THE NUMERICAL SIMULATION OF THE THREE-DIMENSIONAL TELECONNECTIONS IN THE SUMMER CIRCULATION OVER THE NORTHERN HEMISPHERE

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ABSTRACT

In this paper, a quasi-geostrophic, 34-level spherical coordinate model with Rayleigh friction, Newtonian cooling and the horizontal eddy thermal diffusivity is used to simulate the three-dimensional teleconnection in the summer circulation over the Northern Hemisphere.

The computed results show that the change of the heat source over the Tibetan Plateau may cause the change of the atmospheric circulation over the middle and high latitudes in the Northern Hemisphere. When the heat source over the Tibetan Plateau is enhanced, it may cause the Tibetan high to enhance over South Asia and cause the change of the atmospheric circulation over East Asia and North America, i. e., Northeast China and North Japan will be controlled by a trough, which brings about a cold summer in this area. In the same way, an anticyclone will be enhanced over the Okhotsk sea. Moreover, another trough will be formed over Alaska, while another ridge will develop to the northeast of North America. Besides, the Pacific subtropical high will be weakened. These results are in good agreement with those obtained from the observed data.

I. INTRODUCTION

Many interpretations have been made for the mechanism of the three-dimensional teleconnection in the atmospheric circulation over the Northern Hemisphere in winter. For example,the author has interpreted the mechanism of the three-dimensional teleconnection between the winter circulations over high and middle latitudes and over low latitudes from such a viewpoint that there are two wave guides in the stationary planetary wave propagations[1,2]. It is explained by Shukla and Wallace in terms of the numerical simulation that the surface temperature anomalies over the equatorial Pacific ocean may cause the PNA (the Pacific/North America) pattern anomalies in the winter circulation over the Northern Hemisphere[3], and the mechanism of the three-dimensional teleconnection in the winter circulation is also explained.

In 1960s, Asakura found the teleconnections in the summer circulation over the Northern Hemisphere from the observed data using statistical and analytic methods[4]. Gambo and Kudo obtained the teleconnections in the summer circulation over the Northern Hemisphere using the latest data in detial[5]. Their computed results showed that there are teleconnections between the Tibetan high and the circulations over middle and high latitudes in summer. However, the mechanism of these teleconnections are not investigated so far. The author has studied the law of stationary planetary wave propagations over the Northern

Hemisphere in summer using the wave propagation theory in the slowly varying medium[6]. It is pointed out that stationary planetary waves can propagate in the troposphere in summer, and there are two wave guides in the propagating channel, i. e., one branch along which the waves propagate from the subtropical troposphere toward the upper troposphere at middle and high latitudes, and the other branch along which the waves propagate from the lower troposphere at the subtropics upward to the upper troposphere near 30 °N. However, in that paper, the propagating law of stationary planetary waves in summer is discussed theoretically. In order to explain the physical mechanism of the three-dimensional teleconnections in the summer circulation over the Northern Hemisphere more clearly, we will simulate the propagations of the forced stationary planetary waves by means of the numerical experiment.

II. THE FACTS OF THE TELECONNECTION IN THE SUMMER CIRCULATION OVER THE NORTHERN HEMISPHERE.

Asakura computed the teleconnections between the Tibetan high and 500 hPa heights in summer using the observed 500 hPa data for 20 years during 1946—1965. Gambo and Kudo computed the three-dimensional teleconnection between 700 hPa zonally asymmetric

