Vol.22 No.1 JOURNAL OF TROPICAL METEOROLOGY March 2016

Article ID: 1006-8775(2016) 01-0051-06

THERMAL FORCING IMPACTS OF THE EASTERLY VORTEX ON THE EAST-WEST SHIFT OF THE SUBTROPICAL ANTICYCLONE OVER WESTERN PACIFIC OCEAN

YAO Xiu-ping (姚秀萍)[1,2], SUN Jian-yuan (孙建元)[3]

(1. State Key Laboratory of Severe Weather (LASW), Chinese Academy of Meteorological Sciences (CAMS), Beijing 100081 China; 2. China Meteorological Administration Training Center, Beijing 100081 China; 3. Tianjin Weather Observatory, Tianjin 300074 China)

Abstract: By employing the NCEP/NCAR reanalysis data sets (1 000 to 10 hPa, 2.5° × 2.5°), the thermal forcing impacts are analyzed of an easterly vortex (shortened as EV) over the tropical upper troposphere on the quasi-horizontal movement of the Western Pacific Subtropical Anticyclone (shortened as WPSA) during 22-25 June 2003. The relevant mechanisms are discussed as well. It is shown that the distribution and intensity of the non-adiabatic effect near the EV result in the anomalous eastward retreat of the WPSA. The WPSA prefers extending to the colder region, i.e., it moves toward the region in which the non-adiabatic heating is weakening or the cooling is strengthening. During the WPSA retreat, the apparent changes of non-adiabatic heating illustrate the characteristics of enhanced cooling in the east side of the EV. Meanwhile, the cooling in the west side exhibits a weakened eastward trend, most prominently at 300 hPa in the troposphere. The evidence on the factors causing the change in thermal condition is found: the most important contribution to the heating-rate trend is the vertical transport term, followed in turn by the local change in the heating rate term and the horizontal advection term. As a result, the atmospheric non-adiabatic heating generated by the vertical transport and local change discussed above is mainly connected to the retreat of the WPSA.

Key words: diagnostic analysis; easterly vortex (EV); east-west shift of the Western Pacific Subtropical Anticyclone (WPSA); non-adiabatic heating

CLC number: P424.4 **Document code:** A

doi: 10.16555/j.1006-8775.2016.01.006

1 INTRODUCTION

From mid-June to early July, Meiyu usually occurs in the middle and lower reaches of Yangtze River and the basin of Huaihe River (shortened as "Jianghuai area" hereafter), with the characteristics of overcast weather and continuous rain. The heavy rainfall processes in Meiyu seasons are closely related to short-term shifts of the Western Pacific Subtropical Anticyclone (WPSA), who generally acts as one of the most important background circulations (Tao et al.[1]). Conversely, disturbances from internal circulation and external forcing on the synoptic scale can influence the short-term fluctuation of WPSA directly (Zhou et al.[2]; Wang et al. [3]). It is therefore important to determine factors governing the anomalies of the WPSA. Recently, more and more studies proved the importance of non-adiabatic heating effect on the formation and variation of the WPSA (Liu and Wu [4]; Wu et al.[5, 6]), especially in such regions as the Jianghuai area, South China Sea and Bay of Bengal (Wen and He[7]; Wang et al.[8]). The variation of the WPSA position during persistent severe rains in the Jianghuai area is related with the non-adiabatic heating (Wang et al.[9]). Wu et al.[10] pointed out the significance of spatially non-uniform heating on the WSPA's splitting and development. They also found that vertical non-uniform heating has stronger impacts than horizontal non-uniform heating on the formation of enclosed subtropical anticyclone centers. Liu and Yao[11] simulated the influence of vertical non-uniform heating on WPSA in a short precipitation process. Previous studies mainly focus on the effect of mid-latitude synoptic systems on WPSA, but rarely study the low-latitude system. As one of tracing factors, the easterly vortex (EV) over tropical upper troposphere is in agreement with the east-west movement of the WPSA (Zhao et al.[12]; Yao et al.[13]; Yao et al.[14-16]). Zhang et al.[17] diagnosed that spatial non-uniform heating effect was related to the reduction of the positive vorticity of the WPSA. Guo and Liu [18] analyzed the effects of a tropical storm on the occurrence of the asymmetrical instability in the subtropics. Wen and Shi [19] suggested that the condensation latent heating released by rainfall on the west side of WSPA may force an eastward withdrawal of WPSA, while the rainfall to the far west of WPSA will lead to a west-

Received 2014-12-03; **Revised** 2015-10-12; **Accepted** 2016-01-15

Foundation item: LASW State Key Laboratory Special Fund (2014LASW-A03); National Science Foundation of China (41475041)

Biography: YAO Xiu-ping, Professor, Ph.D., primarily undertaking research and teaching of synoptic dynamics.

