THE POSITION VARIATION OF THE WEST PACIFIC SUBTROPICAL HIGH AND ITS POSSIBLE MECHANISM

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ABSTRACT: Using NCEP/NCAR daily reanalysis data and SCSMEX data, an investigation is carried out of the relationship between the position variation of the west Pacific subtropical high (WPSH) and the apparent heating in June 1998 based on the complete vertical vorticity equation. It is found that the non-adiabatic heating plays an important role in the position variation of WPSH. In comparison with climatic mean status, the vertical change of non-adiabatic heating is stronger in the north side of WPSH in June 1998, but weaker in the south side of WPSH. The anomalous non-uniform heating induces anomalous cyclonic vorticity in South China, areas to the south of the Yangtze and its mid-lower valleys, but anomalous anticyclonic vorticity in the Indo-China Peninsula and South China Sea areas lead to the more southward position of WPSH than the mean.

Key words: West Pacific subtropical high; position variation; apparent heating

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1 INTRODUCTION

The seasonal shift of the western Pacific subtropical high (WPSH thereafter) has close relationship with East Asian monsoon and monsoon rainbands, and it is one of the important roles to control the weather and climate in the east area of China by its location and strength variation. In particular, WPSH west-east location and north-south movement are responsible for East Asian monsoon formation, precipitation over the Yangtze River valley and air temperature and precipitation in north and south China [1-2]. In 1998, keeping a more southward and westward location and not withdrawing from South China Sea (SCS) until mid-May, WPSH subsequently did not jump northwards but maintained south of 30°N instead, leading to a later onset of a weaker South China Sea monsoon that resulted in a famous flood year for longer Mei-yu period in the Yangtze River valley and more precipitation [3-4]. More eastward extension of WPSH is favorable for a Mei-yu decrease, even drought in the Yangtze River valley, and there is high temperature persistence in North China. Huang et al. [6] suggested diabatic heating be an important mechanism for forming and maintaining monsoon. As a primary member of the East Asian monsoon, WPSH associates closely to diabatic heating and its west-east and north-south shifts, to a large extent, is due to the spatial patterns of diabatic heating. Wu et al. [7-9] also pointed out that the diabatic heating induced by the East Asian monsoon is a key role affecting the summer subtropical high locations and intensity over the Northern Hemisphere. Thereby in this paper, through comparisons between the severe flood in 1998 and long-term mean pattern, the effects of atmospheric apparent heating source distribution on the location of WPSH and its shift are mainly studied, and the complete form of vertical vorticity equation is used to explain how inhomogeneous heating affects the shape of WPSH. With some factual bases and ideas to predict the summer WPSH variation and flood/drought, the current study can provide a better understanding of the physical cause of flood in the Yangtze River valley due to the shift of WPSH location.

2 DATASETS AND METHODS

The daily NCEP/NCAR reanalysis and 1998
SCSMEX datasets with 2.5°×2.5° horizontal resolution and 1°×1° gridded TBB data from Japan Meteorological Agency are used in this paper.

2.1 Heating source calculation

Atmospheric heating source \( Q_i \) in the paper is calculated as follows

\[
Q_i = c_p \left( \frac{dT}{dt} + \nabla \cdot \mathbf{v} + \frac{dP}{dt} \right) + \frac{\partial}{\partial p} \left( S \partial \omega / \partial p \right) \tag{1}
\]

where \( \kappa = R/c_p \), \( R \) and \( c_p \) are the constants for dry air gas and specific heat at constant pressure respectively and \( \theta \) is the potential temperature. The three terms in the right brackets describe local variation, horizontal advection and vertical transport separately. \( Q_i \) denotes the heating rate per unit time and mass. Eq.(1) can be rewritten as

\[
Q_i = Q_r + L(\bar{e} - \bar{e}) - \frac{\partial}{\partial p} \left( S \partial \omega / \partial p \right) \tag{2}
\]

Eq.(2) is integrated from \( p_r \) (100 hPa) to \( p_s \) (surface pressure) in the whole layer and reaches the following form of

\[
\langle Q_i \rangle = \langle Q_r \rangle + LP + SH \tag{3}
\]

where \( \langle \rangle = \frac{1}{p_s} \int p \langle Q_i \rangle dp \). It can be seen that the atmospheric apparent heating source \( \langle Q_i \rangle \) is consisted of radiative heating (cooling) \( \langle Q_r \rangle \), latent heating from precipitation \( LP \) and surface sensible heating \( SH \).