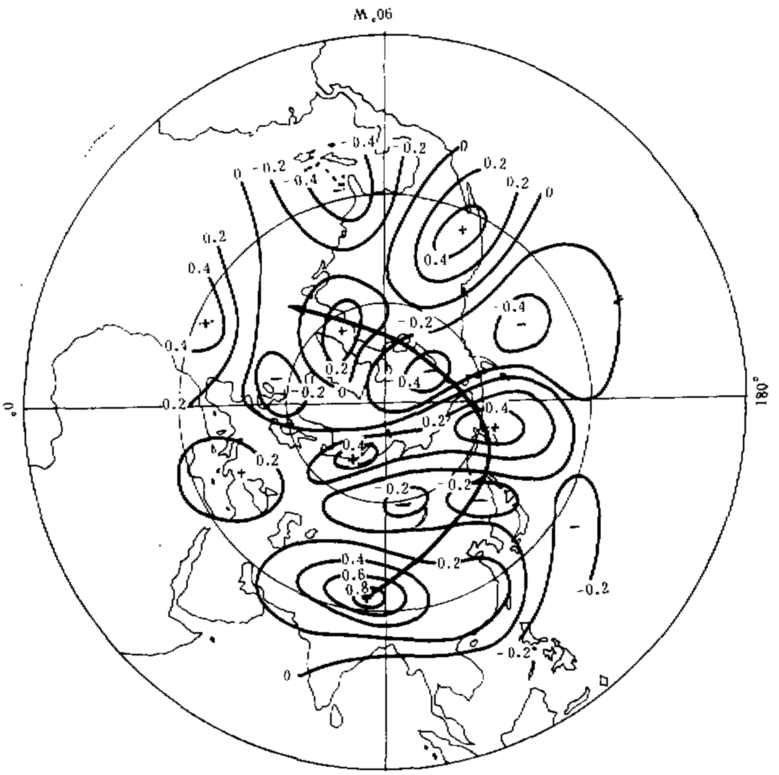

Fig. 1. Simultaneous correlation map between the Tibetan high and 500 hPa heights over the Northern Hemisphere in July of 1946—1965 (After Asakura).

height at the base grid point (25°N, 135°E) and 700 hPa, 500 hPa zonally asymmetric height at the every other grid point for 17 years during 1963—1979. In order to be compared with the model-computed results, Asakura's result is shown in Fig. 1.

In Fig. 1 there is a negative correlation between 500 hPa heights over Northeast China and North Japan and heights over the Tibetan high, while there is a positive correlation between 500 hPa heights over the Okhotsk sea and the Tibetan high. Moreover, there is another negative correlation between 500 hPa heights over Alaska and the Tibetan high, and another positive correlation between 500 hPa height to the northeast of North America can be found. Besides, we may find a negative correlation between 500 hPa heights over the Pacific subtropic area and the Tibetan high. When the Tibetan high is intensified, we can find

(1) a trough develops over Northeast China and North Japan, resulting in a cool summer in that area;

(2) an anticyclone will intensify over the Okhotsk sea;

(3) another trough will be formed over Alaska, and another anticyclone will enhance to the northeast of North America;

(4) and the Pacific subtropical high will be weakened.

In Fig. 1 the arrows show the propagating path of this correlation or the propagating path of the stationary disturbance pattern. From this figure, we may find that the stationary disturbance pattern computed from the observed data can propagate from the subtropics toward middle and high latitudes, and the circle-polar propagation is obvious over high latitudes. Finally, the wave propagates into North America. This shows that there is a close correlation between the Tibetan high and the atmospheric circulation not only over East Asia, but also over North America. The teleconnections in the atmospheric circulation are by no means accidental, but is inevitable. The disturbance pattern in the atmospheric circulation is relative to each other. This is due to the stationary planetary wave propagations. In order to explain the mechanism of the teleconnection, we will simulate these teleconnections by means of numerical model as follows.

III. MODEL AND PARAMETERS.

1. *Model*

In order to simulate the teleconnections in the summer circulation and the propagating process of the forced stationary planetary waves, a steady, quasi-geostrophic 34-level model in which Rayleigh friction, Newtonian cooling and the horizontal eddy thermal diffusivity are included in a coordinate system is used. The derivation of the model can be seen in Ref. [7]. Here, we will write down only the final equations of the model, i. e.,

$$\hat{\Omega}_{n-\frac{1}{2}} \frac{\partial}{\partial\lambda}\left\{\frac{1}{2\Omega_0\sin\varphi}\frac{1}{a^2}\left[\frac{\sin^2\varphi\,\partial}{\cos\varphi\,\partial\varphi}\left(\frac{\cos\varphi}{\sin^2\varphi}\frac{\partial\phi'}{\partial\varphi}\right)+\frac{1}{\cos^2\varphi}\frac{\partial^2\phi'}{\partial\lambda^2}\right]\right\}_{n-\frac{1}{2}}$$
$$+\frac{1}{a}q_{n-\frac{1}{2}}\times\frac{1}{2\Omega_0\sin\varphi}\times\frac{1}{a\cos\varphi}\frac{\partial\phi'_{n-\frac{1}{2}}}{\partial\lambda}=f\left(\frac{\partial\omega}{\partial p}\right)_{n-\frac{1}{2}}-(R_f)_{n-\frac{1}{2}}$$
$$\times\frac{1}{2\Omega_0\sin\varphi}\frac{1}{a^2}\left[\frac{\sin\varphi}{\cos\varphi}\frac{\partial}{\partial\varphi}\left(\frac{\cos\varphi}{\sin\varphi}\frac{\partial\phi'}{\partial\varphi}\right)+\frac{1}{\cos^2\varphi}\frac{\partial^2\phi'}{\partial\lambda^2}\right]_{n-\frac{1}{2}}, \qquad (1)$$