Corresponding author: YAO Xiu-ping, e-mail: yaoxp@cma.gov.cn

ward extension of WPSA.

Previous studies indicate that the quasi-horizontal movement of WPSA is closely related to the non-adiabatic heating and their configurations. This paper analyzes the distribution of heating field over the EV in a heavy rain process during the Meiyu period, and tries to determine how the non-adiabatic heating of EV influences the quasi-horizontal movement of WPSA, which is the leading factor arousing the change of the non-adiabatic heating.

2 DATA AND METHODOLOGY

Since condensation latent heating is the major element in non-adiabatic heating effect for synoptic systems, we use the back algorithm technique by Yanai and Li[20] to calculate the apparent heating. Here, it is described in brief.

First, the apparent heating is written in the form of Q_1.

$$Q_1 = c_p \left(\frac{p}{p_{00}}\right)^{\kappa} \left(\frac{\partial \theta}{\partial t} + \vec{V} \cdot \nabla \theta + \omega \frac{\partial \theta}{\partial p}\right) \quad (1)$$

Then we can get the heating rate $Q = Q_1 / c_p$.

The vertically integrated heating rate is obtained by

$$< Q > = \sum_{p_s}^{p} Q \quad (2)$$

where p and p_s represent the top of the troposphere (100 hPa) and surface pressure respectively.

By using simple scale analysis, the complete form of vertical vorticity tendency equation (Liu et al.[21]) can be rewritten as:

$$\frac{\partial \zeta}{\partial t} = -\vec{V} \cdot \nabla \zeta - \beta v - (1-\kappa)(f+\zeta)\frac{w}{p} + \frac{1}{\theta_z}\vec{\zeta}_a \cdot \nabla Q \quad (3)$$

The last term in the equation represents a vorticity trend due to thermal forcing, which includes horizontal and vertical non-uniform heating.

Eq. (4) shows that the heating rate is related with the local change term (B_1), the horizontal advection term (B_2) and the vertical motion term (B_3).

$$Q = \underbrace{\left(\frac{p}{p_{00}}\right)^{\kappa} \cdot \frac{\partial \theta}{\partial t}}_{B_1} + \underbrace{\left(\frac{p}{p_{00}}\right)^{\kappa} \cdot \vec{V} \cdot \nabla \theta}_{B_2} + \underbrace{\left(\frac{p}{p_{00}}\right)^{\kappa} \cdot \omega \frac{\partial \theta}{\partial p}}_{B_3} \quad (4)$$

During 22-23 June 2003, the first heavy rainfall happened with the westward spreading of the bulk of WPSA. On 24 June, after the eastward retreat of the WPSA, the rainfall process ended. In the meantime, there was an easterly vortex over the tropical upper troposphere south of the WPSA (Fig.1). It is obvious that the anomalous movement of the WPSA is strongly connected with EV in this heavy precipitation process. The distribution of the non-adiabatic heating and its temporal and spatial evolution are analyzed in this paper in order to determine the role of external thermal forcing and how the thermodynamic mechanism of EV influences the quasi-horizontal movement of the WPSA. Data used in this work is a NCEP/NCAR 2.5°×2.5° reanalysis dataset, which includes 1 000 to 10 hPa daily average data.