2.2 Computing inhomogeneous heating-induced vorticity production rate

The complete form of vertical vorticity equation (Wu and Liu\[11\]) can be written as

\[
\frac{\partial \zeta}{\partial t} + \nabla \cdot \mathbf{v} + \frac{\partial}{\partial x} \left[ \frac{f + \xi}{R} \right] \frac{\partial}{\partial y} \frac{\partial Q}{\partial \theta} + \frac{f + \xi}{\theta} \frac{\partial}{\partial z} \frac{\partial Q}{\partial \theta} \tag{4}
\]

where \( \zeta = \frac{\partial \theta}{\partial z} \), and others are weather symbols in common use. Respectively, the first four terms on the right-hand side represent the vertical motion, heating source, internal variation in the atmospheric thermodynamics and effect of frictional dissipation on vorticity; the last three terms on the right-hand side are contributions from inhomogeneous heating. Taking no account of the effects of internal variation in the atmospheric thermodynamics, heating source and frictional dissipation but only the apparent heating source \( Q_i \), Eq.(4) can thus be rewritten as

\[
\frac{\partial \zeta}{\partial t} + \nabla \cdot \mathbf{v} + \frac{\partial}{\partial x} \left[ \frac{f + \xi}{R} \right] \frac{\partial}{\partial y} \frac{\partial Q}{\partial \theta} \tag{5}
\]
From scale analysis [7], the vertical motion and horizontal inhomogeneous heating induced by the atmospheric apparent heating source are at \(10^{-11} - 10^{-12}\) order of magnitudes, which is one order of magnitude or more smaller than the forcing by apparent heating source vertical variation \(10^{-10}\). Then, Eq.(5) is changed to

\[
\frac{\partial \xi}{\partial t} + \nabla \cdot \nabla \xi + \beta v = \left(f + \xi \right) \Omega \frac{\partial \theta}{\partial \zeta} + \frac{1}{\theta} \frac{\partial \Omega}{\partial \zeta} \frac{\partial \theta}{\partial \zeta} + \frac{1}{\theta} \frac{\partial \Omega}{\partial \zeta} \frac{\partial \theta}{\partial \zeta} \frac{\partial \theta}{\partial \zeta}.
\]  

(6)

In the Northern Hemisphere, \(f = 2\Omega \sin \phi\) is always larger than zero and increases by latitude. Generally, \(f + \xi \geq 0\) in large-scale motion and \(\theta = \partial \theta / \partial \zeta\) is also positive.

3 CHARACTERISTICS OF PRECIPITATION, GEOPOTENTIAL HEIGHT AND CONVECTION IN JUNE 1998

From the difference of precipitation between 1998 and climatological mean (Fig.1), we can see that positive anomalies represent more rainfall from South China to Yangtze River Valley and the opposite is true for the South China Sea. Fig.2 shows the 5880 gpm contours of WPSH at the 500-hPa level in 1998 and climatological June. It is obvious that WPSH in 1998 distributed along a west-east zone, spanning about 15 latitudes, with the ridge staying around 15°N and west-extending point around 110°E. Comparing with the climatological mean, the WPSH ridge in 1998 shifted southwards about 5 latitudes and the 5880-gpm contour extended westwards by about 20 longitudes, controlling the South China Sea region. As a primary cause, WPSH anomalies induced above-normal precipitation over the Yangtze River Valley and below-normal precipitation over the South China Sea.

With clouds covering, TBB (black body temperature) reflects the cloud top temperature while it captures the surface temperature in cloudless sky. In general, lower TBB corresponds to robust convection and higher TBB to the regions without clouds. For climatological mean (figure omitted), high TBB regions, in east-west belt shape, are in the subtropical region west of 120°E, and its axis of high values lies around 20°N, showing consistency with simultaneous WPSH extent represented by climatological mean height. So it is appropriate to use the 275-K contour to describe the WPSH region. Fig.3 shows TBB for June 1998. It is different from the climatological situation that high TBB in June 1998 extended near 110°E and the SCS area was under the control of WPSH. Thus, WPSH featured more westward location, which is consistent with the result of analysis of geopotential height and precipitation.