$$\hat{\Omega}_n\frac{\partial}{\partial\lambda}\left(\frac{\partial\phi'}{\partial p}\right)_n-\left(\frac{\partial\hat{\Omega}}{\partial p}\right)_n\frac{\partial\phi'_n}{\partial\lambda}+\sigma_n\omega_n=-\left(\frac{RH}{C_p p}\right)_n-(\alpha_R)_n\left(\frac{\partial\phi'}{\partial p}\right)_n$$

$$+(K_T)_n\frac{1}{a^2}\left[\frac{\partial^2}{\partial\varphi^2}-\tan\varphi\frac{\partial}{\partial\varphi}+\frac{1}{\cos^2\varphi}\frac{\partial^2}{\partial\lambda^2}\right]\left(\frac{\partial\phi'}{\partial p}\right)_n, \quad (2)$$

$$\hat{\Omega}_{n+\frac{1}{2}}\frac{\partial}{\partial\lambda}\left\{\frac{1}{2\Omega_0\sin\varphi}\frac{1}{a^2}\left[\frac{\sin^2\varphi}{\cos\varphi}\frac{\partial}{\partial\varphi}\left(\frac{\cos\varphi}{\sin^2\varphi}\frac{\partial\phi'}{\partial\varphi}\right)+\frac{1}{\cos^2\varphi}\frac{\partial^2\phi'}{\partial\lambda^2}\right]\right\}_{n+\frac{1}{2}}$$

$$+\frac{1}{a}q_{n+\frac{1}{2}}\times\frac{1}{2\Omega_0\sin\varphi}\times\frac{1}{a\cos\varphi}\frac{\partial\phi'_{n+\frac{1}{2}}}{\partial\lambda}=f\left(\frac{\partial\omega}{\partial p}\right)_{n+\frac{1}{2}}-(R_f)_{n+\frac{1}{2}}$$

$$\times\frac{1}{2\Omega_0\sin\varphi}\frac{1}{a^2}\left[\left(\frac{\sin\varphi}{\cos\varphi}\frac{\partial}{\partial\varphi}\left(\frac{\cos\varphi}{\sin\varphi}\frac{\partial\phi'}{\partial\varphi}\right)+\frac{1}{\cos^2\varphi}\frac{\partial^2\phi'}{\partial\lambda^2}\right]_{n+\frac{1}{2}},$$

$$\text{for} \quad n=1,2,3,\cdots,34. \quad (3)$$

where H is the diabatic heating per unit time and unit mass, R is the gass constant, C_p is the specific heat at constant pressure, α_R is Newtonian cooling coefficient, K_T is the horizontal eddy thermal diffusivity, R_f is Rayleigh friction coefficient of perturbation, n represents level in the model, and q is expressed as

$$q=\left[2(\Omega_0+\hat{\Omega})-\frac{\partial^2\hat{\Omega}}{\partial\varphi^2}+3\tan\varphi\frac{\partial\hat{\Omega}}{\partial\varphi}\right]\cos\varphi,$$

Ω_0 is the rotation angle of the earth and $\hat{\Omega}$ is the angle velocity of the basic flow, i. e.,

$$\hat{\Omega}=\frac{U}{a\cos\varphi}.$$

For the planetary-scale motion, the planetary vorticity advection due to the divergent component of motion is important. Thus, in deriving this model equations, the component of non-geostrophic wind v' is included in the planetary vorticity advection term in the vorticity advection, so that we can get a reasonable energy equation[8]. In this way, the model equations (1) and (3) are different from the general vorticity equation in a spherical coordinate system.

For the upper boundary condition, we assume that the vertical p-velocity vanishes at the top of the model, i. e.,

$$\omega=0, \quad at \quad p=p_t(\text{or } z=z_t), \quad (4)$$

For the lower boundary condition, we assume that the p-velocity at p_s is caused by surface topography and by Ekman pumping resulting from the viscosity in the Ekman layer, i. e.,

$$\omega_s=V_s\cdot\nabla p_G-\frac{p_s\cdot F}{2f}\zeta'_s, \quad \text{at} \quad p=p_s(\text{or } z=0), \quad (5)$$

where V_s is the horizontal velocity vector at $p=p_s$ and $p_s=1000$ hPa, for simplicity. F is the friction coefficient and will be treated as a constant (4×10^{-6} s^{-1}), ζ'_s is the vorticity of perturbation at the surface.