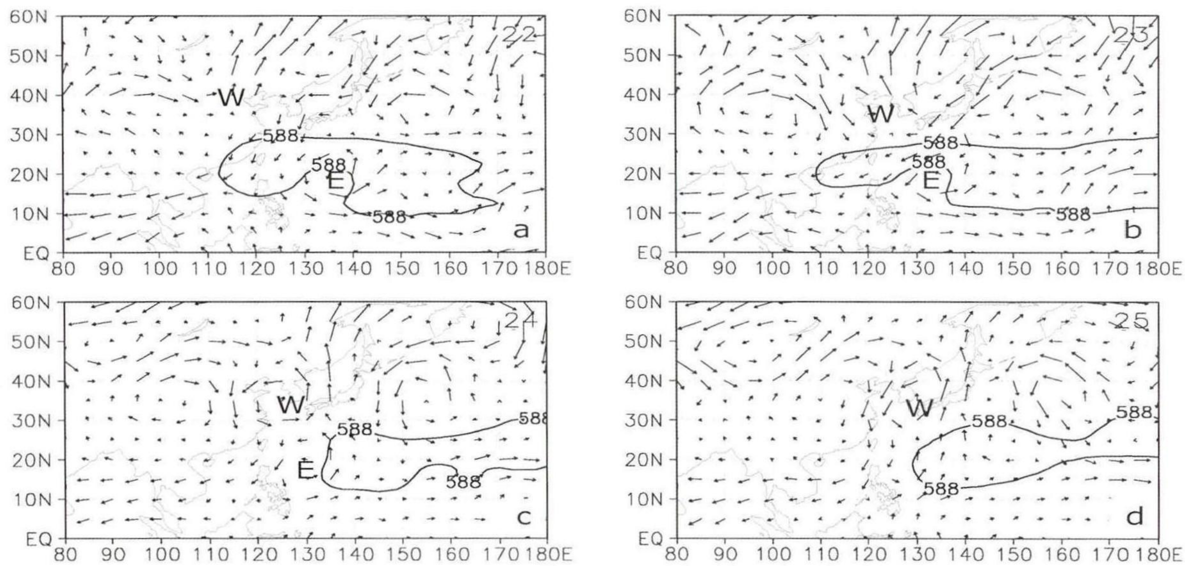

Figure 1. The 588-dagpm contour and the zonal anomalous wind vector (ms^{-1}) at 200 hPa from 22 to 25 June 2003. (a) 22 June; (b) 23 June; (c) 24 June; (d) 25 June. W and E are the central location of the EV and WV, respectively.

3 TEMPORAL-SPATIAL DISTRIBUTION AND EVOLUTION OF NON-ADIABATIC EFFECT

3.1 *The horizontal distribution and evolution of non-adiabatic effect*

From the vertically integrated non-adiabatic heating rate $< Q >$ during 22-25 June 2003 (Fig.2) we can see that the enhancement/reduction of a cool region to the west of EV is in accordance with the westward/eastward of the bulk of WPSA. Besides, the abrupt change of