4 RELATIONSHIP BETWEEN SPATIAL DISTRIBUTION OF DIABATIC HEATING AND LOCATION OF WPSH

There are complex interactions between WPSH and convective heating on the east/west sides and north/south sides. By scale analysis and numerical simulations based on the complete form of vertical vorticity tendency equation, Wu et al. [7-9] confirmed that condensation latent heating had an important role to play in determining the summertime location of Eastern Hemispheric WPSH. Thus, this section will focus on the effects of convection-induced diabatic heating on WPSH anomalies in June-July 1998 and the difference from the climatological mean. It is noted that once the east, west, north and south locations of WPSH were
known, its area is usually determined. Thereby, the effects of diabatic heating on WPSH location, mainly discussed in this paper, also reflect the effects on WPSH strength (area).

Fig.4 shows that WPSH shifts along a north-south direction in June and July. As for the climatological mean (Fig.4a), there is, through the year, a strong heating center south of WPSH that is much stronger than the north side of WPSH. That is due to continuous convective development at ITCZ south of WPSH. WPSH moves northward by season, and during different periods, there is various heating distribution in WPSH ridge and the north of it. In the first ten days of June, WPSH withdrew eastwards and located east of 130°E after the onset of summer monsoon, and convection developed on the west of WPSH (120-130°E) due to weak western ridge and a corresponding weak heating appeared over the WPSH region at 120-150°E. In the middle ten days of June, along with northward movement, WPSH located over a cooling area where radiative cooling and upward sensible heating were dominant, and in the heating area of the subtropical monsoon rainband north of WPSH, \( Q \) significantly increased. It is noted that the contour of 5880 gpm only appeared during this period, which suggests a strongest WPSH at that time. The area encircled by the 5880 gpm contour was corresponding to descending cloudless region, which was thus surrounded by the zero heating contour. Different from the climatology, the WPSH ridge steadily maintained at about 20°N in the first half month of June 1998 (Fig.4b), and there was strong heating north of WPSH and relatively weak convection in the ITCZ south of WPSH. When the convection north of WPSH is stronger than south of it, it is favorable for WPSH to withdraw southward. There was radiative cooling responsible for negative \( Q \) in the region controlled by WPSH. It is noted that latent heating south of WPSH extended northwards twice as WPSH shifted northwards around 16 June and 21–26 June (As shown
by arrows in Fig.4b). It implies that the northward extending of latent heating is in favor of WPSH moving northwards. In addition, around 20 July, remarkably increased $Q_1$ between 25°N and 30°N may response to the second Meiuy of Yangtze River valley.

Fig.5 shows the east-west shift of WPSH in June and July. Climatological southern boundary of WPSH advanced continuously from 15°N to 20°N (Fig.5a), with convection developing south of WPSH (15-20 °N). While there is weak heating in the WPSH area at 15–30°N, and the area encircled by the 5880 gpm contour was in good agreement with the zero heating contour (light shadows represent the area with 500-hPa geopotential height larger than 5870 gpm, and heavy shadows denote the area with 500-hPa geopotential height exceeding 5880 gpm). In comparison with the climatology, westward extension characterized WPSH in June 1998 (Fig.5b, where the areas with the 500-hPa geopotential height exceeding 5880 gpm are shaded). In the first ten days of June, the western ridge point of WPSH located east of 120°E (especially east of 130°E before 6 June); from 11 to 16 June, WPSH extended westward (as shown by solid arrows in Fig.5b), and then moved quickly eastward and again extended to the west of 110°E around June 26th. Temporally, the processes agreed very well with the two northern jumps of WPSH mentioned above. It is noted that there is larger heating to the west of WPSH than in the WPSH itself and remarkably enhanced heating to the west of WPSH is always in company with subsequent western extension. During July 11th to 16th, the processes of WPSH western extension exhibited the same characteristic (As shown by dotted arrows in Fig.5b).

In general, there is relatively weak heating in the WPSH area surrounded by the 5880 contour and the WPSH center is usually a cooling area.

5 DIABATIC HEATING FORCING FOR FORM CHANGING OF WPSH

5.1 Heating effects of north and south of WPSH on its southward and northward movements

At the south (north) side of WPSH (south: 110–
150°E, 10–15°N; north: 110–150°E, 30–35°N), easterly (westerly) was prevalent ($v \approx 0$), and vorticity advection along the $x$ axis was quite weak. Following Eq.(6), we obtain that

$$\frac{\partial \xi}{\partial t} + f + \frac{\xi}{\theta_e} \frac{\partial Q}{\partial \xi} > 0,$$

so $(\frac{\partial \xi}{\partial t})_a > 0$; while at the upper layer,

$$\frac{\partial \xi}{\partial t} + f + \frac{\xi}{\theta_e} \frac{\partial Q}{\partial \xi} < 0,$$