The vertical finite difference scheme used in this model is the same as that discussed in the paper of the β-plane approximate model, i. e., we divide the atmosphere into 34 layers from the earth's surface to the top of this model atmosphere[9]. The finite-difference scheme with a grid interval of $\Delta\varphi=5°$ is used in the latitudinal direction.

Since the relaxation methods are not generally applicable for the model equations obtained above, the method proposed by Lindzen and Kuo is used to solve the model equations[10].

In order to solve these algebraic equations, we assume

$$\phi'(\lambda,\varphi,p)=R_e\sum_{k=1}^{K}\Phi_k(\varphi,p)\exp(ik\lambda). \tag{6}$$

In this way, the lateral boundary conditions are necessary. Thus, we assume that $\Phi_k(\varphi,p)$ should vanish at the pole and equator, i. e.,

$$\Phi_k(\varphi,p)=\begin{cases}0, & \varphi=0,\\ 0, & \varphi=\dfrac{\pi}{2}.\end{cases} \tag{7}$$

2. *Parameters*

(1) Static stability parameters σ_n: the static stability used in this model is calculated from the mean temperature and density at 45°N in July for the U. S. Standard Atmosphere. For simplicity, we will assume that the static stability parameters does not change with latitudes.

(2) The vertical profile of the basic zonal mean wind: we use the profile computed by Murgatroyid[11]. In order to eliminate small-scale features, a smooth operator is used.

(3) The coefficients of Rayleigh friction R_f and Newtonian cooling α_R are the same as those in the β-Plane approximate model.

(4) The horizontal eddy thermal diffusivity coefficient K_T : because the zonal mean winds in the tropics and subtropics in summer are very samll, the thermal diffusivity coefficient in the thermal equivalent equation should be smaller than that in winter and will be treated as a constant (0.1×10^6 m^2 s^{-1}).

Thus, if the forcing source is given, the vertical distribution of stationary planetary waves and stationary disturbance patterns at isobaric surfaces responding to forcing by the forcing source are computed from the model equations.

IV. THE NUMERICAL SIMULATION OF THE THREE-DIMENSIONAL TELECONNECTIONS IN THE SUMMER CIRCULATION OVER THE NORTHERN HEMISPHERE.

In order to simulate the three-dimensional teleconncetions in the circulation over the Northern Hemisphere, we will compute the response of the model atmosphere to forcing by the topography and climatological mean value of the actual heat source and the response to forcing by the topography and the heat sources in which a heating anomaly is assumed on the Tibetan Plateau, respectively.

1. *The Response of the Model Atmosphere to Forcing by the Northern Hemispheric Topography and Climatological Mean Value of the Actual Heat Sources in Summer*

Many investigations showed that the Tibetan Plateau is a strong heat source during the Northern Hemisphere summer, as a heat island is "the atmospheric ocean". Yeh and Gao computed the sensible heat flux and latent heat flux on the Tibetan Plateau, based on long-term records of surface observations[12]. Their results showed that there are great upward fluxes of sensible heat in the western plateau from May to July and significant contributions from the latent heat release in the eastern Plateau from June to August. Ashe computed planetary-scale distribution of the heat sources during the Northern Hemisphere summer using the climatiological data and showed that the maximum heat surce during the Northern Hemisphere summer is located over the Tibetan Plateau[13]. Very recently, Nitta[14] computed the distribution of heat source over the Tibetan Plateau for the summer in 1979 and showed that the maximum mean heating rate is located in the 400—500 hPa layer above the Tibetan Plateau in summer.

We took the actual Northern Hemispheric topography and the climatological distribution of the heat sources over the Northern Hemisphere as the forcing source and computed the distribution of the stationary disturbance pattern responding to forcing by the Northern Hemispheric topography and the climatological mean value of heat source at isobaric levels.

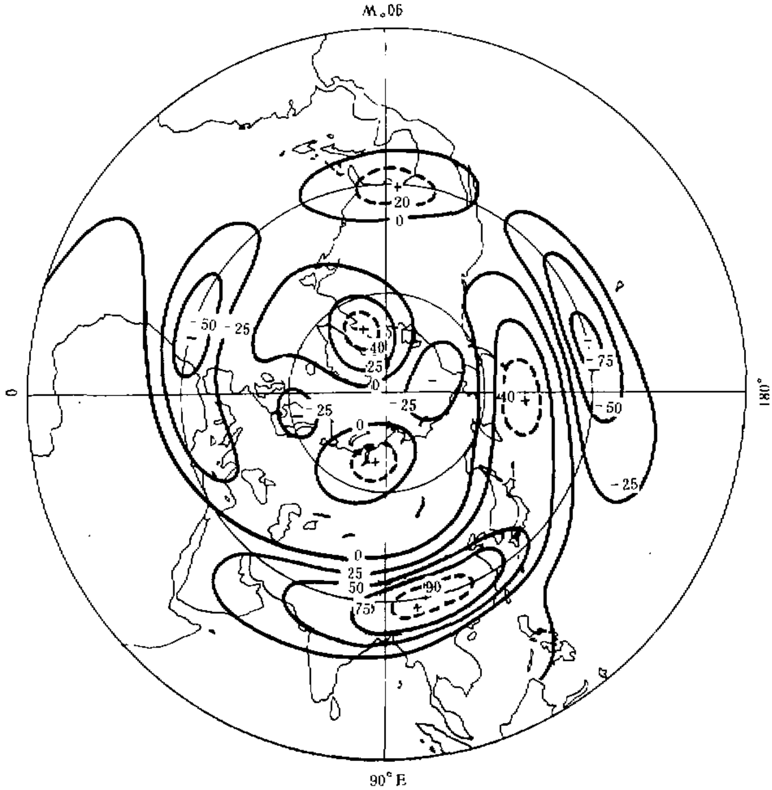

Fig. 2. The disturbance pattern at 300 hPa level (unit in m) responding to forcing by both the Northern Hemispheric topography and climatological mean mean value of heat sources.

Fig. 2 shows the stationary disturbance pattern at 300 hPa level responding to forcing by the Northern Hemispheric topography and the climatological mean value of heat sources. We can find that it is in agreement with the observed distribution. The major disturbances are the Tibetan high and the tropical upper tropospheric trough located over the central Pacific Ocean.

2. *The Response of the Model Atmosphere to Forcing by the Topography and the Heat Sources with a Heating Anomaly over the Tibetan Plateau*

In the previous subsection, we have explained that the Tibetan Plateau is a strong heat source during the Northern Hemisphere summer. The anomaly of this heat source may influence not only the circulation over South Asia, but also the circulation over middle and high latitudes. In order to simulate the process of this influence, first, we assume that an anomaly of an idealized heat source is located over the Tibetan Plateau, and the vertical distribution of the anomaly of the idealized heat source as follows:

$$H_0(\lambda,\varphi,p)=\hat{H}_0(\lambda,\varphi)\exp\left(-\left(\frac{p-\bar{p}}{d}\right)\right), \quad (8)$$

where $d=300\,\text{hPa}$, $\bar{p}=500$ hPa. This means that the vertical distribution of the anomaly of idealized heat source has a maximum in 500 hPa, which is close to the results computed by Nitta from the observed data.

As mentioned above, many investigations showed that a maximum of the heat source is located to the southeast of the Tibetan Plateau during the Northern Hemisphere summer. The anomaly of this heat source may play an important role in the change of the Northern Hemispheric circulation. Thus, we assume that the horizontal distribution of the anomaly of this idealized heat source at 500 hPa is given by

$$\hat{H}_0(\lambda,\varphi)=\begin{cases}\hat{H}_0\left(\sin\frac{\pi(\varphi-\varphi_1)}{(\varphi_2-\varphi_1)}\sin\frac{\pi(\lambda-\lambda_1)}{(\lambda_2-\lambda_1)}\right)^2, & \lambda_1<\lambda<\lambda_2,\ \varphi_1<\varphi<\varphi_2,\\ 0, & \text{otherwise.}\end{cases} \quad (9)$$