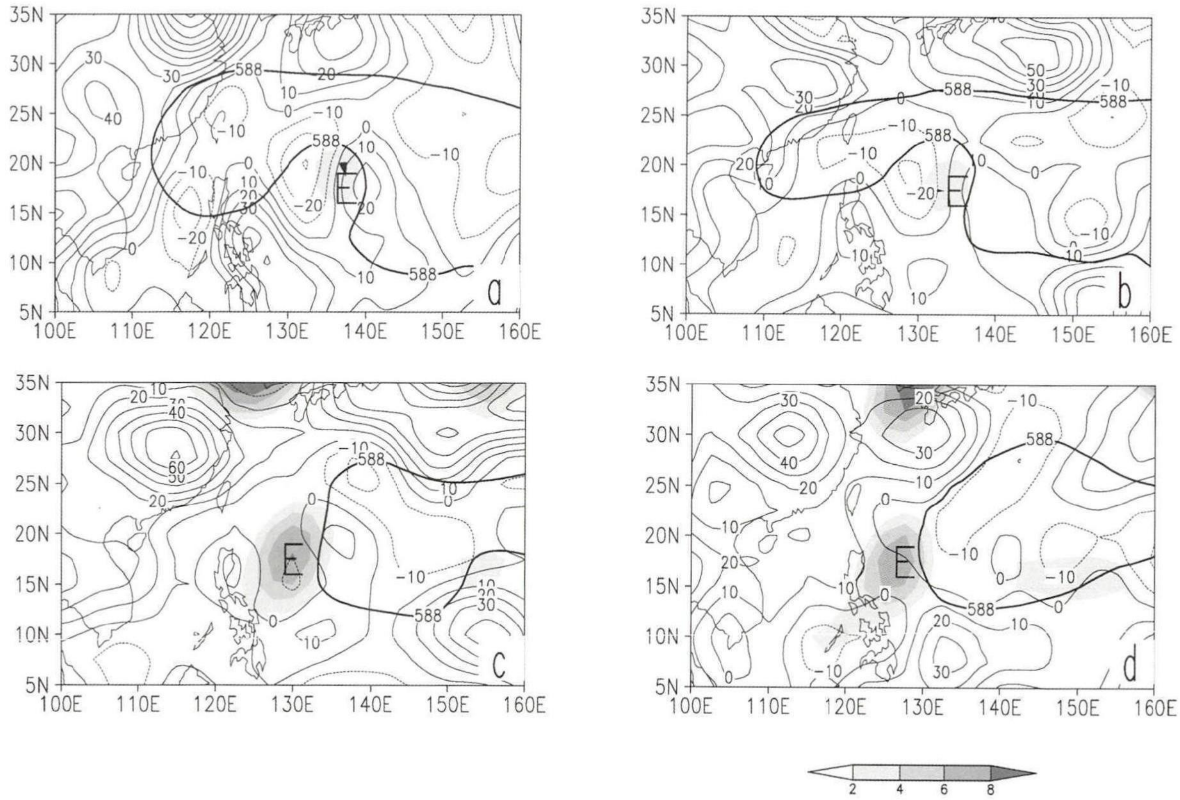

Figure 2. The vertically integrated <Q> for non-adiabatic heating rate (contour, unit: K/d) and vorticity (the shaded area, unit: $10^{-5}s^{-1}$) at 200 hPa from 22 to 25 June 2003. (a) 22 June; (b) 23 June; (c) 24 June; (d) 25 June. Thick solid line denotes the 588-dagpm contour.

non-adiabatic heating near EV is favorable to the abnormal withdrawal of WPSA for about 25 longitudinal degrees.

The cool area in the WPSA is defined as a key region here, which covers the area of 110°–140°E and 12.5°–22.5°N. Table 1 shows the averaged <Q> over the key region from 21 to 25 June 2003, and an obvious change of non-adiabatic heating effect occurs during the eastward retreat of the WPSA. The eastward retreat of WPSA is accompanied with the appearance of anomalies in thermal forcing changing from cooling to heating. It is the cooling field over the key region that induces the westward extension of WPSA. When its intensity weakens or disappears, WPSA moves eastward or splits up.

Table 1. The distribution of daily <Q> averaged over key region (110° to 140°E, 12.5° to 22.5°N) from 21 to 25 June 2003. Unit: K/d

Date	21	22	23	24	25
<Q>	-0.5	-1.7	-1.9	1.5	3.1

3.2 *The vertical distribution and evolution of non-adiabatic effect*

A zonal vertical cross section (Fig.3) of the non-adiabatic heating rate Q and vorticity was made along 17.5°N where the centre of EV lies. It shows that the most prominent EV appears at 200 hPa and a large abnormal change of the vertical distribution of non-adiabatic effect near the EV is clear when the WPSA retreats.

Furthermore, the height-time evolution of Q averaged over 5°×5° to the east of EV center is shown in Fig.4. Along with the eastward retreat of WPSA, $\frac{\partial Q}{\partial z}<0$ occurs under 300 hPa, which may lead to the decrease of cyclonic vorticity and the increase of anti-cyclonic vorticity. The vorticity trend, resulting from the enhancement of cooling at 300 hPa, is in favor of the splitting-up and eastward retreat of the WPSA at 500 hPa. Accompanying with the retreat of WPSA, an abrupt change occurs from strong heating to extreme cooling in the non-adiabatic field at 300 hPa, as shown in Fig.5.

The WPSA continuously moves westward while the intensity of non-adiabatic heating reduces, but the west-moving bulk weakens and shrinks. Changes of thermodynamic structures on the west and east sides of EV are prior to the WPSA retreat, significantly on the day when the eastward retreat happens. Thus the distribution and intensity of the non-adiabatic heating effect near the center of EV can trigger short-term eastward retreats of the WPSA.