so $(\frac{\partial \xi}{\partial t})_u < 0$. Thereby, the heating induced by convective precipitation at the north side is favorable for the development of lower-layer cyclonic vorticity that depresses its northward movement and increased upper-layer anti-cyclonic vorticity that helps it move northwards, which leads to a polar-ward slope of the WPSH ridge axis. In contrast, the heating at the south side produces lower-layer cyclonic vorticity (upper-layer anti-cyclonic vorticity) that helps WPSH to move northward at the lower layer (southward at the upper layer), making the WPSH ridge axis sloping up towards the equator. In this sense, the northward and southward movements of WPSH depend on the magnitudes of vertical variation of diabatic heating at the north side relative to the south side. When heating rate at the south side is larger than the north one, WPSH is in favor of moving northward, whereas WPSH moves southward when the heating rate at the north side is larger.

Fig.6 (a, b) shows day-to-day evolution of $\frac{f + \xi}{\theta_e} \frac{\partial Q}{\partial \xi}$ at the north and south sides of WPSH at 500 hPa for the climatological mean (the solid line) and June 1998 (the dashed line). unit: $10^{-12} \text{s}^2$. 

Fig. 6 Day-to-day evolution of $\frac{f + \xi}{\theta_e} \frac{\partial Q}{\partial \xi}$ at the north (a, 110–150°E, 30–35°N) and south (b, 110–150°E, 10–15°N) sides of WPSH at 500 hPa for the climatological mean (the solid line) and June 1998 (the dashed line). unit: $10^{-12} \text{s}^2$. 


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500 hPa for the climatological mean and June 1998, respectively. The northern heating rates for June 1998 have larger vertical variation than the climatology most of the time, namely \( \frac{f + \xi}{\theta_e} \frac{\partial Q}{\partial z} > \frac{0}{\theta_e} \) at 500 hPa due to the vertical variation of the diabatic heating in June 1998. This is unfavorable for the northward movement of WPSH; whereas, the southern heating rates have smaller vertical variation than the climatology in all time except the end of June, namely \( \frac{f + \xi}{\theta_e} \frac{\partial Q}{\partial z} < \frac{0}{\theta_e} \) at 500 hPa due to the vertical variation of the diabatic heating in June 1998, which is favorable for the anomalous increase of anti-cyclonic vorticity at the south side of WPSH and southward movement. With the effects of both north and south diabatic heating, the WPSH extended more southwards in June 1998.

5.2 Anomalous distribution of vorticity production rates resulting from diabatic heating at 500 hPa

In order to further explain the effects of the vertical variation of diabatic heating on the locations and intensities of WPSH, the anomalous distribution of vorticity production rates \( \frac{f + \xi}{\theta_e} \frac{\partial Q}{\partial z} \) at 500 hPa due to the vertical variation of the diabatic heating in June 1998 are shown in Fig.7. It can be seen from the figure that there are positive production rates of vorticity in South China, south of the lower reaches of the Yangtze River, middle and lower reaches of the Yangtze River and North China, which is favorable for convective activity and precipitation. Indo-China Peninsula and South China Sea mainly have negative anomalies, which is beneficial to the westward extension and southward movement of WPSH. It is consistent with the distributions of height, precipitation and TBB, and confirms the effects of anomalous diabatic heating on the form and intensity anomalies of WPSH.

6 CONCLUSIONS

(1) The subtropical diabatic heating plays an essential role in the location changes of WPSH. In contrast to the climatology, enhanced heating at the north side of WPSH and depressed ITCZ convection at the south side of WPSH in June of 1998 are favorable to the southward movement of WPSH, for the north convection is stronger than the south. Along with the northward movement of WPSH, the convective latent heating extends northwards from its south area, which is in favor of the northward movement of WPSH.

(2) The heating west of WPSH is generally larger than that inside the latitudes of WPSH in June 1998 and each of the westward extension of WPSH corresponds to a significantly enhanced heating west of WPSH and the latter is prior to the former.

(3) The vertical variation of heating rates north of WPSH are larger than the climatology in most of June 1998, which is unfavorable for WPSH to move northward. On the other hand, the vertical variation of heating south of WPSH is mainly less than the climatology in June 1998, which is favorable for the anomalous increase of anti-cyclonic vorticity south of
WPSH and southward movement. The heating north and south of WPSH work together to make WPSH extend more southward in June 1998.

REFERENCES:


