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IMPACT OF THE HEATING OVER SOUTH ASIA UPON THE SUBTROPICAL HIGH OVER WEST-PACIFIC*

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ABSTRACT

A case is reported, during which the Subtropical High over the Western Pacific (hereafter. SHWP in abbreviation) shifted northwestward and mei-yu at Changjiang River valley ended. Several numerical experiments on SHWP activity influenced by the heating over south Asia monsoon area are carried out, and the statistic significance of the results is checked. The results indicate that the enhancement of positive heating over South Asia will motivate a wave-like series of anomaly centers, which propagate northeastward from the maximum heating center. so that a strong positive potential height anomaly center will set up from North China to Japan at Day 3, resulting in the enhancement of SHWP. Comparison of the influence upon SHWP by the heating over south Asia monsoon area with that over ITCZ area south to SHWP is also carried out. It is pointed out that the heating over South Asia monsoon area tends to favor SHWP northward movement while the heating over ITCZ area tends to favor SHWP westward stretching. As for the time to begin to influence on SHWP, the heating over south Asia monsoon area favors the enhancement of SHWP after Day 3 while that over ITCZ south to SHWP effects after Day 5.

Key words: heating over south Asia monsoon; west Pacific subtropical high; numerical experiments

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I . INTRODUCTION

The subtropical high over western Pacific (SHWP) is the circulation system that most severely influences the weather and climate in China. The research on the impact factors of SHWP is of interest for many researchers. Tao and Zhu (1964) point out that the shift of SHWP relates to the long wave adjustment. Yu and Zhao (1993) have studied the relationship between east Asia monsoon and south Asia monsoon by comparison of heating fields and circulation characteristics of two intra-seasonal transferring processes of SHWP, during one of which SHWP persists in a south position but in a north position in the other. Zhong (1991), using a hybrid-coordinate, 5-level primitive equation model, simulates the impact on east-west movement of SHWP of the heating over ITCZ south to it and that over the monsoon rain belt over Changjiang-Huaihe river basin in China individually. He concludes that both of the heating favors the westward shift of SHWP. Huang (1986) studies the relationship between the activity of SHWP and SSTA over the South China Sea and western Pacific east of the Philippines by means of observation, theoretical analyses and numerical simulation. Both observational studies (Huang

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and Yu, 1962) and numerical experiments (Yang and Huang, 1989) indicate that the enhancement of Austrian High will result in the enhancement of SHWP, because it will induce the strengthening of across-equatorial flow thus the increase of convective activity around the Philippines and Hadley cell.

The problem how the SHWP is influenced by the synoptic processes over south Asia deserves more study. Chen, Zhu and Luo et al.(1991) consider that both monsoon systems and their perturbation vary first over east Asia and then propagate into south Asia. The India monsoon is weak when SHWP moves westward or northward. Murakami, Chen and Xie (1986) have found that the phase of heating over Bay of Bengal is opposite to that over Philippines by means of EOF analysis of low-frequency components of OLR. It can be inferred easily that strong south Asia monsoon does not favor the enhancement of SHWP considering the connection between the convective activity around Philippines and SHWP. But Guo and Wang (1988) pointed out that the precipitation in India monsoon area is positively related to that in North China, and that SHWP becomes strong and move northward when Indian monsoon becomes strong. It can be concluded that the enhancement of south Asia monsoon will favor the enhancement and northward movement of SHWP during mei-yu range. Zhuang and Ji (1997) showed that the enhancement of heating over south Asia monsoon area will favor the enhancement of SHWP by both observation studies and numerical experiments using a barotropic model. Therefore how the activity of SHWP is influenced by south Asia monsoon is not yet clear. This paper will investigate the impact of the heating over south Asia monsoon area upon SHWP using a numerical model, in comparison with that over ITCZ region south to SHWP.

II. DESCRIPTION OF NUMERICAL EXPERIMENTS

In order to analyze the impact upon SHWP of south Asia monsoon, one simple experimental method is to change the synoptic systems over south Asia in the model and then compare the difference of SHWP. The method is suitable in barotropic model, but in baroclinic model, which can describe real synoptic processes better, one will have to encounter with a series of problems such as the coordination between height and temperature field, between upper and lower level systems, and the treatment of boundary. Now we devise a new experimental method in terms of heating.

The basic idea is as below. First, choose a real synoptic process, during which SHWP shift northward, and calculate global heating distribution by the thermodynamic equation, then conduct a forecast (Exp.1) for this process using an extended range model. If the evolution of the forecast SHWP is similar to that in reality, then another forecast (Exp.2) will be carried out by the model but without diabatic physical processes except the constant process-averaged heating. If the evolution of SHWP by the later forecast is also similar to that by control run, then the third forecast (Exp.3), same as the second forecast only except without heating over south Asia, is done. Therefore the impact of south Asia upon SHWP can be inferred by comparing the second run with the third run.