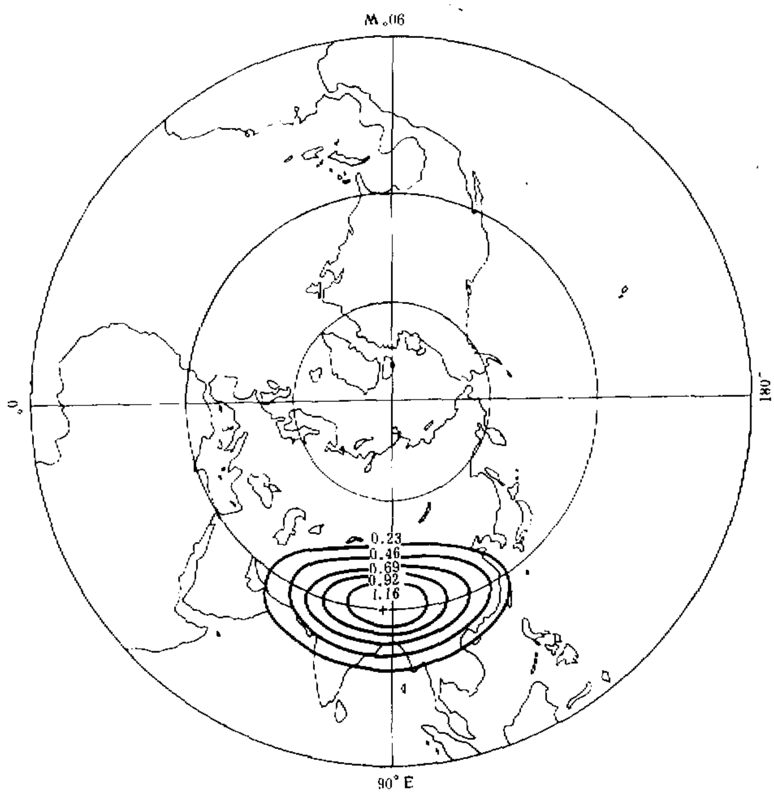

Fig. 3. The horizontal distribution of an anomaly of the idealized heat source(K/day).

Here, the heating rate $\frac{1}{C_p}\hat{H}_0=1.38\text{K/day}$, $\lambda_1=45°\text{E}$, $\lambda_2=135°\text{E}$, $\varphi_1=15°\text{N}$, $\varphi_2=45°\text{N}$. Fig. 3 shows the horizontal distribution of the anomaly of this idealized heat source. We may find that this anomaly of the heat source is located over the Tibetan Plateau with a center at 90°E, 30°N. The anomaly of the heat source is positive i. e., the heat source is intensified over the Tibetan Plateau.

We add the anomaly of the heat source to the climatological distribution of the heat sources over the Northern Hemisphere. Later we will compute the stationary disturbance pattern at isobaric surfaces and the vertical distribution of amplitude and phase of waves for wave number k in the case when the anomaly of the heat source is caused over the Tibetan Plateau.

In order to compare the stationary disturbance pattern at isobaric levels, amplitude and phase for wave number k in the anomaly case with the noraml case of heat source over the Tibetan Plateau, we subtract the amplitude, phase of stationary planetary wave for wavenumber k and the height values of stationary disturbance at the isobaric surfaces in the normal case from these in the anomaly case of heat source over the Tibetan Plateau, i.e.,

$$(z^*)'=z'-z_0'. \tag{10}$$

Here, z' is the height of perturbation, responding to forcing by the heat sources in which the anomaly is caused over the Tibetan Plateau, at a grid point at an isobaric surface. z_0' is the height of perturbation in the normal case, i. e., the height value of perturbation, responding to forcing by the topography and the clamatological mean heat sources, at a grid point at an isobaric surface. Thus, $(z^*)'$ is the anomaly height value of perturbation in the anomaly case of heat source over the Tibetan Plateau.

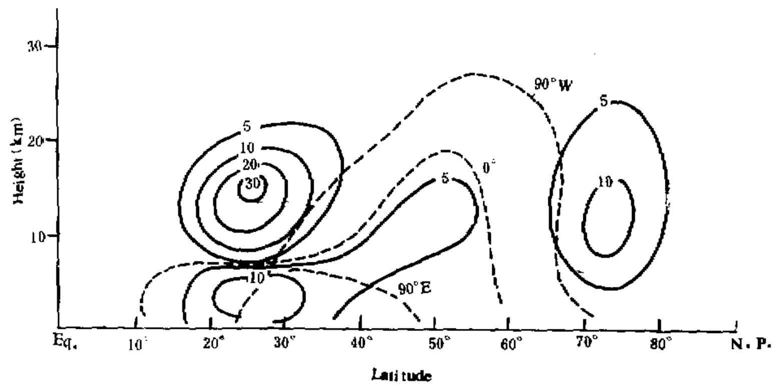

Fig. 4. The anomaly distribution of amplitude (m) (solid curves) and phase (dashed curves) of quasi-stationary planetary wave for wave number 1 in the anomaly case of heat source over the Tibetan Plateau.

