diabatic heating vertical profile in different regions. It is indicated that within the domain of SAH activity, the diabatic heating comes mainly from the latent heat released from condensation in convection, but the sensible heating has little effect. Specifically, as convection is initiated at pentad 22 over the IP (Figure 4b), the SAH comes into its initial phase of establishment. After the convection is initiated in the BoB, the summer monsoon begins there at pentad 25, followed by the rapid development of convection in the BoB (Figure 4a) and the SAH complete construction. From pentads 26 to 28, the SCS diabatic cooling changes into diabatic heating that intensifies rapidly (Figure 4c) in association with the onset of SCS summer monsoon. In generally, the BoB summer monsoon onset date is pentad 25 and the SCS summer monsoon builds up at pentad 28. Hence in the SAH initial establishment phase, the BoB summer monsoon starts, while in the SAH complete construction phase, the summer monsoon onsets on the SCS. Besides, the maximum heating level is different over the IP and SCS. For instance, the maximum heating level over the IP and BOB is around 600 hPa, whereas the level over the SCS is around 400 to 500 hPa. Such inconsistency is related to the different precipitation nature. For the IP, the precipitation is basically due to the topography, and therefore, the maximum heating level is lower. But for the SCS, the precipitation basically results from convection, so that the maximum heating level is higher.

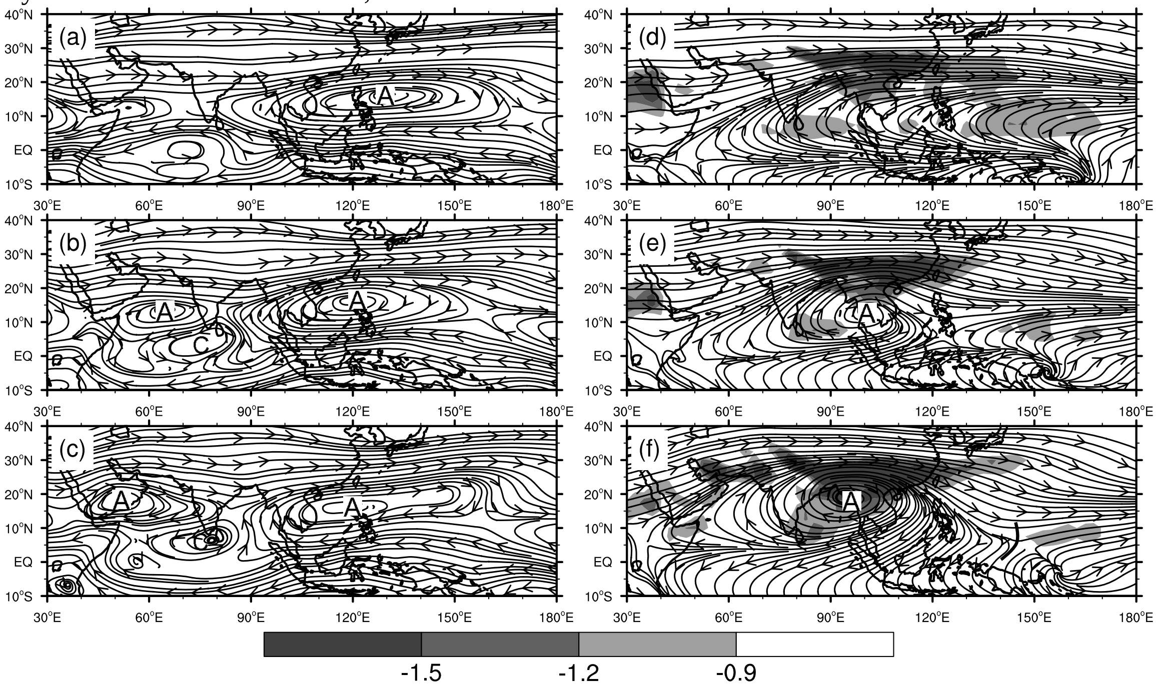

Figure 3. Patterns of barotropic (baroclinic) modes of the flow fields shown in a-c (d-f), with the pre-establishment phase in a and d, the initial-form phase in b and e, and the complete establishment phase in c and f. The trough line is denoted by the bold solid line and the baroclinic vorticity (10^{-5} s^{-1}) by shading. The scale below the figure is the intensity of baroclinic vorticity.

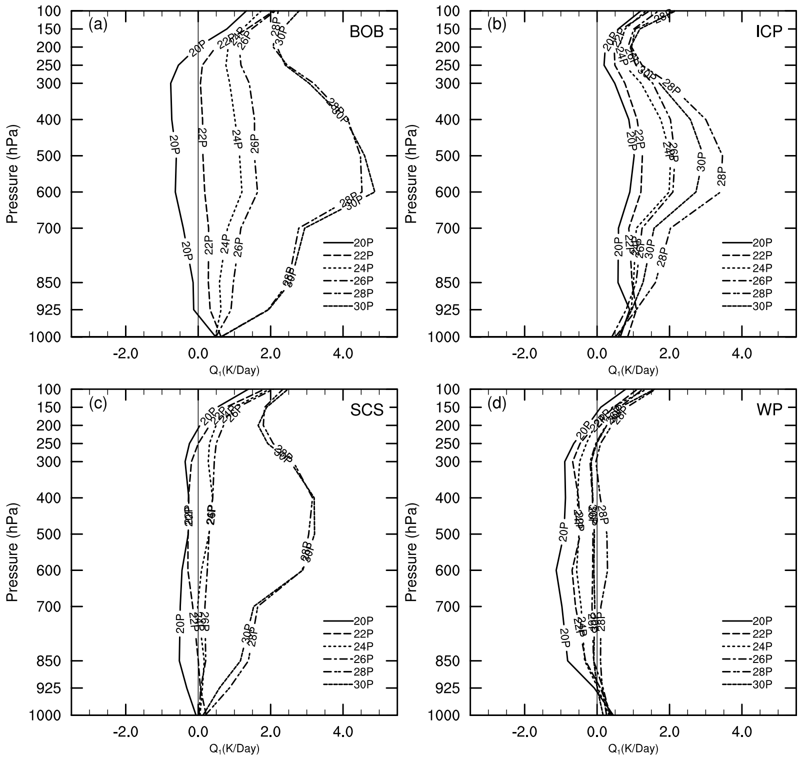

Figure 4. Change in the heating profiles in the Bay of Bengal (10-20°N, 90-100°E) in (a), the Indochina Peninsula (10-20°N, 100-110°E) in (b), SCS (10-20°N, 110-120°E) in (c) and West Pacific (10-20°N, 140-160°E) in (d). Units: K day^{-1}.

However, the diabatic heating profile changes little over the West Pacific from April to May (Figure 4d), implying that the development of TUTT is not directly due to the local diabatic heating effect. Then what contributes to the TUTT development and its association with the SAH establishment, as well as the fact that changes in diabatic heating influence the SAH establishment over the IP, will be analyzed below.

4.1 *Dynamic interpretation of the genesis and intensification of SAH*

Figure 5a shows that in early April, the very weak diabatic warming occurs above the BoB, the SCS and the IP. Due to the fact that weak ascending motion takes place over the IP in correspondence with feeble divergence at higher levels (Figure 2a), the SAH has not formed there yet. Over the BoB, on the other hand, the subsidence can be observed in the lower troposphere, indicating the summer monsoon has not been established there. In the early stage of SAH (Figure 5b), the diabatic heating is enhanced remarkably over the IP and upward motion is amplified profoundly and so is high-level divergence (Figure 2b), indicating that the SAH has formed initially there. At the same time, over the BoB sinking motion begins to turn to rising motion which can reach the tropopause. It is implied that the diabatic heating due to condensation is balanced by the adiabatic ascending and the heating energy transforms to the available geopotential energy. In the SAH complete construction period (Figure 5c), the latent heating gets reinforced over the IP considerably. Another latent heating center appears in the vicinity of the South China Sea. Yet with the onset of summer monsoon over the BoB, the updraft intensifies and the divergence at upper levels spreads significantly westward (Figure 2c), indicating the complete establishment of the SAH. This illustrates that the SAH genesis and enhancement bear a close relation to markedly intensified rising motion and upper-air divergence from the BoB to the IP, which are closely associated with the initiation and amplification of convection there. Consequently, it is necessary to gain further insight into the signatures of convection development (Figure 6) such that efforts are made to explore the evolutions of the atmospheric apparent heat source Q_1 and meridional circulation from the BoB to the IP in different phases of the SAH establishment (Figures 7a to 7c).