The adopted model is IAP T42L9, a global spectral model developed by Ji et al.(Ji, Chen, Zhang et al., 1990; Zhang, Li and Ji et al., 1995). Its dynamic frame was, on the basis of ECMWF model, formed by introducing hydrostatic extraction, in horizontal triangle truncated wave number 42, in nine vertical levels, using terrain-following Sigma coordinate(σ $=p/p_S$). The main physical processes include radiation, vertical turbulent transfer, surface process, large-scale condensation and cumulus convection, horizontal diffusion, subgrid-scale gravity wave drag, etc., and their parameterization is seen in Zhang et al. (Zhang, Li and Ji et al., 1995). The model has good performance so that some complex synoptic processes, such as the termination of mei-yu, the northward shift of subtropical high, the evolution of tropical storms, can be well forecasted .

The initial fields used in the experiments here are selected from the assimilation dataset of National Meteorological Center of China on 12UTC 5 July 1995. The model is integrated 7 days forward in time with output every 3 hours in order to get enough samples for significance check. Below are the experiments in detail.

Exp.1,i.e. a control run, including all physical processes.

Exp.2, a run that removes all model diabatic physical processes but retains mean heating from 5 to 12 July instead. The heating here should be interpolated into Sigma level of the model.

Exp.3, the run same as Exp.2 except for removal of the heating over south Asia. At the boundary no smoothing has been done.

Exp.4, the run same as Exp.2 except for removal of the heating over ITCZ region south to SHWP with the boundary as Exp.3.

The areas to discard heating for Exp.3 and Exp.4 were formed in Fig.1 considering two factors, i.e. (1) situating in south Asia and ITCZ south to SHWP and (2) including corresponding positive heating centers. Exp.4 aims to check the impact upon SHWP of heating over ITCZ south to SHWP and provides comparison basis for Exp.3.

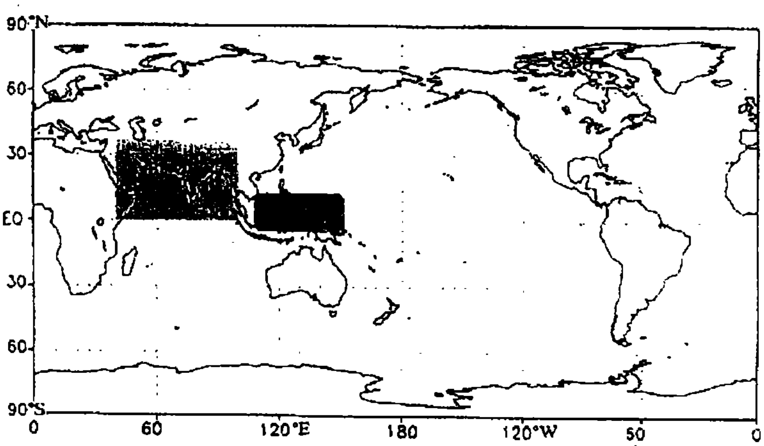

Fig.1 The regions in which heating is eliminated in Exp.3 and Epx4, with big shaded windows standing for Exp.3 and small dense windows for Exp.4

III. DESCRIPTION OF THE CASE SELECTED AND THE CONTROL RUN

1. *The mei-yu ending process in July 1995*

The mei-yu of 1995 ended on 8-9 July basing on the analysis of Chinese Central Weather Service. The analysis below shows that the evolution of Eurasia circulation of height field during this process is typical at 500hPa. On 5 July (Fig.2a) the west boundary of the contour 588 of SHWP situated over south China with west ridge-point at 112 ^{O}E and the north boundary of 592 at 31^{O}N, 1-2 latitudinal degree south to Japan, and the center of main body of SHWP at 142 ^{O}E. A typical "twin blocking" circulation over Eurasia is clear. On 6 July (Fig.2b) the most evident change was the weakening of the blocking over Okhotsk Sea compared with 5 July, and the center enclosed by the contour 568 no longer existed again. On 7 July (Fig.2c) the circulation