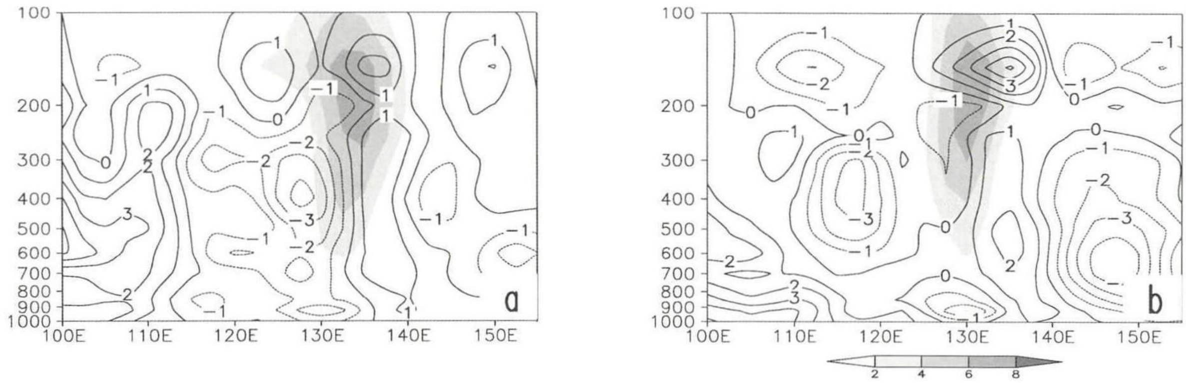

Figure 3. The zonal-vertical cross-sections of non-adiabatic heating rate Q (contour, unit: K/d) and vorticity (the shaded area, unit: $10^{-5}s^{-1}$) along 17.5°N on 23 June (a) and 24 June (b) 2003.

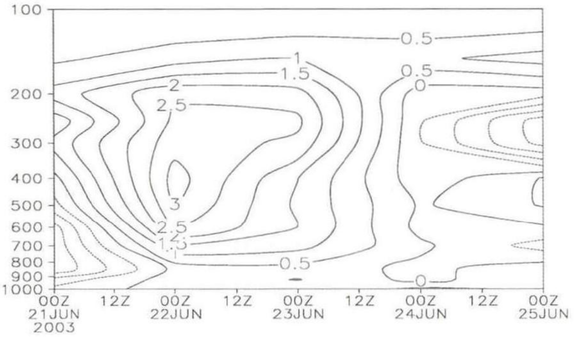

Figure 4. The height-time evolution of Q averaged over 5°×5° on the east side of the EV center from 21 to 25 June 2003. Unit: K/d. Solid line denotes Q>0. Dotted line denotes Q<0.

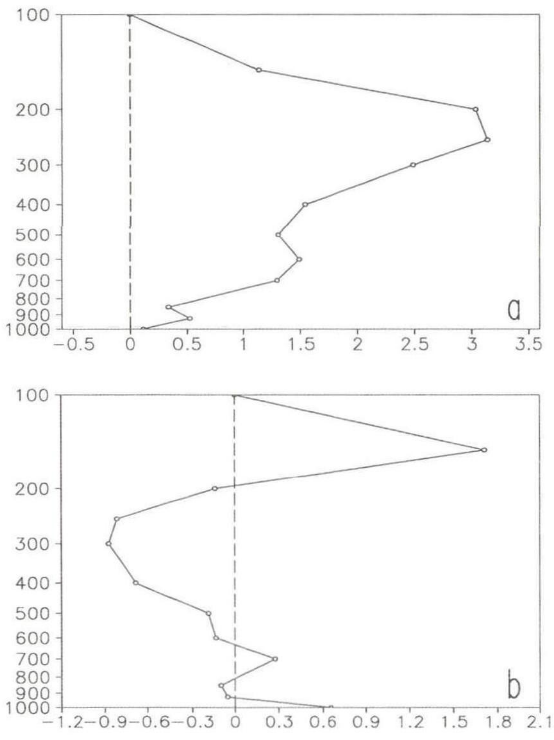

Figure 5. The profile of Q averaged over 5° on the east side of the center of EV on 23 June (a) and 24 June (b) 2003. Unit: K/d.

4 FACTORS OF NON-ADIABATIC EFFECT

In order to identify the primary factors which cause the change of non-adiabatic effect, we analyze the contribution terms at 300 hPa. According to Eq. (4), the change of thermal condition is generated by the local change term, horizontal advection term and vertical transport term.