Fig. 4 shows the anomaly distribution of amplitude and phase of quasi-stationary planetary wave for wave number 1 in the case when the anomaly of theat source is caused over the Tibetan Plateau. From Fig. 4, we can find that the amplitude of quasi-stationary planetary wave for wave number 1 has a maximum in the upper troposphere near 30°N, and a secondary peak in the upper troposphere at high latitudes. The distribution of phase shifts westward with the increasing latitude from the subtropics. This explains that the quasi-stationary planetary wave responding to forcing by the heat source over the Tibetan Plateau can propagate from the subtropics toward middle and high latitudes. Thus, the anomaly of wave can propagate from the subtropics toward middle and high latitudes. This result is in agreement with the propagating law of stationary planetary waves during the Northern Hemisphere summer, obtained theoretically in Ref. [6]. This explains that the anomaly of heat source over the Tibetan Plateau influences not only the circulation over South Asia, but also the circulation over the anomaly of quasi-stationary planetary waves over middle and high latitudes in the Northern Hemisphere.

In the following, we shall compute the anomaly of disturbance height field repsonding to forcing by the anomaly of heat source over the Tibetan Plateau.

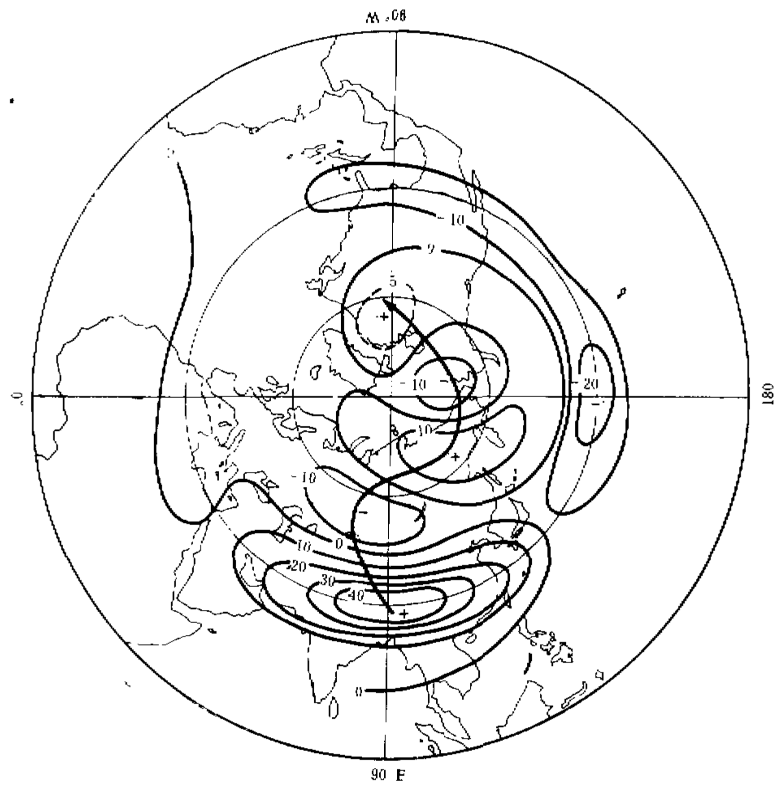

Fig. 5. The anomalies of disturbance height field at 300 hPa level due to the anomaly of heat source over the Tibetan Plateau (unit in m).

Fig. 5 shows the anomalies of disturbance height field responding toxforcing by the anomaly of heat source over the Tibetan Plateau, at 300 hPa level, i. e., the distribution of

$(z^*)'$. From Fig. 5 we can find that when a heat source is enhanced over the Tibetan Plateau, due to the forcing effect of the heat source, a positive anomaly of disturbance height field is formed over South Asia, and a negative anomaly over Northeast China and North Japan. Another positive anomaly may be found on the Okhotsk Sea, and a negative anomaly region and a positive one may be also found over Alaska and the northeast of North America, respectively. Moreover, a negative anomaly is formed over the Pacific subtropical region. Namely, when a heat source is intensified over the Tibetan Plateau, the Tibetan high is intensified over South Aisa, a trough will be deepend over Northeast China and North Japan, Moreover, a high may be enhanced over the Okhotsk Sea another trough and another high is formed over Alaska and the northeast of North America,respectively. Thus, we may find that the stationary disturbance pattern propagates from the subtropics toward middle and high latitudes at 300 hPa level, while circle-polar propagation is evident in high latitudes and propagates into North America, finally.