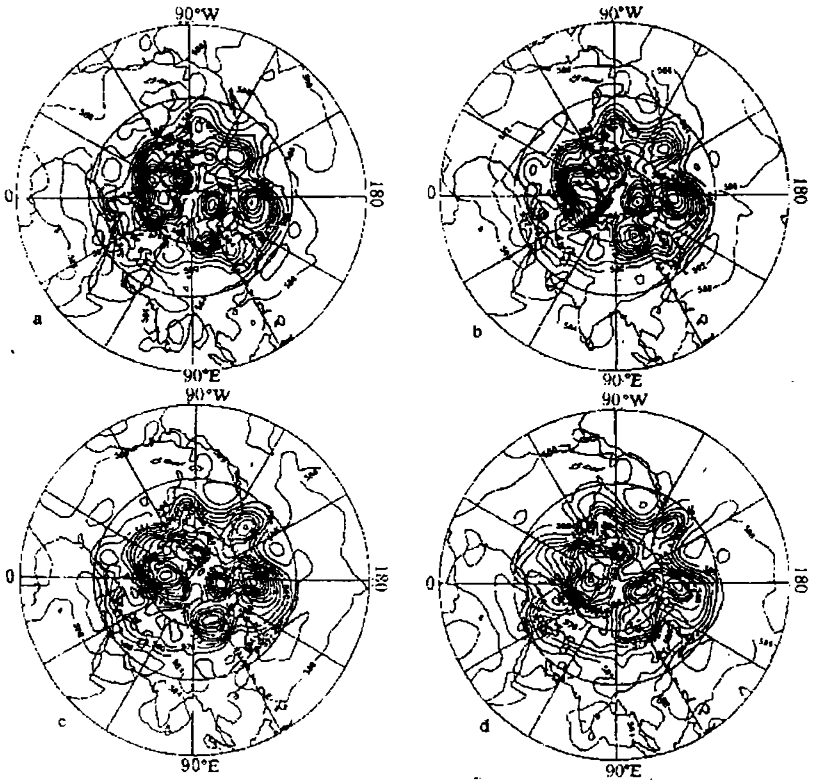

Fig.2 Height field at 500hPa over Northern Hemisphere on 5~8 July, 1995, a~d represents 5-8th respectively

transferred abruptly with enlarged area on land enclosed by 588, and the north boundary of 592 shifted northward by 2 latitudinal degrees and reached Japan. Meanwhile the center enclosed by 592, i.e. the center of main body of SHWP moved westward, and the blocking over both Okhotsk Sea and Ural mountains and the trough over Baikal Lake weakened. The "twin blocking" pattern collapsed. On 8 July (Fig.2d) the center enclosed by 592 continued moving westward and the west ridge-point of the contour 588 stretched westward and the north bound shifted northward. On 9 July circulation similar to 8 July maintained on the whole. It can be concluded that the evolution of circulation during 6 ~ 9 July is typical of mei-yu termination.

2. *The result by control run*

Fig.3 represents 7 ~ 9 July forecast height field. It can be seen easily that the model succeeds in forecasting the evolution of middle-high latitude systems such as the collapse of blocking over Okhotsk Sea and over Ural mountain and the filling up of a trough over Baikal Lake. But evidently SHWP forecast is 40 gm weaker than that in reality. A similar trend is also seen in other runs and it is caused by systematic errors of the model. Considering the circumstances we may choose 584 as the characteristic line here and find that the model is successful in forecasting the evolution of SHWP.

Below we analyze the evolution of SHWP forecast from 7 to 9, July. On 7 July the area on land enclosed by the contour 584 is small with the west ridge-point at about 118 °E and the center enclosed by 588, i.e. the center of the main body, at 145°E. On 8 July (Fig.3b) the area enclosed by 584 enlarges evidently with the west ridge-point moving westward to 115 °E, and the

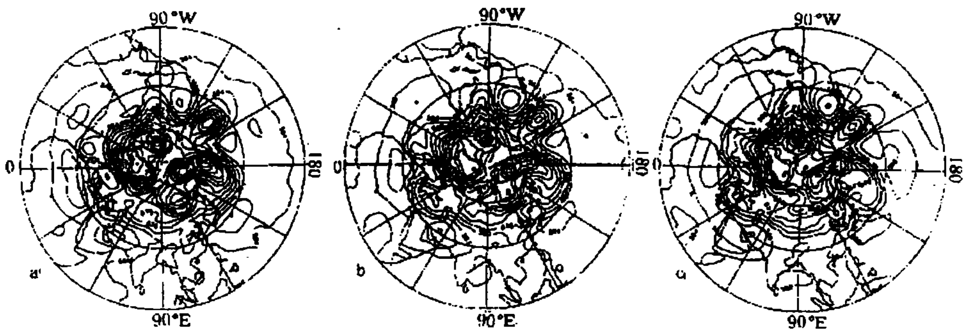

Fig.3 Forecasted geopotential height at 500hPa over north hemisphere by control experiment, a. b, c represents 7th, 8th, 9th July, respectively

center also moves westward to about 135 ^{0} E. On 9 (Fig.3c) the area on land enclosed by 588 moves westward. In comparison with that on 8 July the ridgeline of 588 shifts northward and the high covers more area of Japan. On 10 July SHWP remains at the same position as on 9 July. It can also be seen that the model well captures the SHWP westward movement and northward shift in the wind field at 500hPa (not shown). In one word, the model succeeds in forecasting this process, during which the blocking patterns collapse and SHWP shifts northward and mei-yu terminates.