By comparing the similarities and differences between Fig.6 and Fig.7, we discuss the horizontal pattern for all terms near the EV center and in the area of the WPSA. Results shows that the contribution to the change of heating rate near the EV from the vertical motion term is maximal, followed in turn by that from the local change term and that from the horizontal advection term. As to the reduction of heating in the WPSA, the vertical motion term is the most relevant. Therefore the leading contribution term is the vertical motion, followed in turn by the local change term and the horizontal advection term.

5 CONCLUSIONS AND DISCUSSIONS

(1) The distribution and intensity of the non-adiabatic effect near the EV can influence the quasi-horizontal movement of the WPSA.

(2) Significant change of non-adiabatic heating can be detected before and after the retreat of WPSA, with the characteristics of enhanced cooling on the east side and a weakened eastward trend on the west side of the EV, which is prominent at 300 hPa in the troposphere.

(3) The WPSA prefers to extend to the colder region, thereupon moves toward where the non-adiabatic heating is weakening or the cooling is strengthening.

(4) Among the terms contributing to the non-adiabatic heating near the EV, vertical transport is the foremost element. The local change term is the secondarily important reason leading to the abrupt retreat of the WPSA, while the horizontal advection term has the minimal effect.

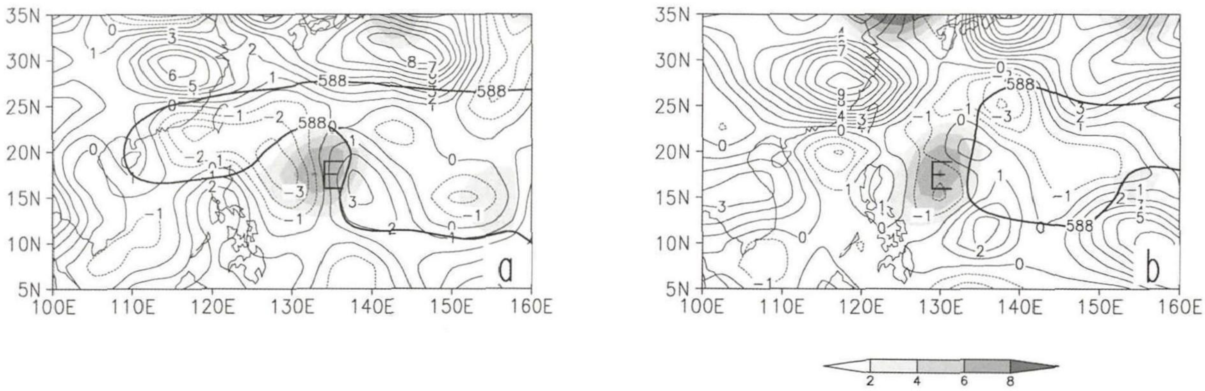

Figure 6. The non-adiabatic heating rate Q at 300 hPa on 23 June (a) and 24 June (b) 2003. The units and symbols are the same as in Fig.2.