The convection development can be presented clearly in the OLR evolvement in the SAH establishment (Figure 6). Anterior to the establishment, there is little deep convection over the IP (Figure 6a), corresponding to the anticyclone on the ocean near the equator. Across the IP both the diabatic heating core and the ascending center are still on the Asian-Australian “maritime continent”, and only with the lower rising air owing to the local surface sensible heating over the IP (Figure 7a). In the SAH initial formation phase, the convection center is still on the Sumatra (Figure 7b), but the local convection over the IP is developing (Figures 6b and 7b). This is because in this phase, the surface sensible heating maximum (Figure 8b), which is corresponding to the local terrain, can lead to a lower cyclonic flow over the IP. And the lower water vapor is transported to the IP by the south wind (Figure 8a) to the east of the lower cyclone and produces the local precipitation. When the wet southerly meets the Shan Plateau, the ascending due to climbing effect of the mountain will contribute to the precipitation development. Thus, over the IP, the surface sensible heating collaborates on the local enhancing rainfall with the orographic forcing in the SAH initial formation phase. With the enhancement of local convection, the divergence increases at high levels and the SAH forms initially over the IP.

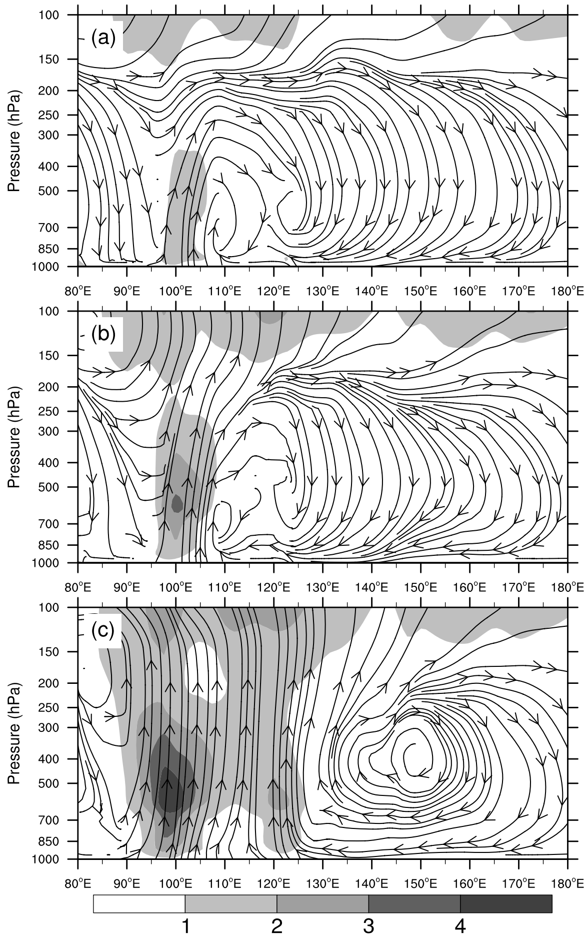

Figure 5. The longitude-height cross section of zonal circulation and diabatic heating rate Q_1 (shading, K day^{-1}) along 10-20°N in the SAH (a) pre-establishment phase, (b) initial formation phase and (c) complete construction phase.

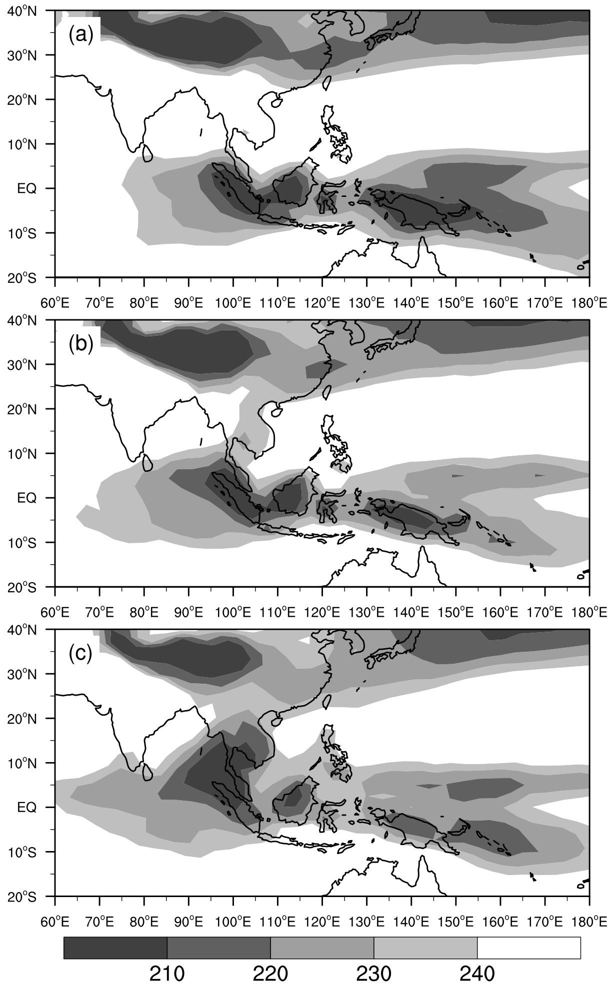

Figure 6. The evolution of OLR (W m^{-2}) in the process of SAH establishment above the IP: (a) pre-establishment phase, (b) initial formation phase, (c) complete construction phase. Shading: OLR<240W m^{-2}.

The foregoing process can be explained via Eq. (8). In the SAH initial formation phase the upper-air anticyclone is weak enough and so is the meridional wind over the IP, Thus the geographic vorticity advection is so feeble that Eq, (8) can be rewritten as

$$\frac{\partial \zeta}{\partial t} \propto \frac{f+\zeta}{\theta_z}\cdot\frac{\partial Q_1}{\partial z}, \theta_z \neq 0, \qquad (9)$$

which implies that in the SAH initial formation phase the local change of relative vorticity is produced mainly by the vertical difference of diabatic heating. From Figures 4 and 8 we can see that for $\frac{\partial Q_1}{\partial z} < 0$ at high levels, $\frac{\partial \zeta}{\partial t} < 0$, suggesting the divergence reinforcement and development of an anticyclone so that the SAH comes into its initial stage.

Furthermore in the SAH complete construction (Figure 6c), with the meridional temperature gradient strengthening, the low-valued OLR moves northward along the Asian-Australian "maritime continent" to the IP[28]. The OLR displacement represents the deep convection shifts onto the IP with the rising motion strengthening rapidly (Figure 8c). In these circumstances the localized ascending core shifts to the mid-troposphere over the IP and divergence intensifies further at high levels. While the localized convection gets amplified over the IP, a diabatic heating center moves onto there, with the rising motion intensifying quickly (Figure 8c). The strengthening latent heating and enhancing rising motion constitutes a positive feedback process. As the summer monsoon begins over the BoB, the OLR declines quickly in its eastern part and deep convection appears (Figure 6c) so that the latent heating released by condensation increases under the SAH. During this time, since the SAH has established preliminarily over the IP, the deepening of convection and development of the upper-level anticyclone make up a positive feedback system. Specifically, the strengthening of convection can help the SAH develop, and vice versa. The causality between the IP convection and the upper-level atmospheric circulation will be studied with numerical models in future. From Figures 4 and 6a, additionally, we see that before the SAH genesis over the IP, the southwest wind prevails from the BoB to the IP at high levels. While after its complete construction, the northeast flow is dominant at the high levels in this area. This indirectly demonstrates the close relationship of the SAH establishment in the IP to the onset of summer monsoon over the BoB. Moreover, when the convection becomes stronger in this period, for the presentation of stronger upper-level meridional flow, the geostrophic vorticity advection is necessary to be taken into account. Then the TUTT builds up over the ocean to the east of the Philippines. Wu et al.[40] have pointed out that there exists a positive feedback between the meridional wind of the local cyclone and the convective heating. The linkage between the atmospheric response and the TUTT formation will be explained in the next section.

4.2 *Dynamic interpretation of the developing and deepening of TUTT*

In the SAH complete construction phase, as mentioned above, the merdional flow is necessary to be included. In theory, when convection is strong, the negative vorticity production-caused geostrophic vorticity advection is induced to compensate the negative vorticity increment, and at this time the response of the circulation to latent heating has changed. In the SAH complete construction phase, the merdional wind is strong and the upper circulation is developing so that Eq. (8) is applicable. Figure 9d shows the change of the vorticity in the SAH complete construction phase. The result shows that the vorticity change is one order of magnitude smaller than the geographic advection and the vertical difference of diabatic heating. It implies that the atmospheric response is quasi-steady and the geographic advection and the vertical difference of diabatic heating is dominant in this period. The decrease (increase) with height of a heating Q_1 produces negative (positive) vorticity. Based on the thermal adaptation theory, in a steady state and in the absence of zonal advection, this must be balanced by positive (negative) geostrophic vorticity advection that is brought about by meridional winds from high (low) latitudes. Hence in the heating region above there will be an anticyclone to the west and a cyclone to the east of the heating source.