Anomaly Correction Coefficient (ACC) is an important index to evaluate the ability of numerical models. Generally the forecast with ACC>0.6 is chosen as the criterion of useful forecasts and the number of days with ACC>0.6 as the efficient forecast time. Tab.1 shows the verified result of 500hPa height of this process. For this case, the efficient forecast time is more than 5 d over extra-tropical regions over Northern Hemisphere, nearly 5 d over the globe and 4 ~ 5 d over the tropics. It is consistent with that shown in Fig.3.

Ⅳ. METHOD FOR DIABATIC HEATING CALCULATION

The heating field used in all these experiments are calculated by thermodynamic equation (He, John and Song et al., 1987):

Tab.1 Anomaly Correction Coefficient between forecasted height and real height at 500 hPa

region	6 July	7 July	8 July	9 July	10 July	11 July	12 July
20°N~90°N	0.9604	0.8650	0.8101	0.7237	0.6391	0.5284	0.4759
20°S~20°N	0.5068	0.4578	0.6479	0.6009	0.5261	0.6196	0.5936
90°S~90°N	0.9292	0.8689	0.8333	0.7342	0.5617	0.4112	0.3890

$$q = C_p \frac{dT}{dt} - \frac{RT}{P}\frac{dP}{dt} \tag{1}$$

where q is mean heating, (1) can be written in the pressure coordinate system:

$$q = C_p \left(\frac{p}{p_0}\right)^{\kappa} \left[\frac{\partial \theta}{\partial t} + \vec{V} \bullet \nabla \theta + \omega \frac{\partial \theta}{\partial p}\right] \tag{2}$$

where $\theta = T(\frac{p_0}{p})^k$ potential temperature, p_0=1000 hPa, $\omega = \frac{dp}{dt}$, $\kappa = (C_p - C_v)/C_p$, where C_p, C_v are the specific heat of air at constant pressure and at constant volume, respectively.

The circulation data used here come from the assimilation system of National Meteorological Center of China. The data set contains two analysis field a day, i.e. 00UTC,12UTC, including H, T, u, v at 12 isobaric levels (1000、850、700、500、400、300、250、200、150、100、70、50 hPa) and R_h at 6 lower levels. ω, the vertical velocity, is deduced from the horizontal wind considering mass balance corrections, as can be seen in reference (He, John and Song et al., 1987).

Before calculating, T, u, v will be interpolated into 19 vertical p-levels with even intervals of 50 hPa from 12 uneven levels using cubic spline. Horizontal and time derivatives are estimated by central difference, and vertical derivative was computed by central differences from 1000 to 100 hPa, by forward difference at 100hPa, and by cubic spline on surface.

The vertically integrated diabatic heating Q are the integral over the mass of an air column with heating q. Q can be calculated by means of the equation below by trapezoidal formula.

$$Q = c_p \int_{p_t}^{p_s} [c_p (\frac{p}{p_0})^\kappa \frac{d\theta}{dt}] \frac{dp}{g} \tag{3}$$

Fig.4 shows the mean heating distribution for 5-12 July. It can be seen that there exist two strong centers with more than 300 W/m^2, one over south Asia and another over ITCZ south to SHWP. The areas with heating removed in Exp.3 and Exp.4 contain such heating centers (See Fig.1), thus the heating impact upon SHWP can be analyzed here. Fig. 4b shows the vertical profile of mean heating 5 ~ 12 July over the center of south Asia. From Fig.4b we can see that the strong and deep heating with the rate more than 5K/d from 850 hPa to 400 hPa around the center is in good agreement with climatology during summer over the area.

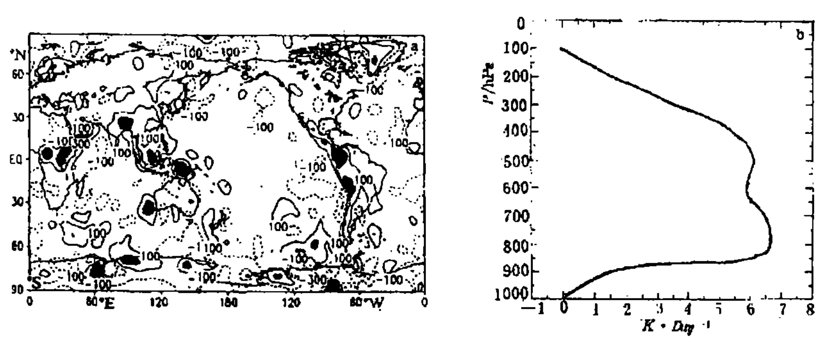

Fig.4 a: Horizontal distribution of integrated heating of vertical column, contours of -300, -100, 100, and 300 are analyzed, values larger than 300 are shaded, unit: W/m^2; b: Vertical profile of mean heating on 5 ~12 July over the center of south Asia area

V. RESULT ANALYSIS

1. *The impact of heating over south Asia upon SHWP*

Exp.2 provides the basis for Exp.3 and Exp.4 to analyze the impact of heating upon SHWP.