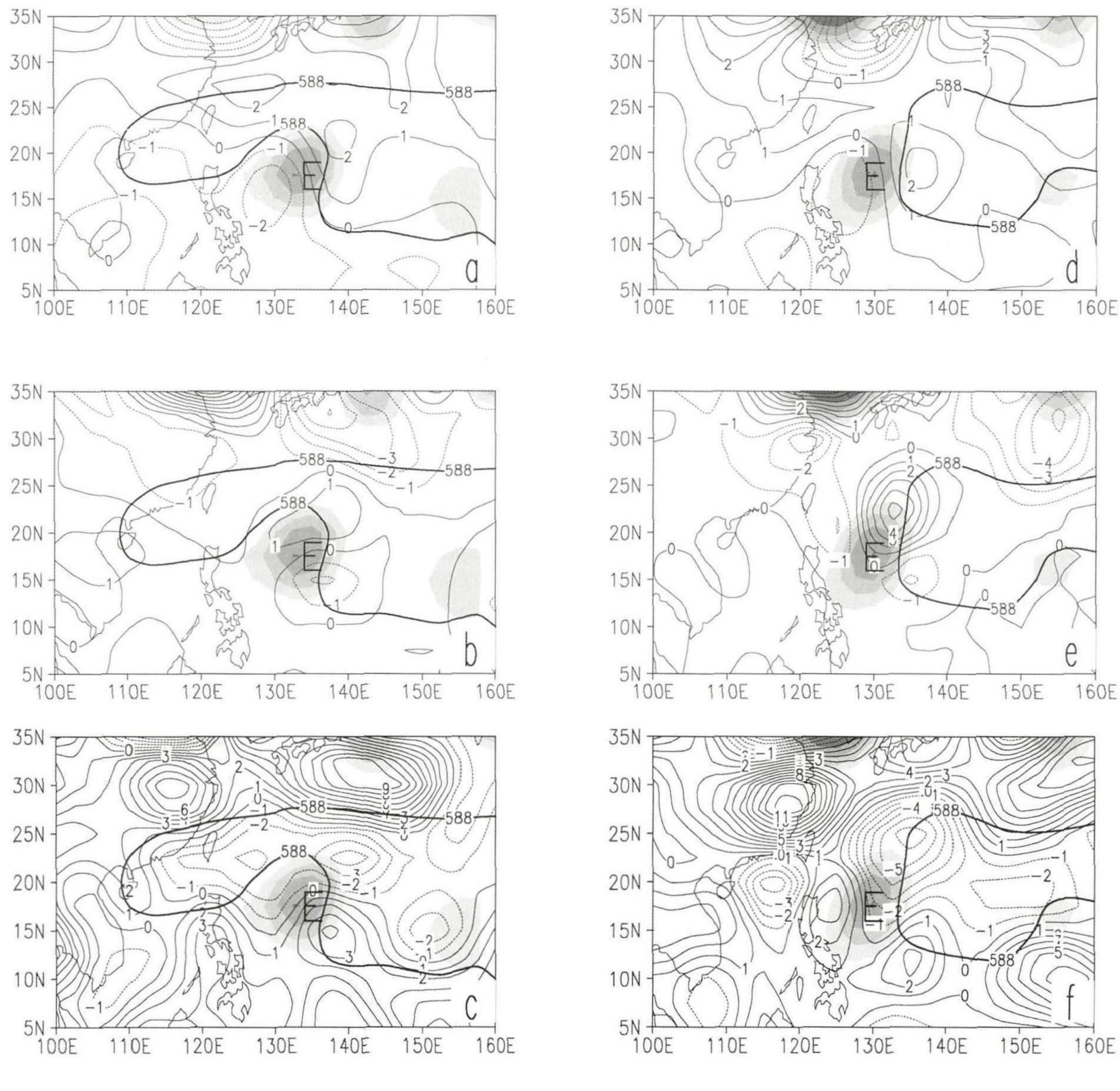

Figure 7. The contribution terms of Q at 300 hPa on 23 June (a-c) and 24 June (b-d) 2003. (a) and (d) for B_1; (b) and (e) for B_2; (c) and (f) for B_3. The units and symbols are the same as in Fig.2.

REFERENCES:

[1] TAO Shi-yan, ZHAO Si-xiong, ZHOU Xiao-ping. The research progress of the synoptic meteorology and synoptic forecast [J]. Chin J Atmos Sci, 2003, 27 (4): 451-467 (in Chinese).

[2] ZHOU Bing, HE Jin-hai, XU Hai-ming. Effect of torrential rain on variability of Subtropical High [J]. Quart J Appl Meteorol, 2004, 15(4): 394-406.

[3] WANG Li-juan, CHEN Xuan, GUAN Zhao-yong, et al. Features of the short-team position variation of the Western Pacific Subtropical High during the torrential rain causing severe floods in Southern China and its possible cause [J]. Chin J Atmos Sci, 2009, 33(5): 1 047-1 057.

[4] LIU Yi-min, WU Guo-xiong. Reviews on the study of the subtropical anticyclone and new insights on some fundamental problems [J]. Acta Meteorol Sinica, 2000, 58(4): 500-512.

[5] WU Guo-xiong, CHOU Ji-fan, LIU Yi-min, et al. Dynamics of the Formation and Variation of Subtropical Anticyclones [M]. Beijing: Science Press, 2002, 97-101 (in Chinese).