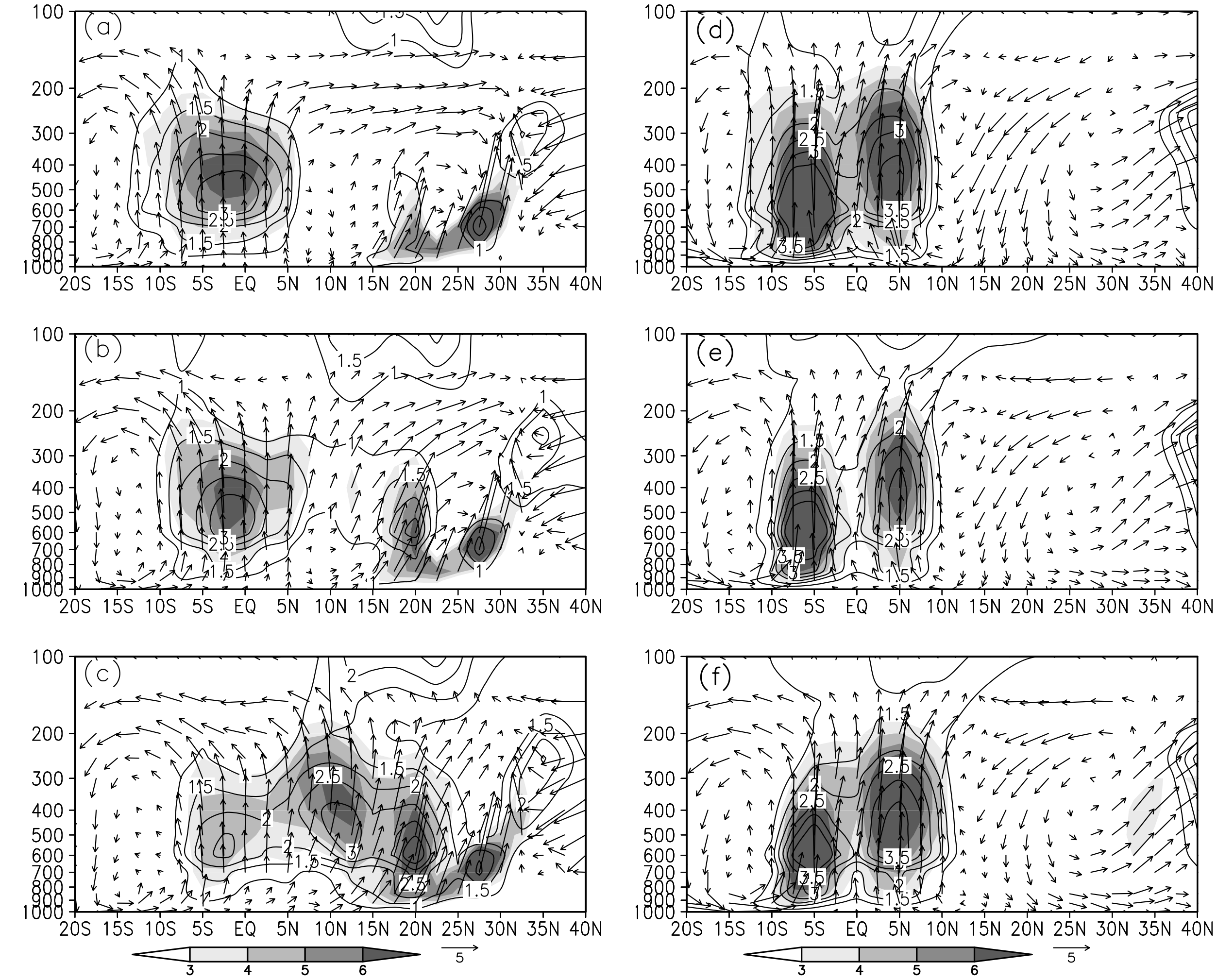

Figure 7. The height-latitude cross sections of the meridional cell (vectors, m s^{-1}), vertical velocity (shading, 10^{-2} Pa s^{-1}) and height-varying apparent heat source Q_1 (contours, W m^{-2}) along the SAH (95-110°E, left panels) and the east high-level anticyclone (140-160°E, right panels), with (a) and (d) for the pre-establishment stage, (b) and (e) for initial formation, and (c) and (f) for full genesis.

The relationship between βv and $\frac{f+\zeta}{\theta_z}\cdot\frac{\partial Q_1}{\partial z}$ have been investigated in the SAH complete construction phase. Here we concentrate on the latitudes from 10°N to 20°N where the SAH establishment and TUTT formation take place. The result of vertical difference of diabatic heating item ($\frac{f+\zeta}{\theta_z}\cdot\frac{\partial Q_1}{\partial z}$) is shown in Figure 9a. Both the maximum positive and negative values are over the BoB, where the convection is the strongest in this phase. In the upper troposphere of BoB, there exists an evident negative vertical difference of diabatic heating. According to Eq. (10), it can produce the βv configuration in the upper troposphere.