On the height map at 500hPa of Exp.3 for 6 July, the area in southeast coastal China enclosed by the contour 588 is small and the main body of SHWP is more eastward than normal with the ridge line south to 30 $^{\circ}$N and the contour of 592 south to Japan. On 7 July the area enclosed by 588 in southeast China increases and the main body moves westward greatly with the contour 592 stretching westward and the north bound of the contour 588 movement going northward, reaching central Korean Peninsula. On 8 ~ 9 July SHWP continues strengthening. This is to say that the forecast of Exp.2 is basically in agreement with the evolution of real SHWP.

Next, we will analyze SHWP of Exp.3. In order to describe the activity of SHWP objectively, researchers define some indexes such as the area index, the strength index, the west-end point of the contour 588, the latitudinal position of its ridge line at 120°E, etc. Here we adopt the area and strength indexes. Considering a weaker forecast of SHWP by the model than the reality, we redefine them as below. Here the area index is defined as the total number of the Gaussian grids where the geopotential height is greater than or equal to 5840 gm over the region 110°E ~ 180° in east -west direction and north to 10°N in north-south direction, while the strength index is the sum of height departure from 5840 on the grid points with the height there greater than or equal to 5840 .

Fig.5 shows the comparison of the evolution of the area and strength indexes of forecast SHWP by Exp.2 and Exp.3 respectively. We can see clearly that the two indexes of Exp.2 are almost equal to those of Exp.3 during the first two days, i.e. 6 ~ 7 July. But after 8 July the two indexes of Exp.3 are smaller than those of Exp.2 and this trend remains till 12th July.

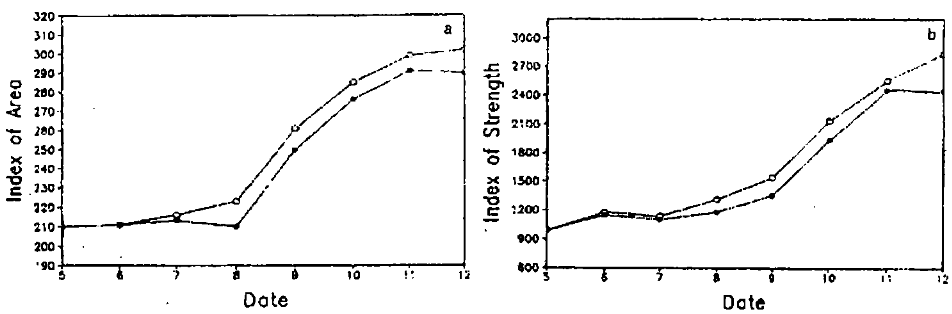

Fig.5 a) daily evolution of Area Index of subtropical high over western Pacific in which "o" represents Exp.2 and "●" represents Exp.3; b) same as a) but for Strength Index

Fig.6 shows the forecast of Exp.2 and Exp.3 on 9 July respectively. There is little difference between the two runs for middle-high latitude systems including their position and strength. But there is evident difference for tropical circulation e.g. over the south Asia, east Asia and western Pacific. For Exp.2 there is a ridge over the Bay of Bengal region and the center of main body of SHWP is situated over the Yellow Sea and Bohai Sea with the contour 588 stretching into Indian-Bengal area and a center enclosed by 596. But in Exp.3 there is a trough instead of the ridge of Exp.2 over India and the main body of SHWP moves southward with west bound of 588 having eastward movement and the contour 592 being open. The result in Fig. 6 together with that in Fig. 5 shows that SHWP weakens evidently after Day 4 discarding the heating over south Asia. It is to say that the change of the heating over south Asia will have influence on the activity of SHWP after Day 3, and the enhancement of positive heating favors the strengthening of SHWP. This conclusion is in agreement with Guo et al.(1988) and Zhuang et al.(1997).

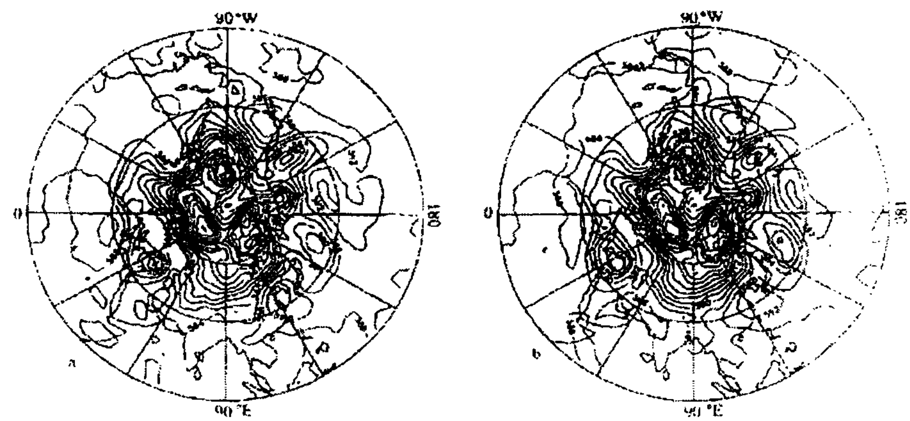

Fig.6 a) forecast geopotential height at 500 hPa over North Hemisphere by Exp.2 on 9th July; b) same as a) but for Exp.3

2. *Physical analysis of impact of the heating over south Asia upon SHWP*

Exp.3 is different from Exp.2 in that the removal of the heating over south Asia, being equivalent to that Exp.2 is the run laying the same heating over south Asia on basis of Exp.3. On the basis of it, a perspective analysis is carried out as below. Fig.7 shows the 500-hPa-height difference between Exp.2 and Exp.3 from 6-9 July. On 6 July a weak positive departure center forms at the heating center with a negative departure center northeast to it and another negative center northwest to it. On 7 July (Fig.7b) the positive center changes little but the negative center depresses and widens. On 8 July (Fig.7c) a large negative departure area develops over North China and Japan downstream of the negative center northeast to the heating center, so that the SHWP enhances and the negative departure center continues developing and widening westward. On 9 July (Fig.7d) a wave-like series of departure centers is obviously propagating northeastward with anomaly (+) over the Bay of Bengal, (-) over eastern Tibetan Plateau, (+) over North China and Japan and (-) over the Okhotsk Sea. The positive center over Bengal Bay joins with that over North China and Japan by a weak positive departure belt. This kind of anomaly series favors the strengthening of SHWP. On 9 ~ 11 July the positive center remains stable. It is consistent with that indicated by the area and strength indexes in Exp.2 and Exp.3.

Based on the analyses above, it can be concluded that the heating over south Asia will motivate a wave-like departure series propagating northeastward, thus a strong positive departure center will develop over North China and Japan after Day 3, which will favor strengthening of SHWP.

3. *Comparison with ITCZ heating south to SHWP*

The influences of the ITCZ heating upon the activity of SHWP have been emphasized. Huang (1986) studied this problem systematically. Now this kind of heating south to SHWP is removed in Exp.4. Fig.8 shows the difference of height at 500 hPa between Exp.2 and Exp.3 from 7 ~ 10 July. On 7 July (Fig.8a) a negative departure center develops at the ITCZ heating center. On 8 July (Fig.8b) a weak positive center develops over the region from the middle basin