[6] WU Guo-xiong, LIU Yi-min, REN Rong-cai, et al. Relation between subtropical anticyclone and vertical motion in steady state [J]. Acta Meteorol Sinica, 2004, 62 (5): 587-597.

[7] WEN Min, HE Jin-hai. Ridge movement and potential mechanism of Western Pacific Subtropical High in summer [J]. J Nanjing Inst Meteorol, 2002, 25(3): 289-297.

[8] WANG Li-juan, WEN Min, LUO Ling, et al. The relationship between the position variation of the Western Pacific Subtropical High and the apparent heating [J]. J Trop Meteorol, 2005, 21(5): 488-496.

[9] WANG Li-juan, CHEN Xuan, GUAN Zhao-yong, et al. Relationship between the position variation of the Western Pacific Subtropical High and the diabatic heating during persistent heavy rain events in Yangtze-huaihe River Basin [J]. J Trop Meteorol, 2011, 27(3): 327-335 (in Chinese).

[10] WU Guo-xiong, LIU Yi-min, LIU Ping. The effect of spatially non-uniform heating on the formation and variation of subtropical high. I: Scale analysis [J]. Acta Meteorol Sinica, 1999, 57 (3): 257-263 (in Chinese).

[11] LIU Huan-zhu, YAO Ming-ming. Numerical simulation on the precipitation and variation of the location and intensity of the subtropical high [J]. Quart J Appl Meteorol, 2000, 11(4): 385-391 (in Chinese).

[12] ZHAO Bing-Ke, YAO Xiu-Ping, WU Guo-Xiong. The structure and activity characteristics of the Western Pacific Subtropical Anticyclone and its dynamical mechanism during the Meiyu period over the Huaihe River Basin in 2003 [J]. Chin J Atmos Sci, 2005, 29(5): 771-779.

[13] YAO Xiu-ping, WU Guo-xiong, LIU Yi-min, et al. Case study on the impact of the vortex in the easterlies over the tropical upper troposphere on the Subtropical Anticyclone over Western Pacific Ocean [J]. Acta Meteorol Sinica, 2007, 65(2): 198-207 (in Chinese).

[14] YAO Xiu-ping, WU Guo-xiong, LIU Yi-min, et al. Case study on the impact of the vortex in the easterlies in the tropical upper troposphere on the Western Pacific Subtropical Anticyclone [J]. Acta Meteorol Sinica, 2009, 23 (3): 363-373.

[15] YAO Xiu-ping, WU Guo-xiong, LIU Huan-zhu. Structural and evolution characteristics of the easterly vortex over the tropical region [J]. J Trop Meteorol, 2008, 14(1): 85-88.

[16] YAO Xiu-ping, WU Guo-xiong, LIU Huan-zhu. Structural and evolution characteristics of the easterly vortex over the tropical region [J]. J Trop Meteorol, 2008, 14(1): 85-88.

[17] ZHANG Qin, YAO Xiu-ping, SHOU Shao-wen. The composite analysis of the relationship between the abnormal retreat of the subtropical anticyclone over the Western Pacific Ocean and the easterlies vortex in Meiyu Period [J]. Chin J Atmos Sci, 2011, 35(1): 29-40.

[18] GUO L, LIU Y. The effect of diabetic heating on asymmetric instability and the Asian extreme climate events [J]. Meteorol Atmos Phys, 2008, 100: 195-206.

[19] WEN Min, SHI Xiao-hui. Relationship between activity of the Western Pacific Subtropical High and condensation latent heating in summer of 1998 [J]. Plateau Meteorol, 2006, 25(4): 616-623.

[20] YANAI M, Li C. Mechanism of heating and the boundary layer over the Tibetan Plateau [J]. Mon Wea Rev, 1992, 122(21): 305-323.

[21] LIU Yi-min, WU Guo-xiong, Liu Hui. The effect of spatially non-uniform heating on the formation and variation of subtropical high. III: Condensation heating and South Asia high and western Pacific subtropical high [J]. Acta Meteorol Sinica, 1999, 57 (5): 525-538 (in Chinese).

Citation: YAO Xiu-ping, SUN Jian-yuan. Thermal forcing impacts of the easterly vortex on the east-west shift of the subtropical anticyclone over western Pacific Ocean [J]. J Trop Meteorol, 2016, 22(1): 51-56.