Figure 9b is the vertical distribution of the βv item. In the upper troposphere, this item represents evident negative values on the ocean where the TUTT forms, but the positive values are situated to the west of the IP. The negative value of βv is corresponding to the upper-level north wind, which transports positive geostrophic vorticity from mid-latitudes to the ocean and causes the TUTT to deepen and

Figure 9. Pressure-longitude cross sections of $\frac{\partial \zeta}{\partial t}$ (d, units: $1e^{-11}$ s^{-2}), $\frac{f+\zeta_z}{\theta_z}\cdot\frac{\partial Q_1}{\partial z}$ (a, units: $1e^{-11}$ s^{-2}), βv (b, units: $1e^{-11}$ s^{-2}) and deviation of stream function from the zonal mean (contours in c, units: $1e^{6}$ s^{-1}) as well as Q_1 (shaded in c, units: K day^{-1}) averaged from 10°N to 20°N in the SAH complete construction phase.

5 SUMMARY AND DISCUSSIONS

From the foregoing study we conclude as follows.

(1) Between late April and early May the diabatic heating features change in southern Asia, leading to the SAH genesis and intensification over the IP and the TUTT developing and deepening over the ocean to the east of the Philippines. The results show that the SAH establishes locally rather than moving westward to the IP from the ocean. Then, after the

SAH establishment, the TUTT forms in the vicinity of 150°E. The construction of the two synoptic systems is both due to the atmospheric thermal factor in Southern Asia.

(2) The SAH establishment is mainly a result of changes in the atmospheric thermal factor in southern Asia. In late April, when convection gets increased over the IP due to the local thermal effect and the topography forcing, the rising motion and divergence reinforce at high levels. The SAH forms initially over the IP in such background. At this time, the SAH remains weak, corresponding to feeble meridional air and geostrophic vorticity advection over the IP. We thus claim that the vertical difference in diabatic heating Q_1 is the dominant cause of change in high-level relative vorticity. In early May, as convection moves onto the IP along the "maritime continent", convection gets further amplified over the IP and at this time the summer monsoon begins over the eastern BoB, giving rise to strong updraft there, both of which act together to intensify the SAH rapidly and make it spread westward, thus inducing the SAH to fulfill its establishment over the IP. Besides, the SAH complete construction can make the local convection stronger through the pumping effect. Meanwhile, the reinforced anticyclone at high levels increases meridional flow there. According to the thermal adaptation theory, the equatorward air is responsible for transporting positive geostrophic vorticity advection into the region of negative vorticity production, thereby realizing the steady response of circulation to diabatic heating. During this time, the BoB diabatic heating becomes strong because of the BoB summer monsoon activity, and the stationary response is available so that the evident north wind appears in the upper troposphere and the responding cyclone to the east of SAH gives rise to the damping geopotential height, which helps the TUTT form. In fact, the formation of TUTT is at least the result of high PV transportation from mid-latitudes by the northerly of the anticyclone[41]. At the same time, the negative geostrophic vorticity advection to the west of the BoB is beneficial to the SAH strengthening and expanding westward. The SAH establishment and the TUTT formation constitute the dominant characteristic of the upper atmosphere circulation of Northern Hemisphere in boreal summer.

To sum up, the SAH establishment over the IP bears a close relation to vertically heterogeneous heating in Southern Asia. As the SAH is in its initial form, the summer monsoon begins over the BoB but when the SAH completes its genesis the SCS monsoon gets started. Hence, the SAH intraseasonal evolution relates closely to the march of monsoon in the eastern Asian area. However, Wang et al.[42] noted that the air-sea coupling in the monsoon region is of much importance to Asian summer monsoon, among other things, the atmospheric feedback on SST and it is, thus, inappropriate to view the monsoon simply as the atmospheric response to SST forcing. Since the SAH is in the Asian monsoon region, the air-sea coupling should be taken into account during the establishment. In addition, in the SAH complete construction phase the Subtropical High Belt starts splitting. It is also necessary, in the future, to investigate the linkage between the SAH establishment and the Subtropical High Belt splitting. Many factors, such as ENSO and NAO[43, 44], affect the SCS summer monsoon multi-scale climate variability[45-47]. However, the role of SAH establishment in the interannual variability of SCS summer monsoon is still unclear.

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