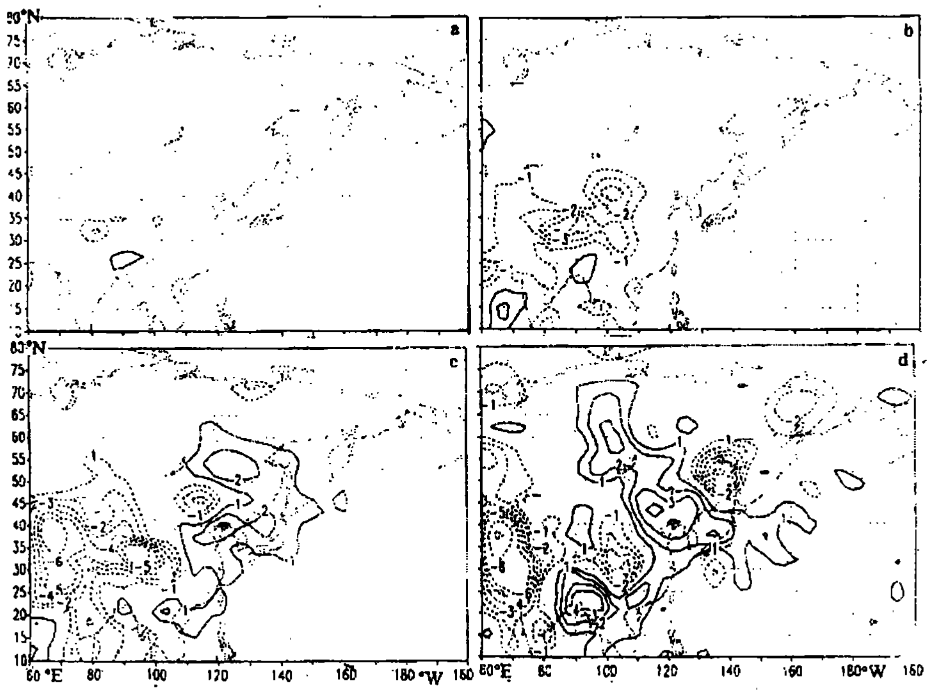

Fig .7 500 hPa height difference between Exp.2 and Exp.3 , unit: dagm, a-d represent 6th to 9th July, respectively

of the Changjiang river to the upper basin of Yellow River in north-south direction, north-northwest to the heating center and the initial negative center depresses. On 9 July (Fig.8c) a new weak positive center develops from the East China Sea to Japan and the positive center which forms on the previous day moves a little southward. A negative center develops over northeast China and Japan sea with a weak positive center over the Okhotsk Sea. Now a wave-like series of anomaly centers is also clear. On 10 July (Fig.8d) the positive center over the middle basin of the Changjiang River develops and merges with that over the East China Sea, favoring the westward movement of SHWP. Other centers remain and develop in their original position, and the wave-like departure center series is clearer.

The results of Exp.3 and Exp.3 indicate that the heating over both south Asia and ITCZ south to SHWP will trigger off a wave-like anomaly series propagating northeastward and thus favor the strengthening of SHWP. But the differences in both the date of the series set-up and the phase of the departure centers between the two heating zones are evident. The anomaly series of Exp.3 is west to that of Exp.4. From position and propagation direction of the series we can conclude that the heating of Exp.4 will favor westward movement of SHWP, because the motivated anomaly center is situated in the region from the middle basin of the Changjiang River to Japan along the east-west direction, while the heating of Exp.3 will favor the northward movement of SHWP because the positive center motivated by it is situated in the region from North China to Japan north to the center. As for the date to begin the influence, the heating over south Asia is on Day 3 (8 July, see Fig.7c) but on Day 5 for ITCZ. The conclusion that the heating over ITCZ

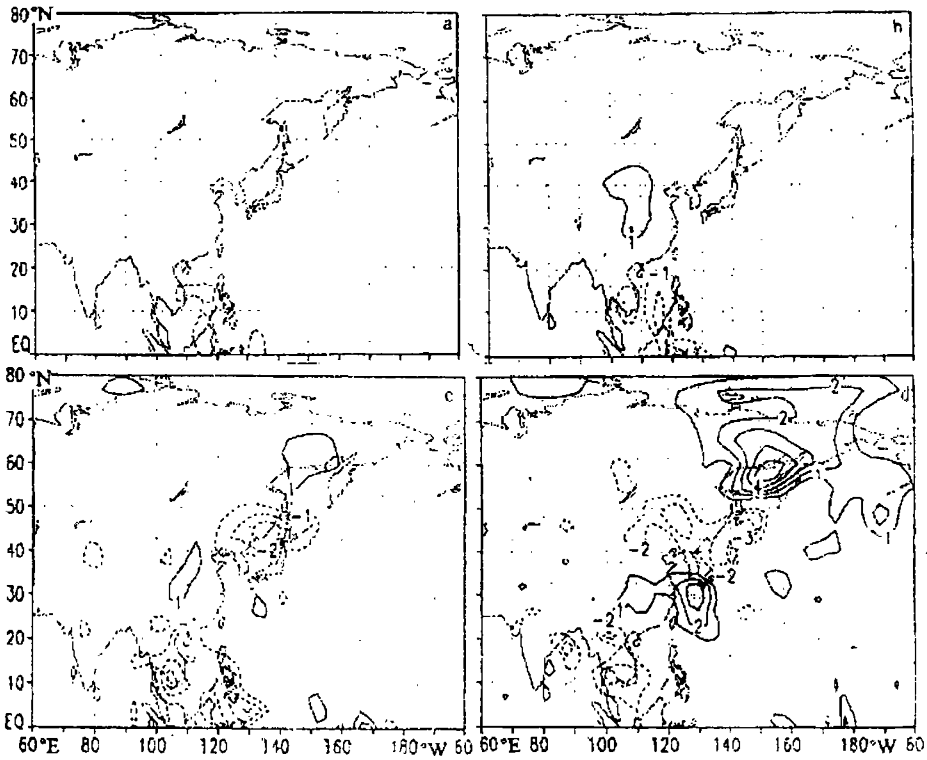

Fig.8 Height difference at 500hPa between Exp.2 and Exp.4 ,unit: dagm. a–d represent 6th to 10th July, respectively

favors the stretching of SHWP is in agreement with Zhong.

The role of the Hadley cell is emphasized in the past when one explains the impact of tropical heating on SHWP, and the idea prevails that heating can not motivate propagating wave train in the easterly. But Sardehmukh and Hoskins (1988) point out that the vorticity advection of divergent wind produced by tropical heating will be acting as a source of Rossby wave in the area with great longitudinal gradient of zonal wind, thus the heating will arouse propagating Rossby wave as soon as a wind response is set up at the southern side of the critical line. More recently, Ting (1996) simulated and found a wave-train-like response in the extra-tropical atmosphere to tropical heating using both barotropic and baroclinic models respectively. Therefore, the result here is possible that heating over both south Asia and ITCZ will motivate a wave-train-like anomaly series, but their dynamical processes need to be investigated forward.

VI. STATISTIC SIGNIFICANCE CHECK

It is necessary to carry out the significance check for the difference between Exp.2 and Exp.3, between Exp.2 and Exp.4, and between Exp.3 and Exp.4 over the global area or subtropical High governing area. A statistical check method for the difference between two fields, called as Permutation Procedure method, is used here. Shao, Qian and Wang (1998) use this method to conduct a significance check for the difference between two simulation fields of a climate model.

one considering the diurnal variation of solar radiation while the other not. Now significance checks are done for forecast height difference every 3 hours at 500hPa between Exp.2 and Exp.3, between Exp.2 and Exp.4, and between Exp.3 and Exp.4 over the global area and over SHWP area (110°E ~ 180°, 10 °N ~ 50°N), respectively. Tab.2 shows the check result with the confidence limit at 95%. In Tab.2 P_0 represents the proportion of significant regions, and "Sig(%)" represents the evidence level, i.e. accidental probability. The greater the variable "Sig(%)", the less confident the hypothesis that the difference of two fields is evident.

We can see that in subtropical areas there exists confident differences between Exp.2 and Exp.3, and between Exp.2 and Exp.3, and between Exp.3 and Exp.4, with the confidence level less than 5%, except in Exp.2 and Exp.3 with confidence level 5.6% and 8.8% for t-check and F-check respectively, but both of them less than 10%. Correspondingly, the confidence area is greater than 10% except in Exp.2 and Exp.3. Over the global area both the result difference between Exp.2 and Exp.3 and that between Exp.3 and Exp.4 pass the confidence limit of 95% with the confidence level less than 5%, but that between Exp.2 and Exp.4 does not pass the confidence check. That may be due to the fact that the area removing heating in Exp.4 is so small that the influence is little over the SHWP area.

Tab.2 Significance checks of forecast height field at 500 hPa over global and subtropical high areas

		Global area		SHWP region	
		P_0	Sig(%)	P_0	Sig(%)
t-Check	Exp.2.Exp.3	0.21716	2.60	0.14286	5.60
	Exp.2.Exp.4	0.09692	17.0	0.32143	2.80
	Exp.3.Exp.4	0.21423	6.40	0.32692	3.40
F-check	Exp.2.Exp.3	0.08252	0.00	0.04945	8.80
	Exp.2.Exp.4	0.03796	20.4	0.11813	4.40
	Exp.3.Exp.4	0.13049	0.80	0.21154	1.00

VII. CONCLUSIONS

A medium-range weather process is reported, during which SHWP shifts northward and mei-yu ended, several numerical experiments are carried out to investigate the impact upon SHWP of heating over south Asia, in comparison with that over ITCZ south to SHWP, and significance check is completed for the results in this research. Some conclusions as below can be drawn.

a. The enhancement of positive heating over south Asia will motivate a series of anomaly centers like a wave train, which propagates northeastward from the maximum heating center, thus a strong positive anomaly center will set up from North-China to Japan and result in the strengthening of SHWP from Day 3.

b. The comparison of influences upon SHWP between the heating over south Asia and that over ITCZ area south to SHWP is also carried out. It is found that the heating over south Asia will favor the northward movement of SHWP while that over ITCZ area is in favor of SHWP stretching westward.

c. As for the date on which the influence begins on SHWP, the heating over south Asia will favor the strengthening of SHWP after Day 3, but that over ITCZ south to SHWP after Day 5.

It must be pointed out that all these conclusions are drawn from a single case, and they may not apply for other cases because the activity of SHWP is influenced by many systems including those from the westerly, subtropics, tropics and even Southern Hemisphere. There are not clear conclusions about the influence upon SHWP of the heating over south Asia. Only one kind of possible mechanics is put forward here. But it is meaningful to understand the impact and interaction between the east Asia monsoon and south Asia monsoon.

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