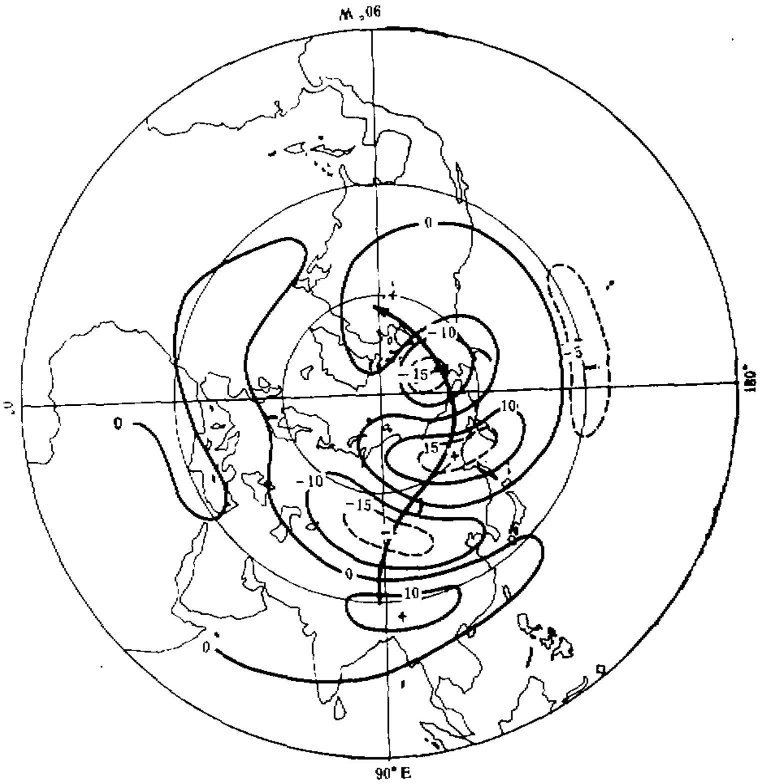

Fig. 6. As in Fig. 5 except for at 500 hPa level.

Fig. 6 shows the anomaly of disturbance height field, responding to forcing by the anomaly of heat source over the Tibetan Plateau, at 500 hPa level. The case is the same as shown in the distribution at 300 hPa level, i. e. when a heat source is enhanced over the Tibetan Plateau, a positive anomaly of disturbance heigh field is found over South Asia, a negative anomaly of disturbance heigh field is found over South Asia, a negative anomaly over Northeast China and North Japan, another positive anomaly may be found over the Okhotsk Sea, and a negative anomaly region and a positive one may be also found over Alaska and the northeast of North America, respectively. Moreover, a negative anomaly region is formed over the Pacific subtropical region. Namely, when a heat source is enhanced over the Tibetan Plateau, due to the forcing effect of heat source, the Tibetan high is enhanced over South Asia, while a trough is formed over Northeast China and North Japan. These may bring about a hot summer in South China and West Japan and a cold summer from Northeast China to North Japan. A high will be enhanced over the Okhotsk Sea. It is favourable for the maintenance of plum rains in China. Moreover, the Pacific subtropical high is weakened.

The results obtained by our model are in good agreement with those obtained by Asakura from the observed data. This can explain that the anomaly of heat source over the Tibetan Plateau may cause not only the circulation anomaly over South Asia, but also the circulation anomaly over East Asia. Therefore, this fact may explain that there is a good teleconnection, not only between the circulations over South Asia and over East Asia, but also between the circulations over South Asia and over North America. These teleconnections are due to the three-dimensional propagations of stationary planetary waves responding to forcing by the heat source over the Tibetan Plateau through the propagating guides of waves. Namely, the teleconnections in the summer circulation result from the forced stationary planetary wave propagations toward middle and high latitutdes.

V. CONCLUSIONS AND DISCUSSIONS

In this paper, a quasi-geostrophic, 34-level spherical coordinate model with Rayleigh friction, Newtonian cooling and the horizontal eddy thermal diffusivity is used to investigate the propagations of stationary planetary waves and stationary disturbance pattern responding to forcing by the anomaly of heat source over the Tibetan Plateau,and the physical mechanism of the teleconnections in the general circulation during the Northern Hemisphere summer are explained.

The results computed by this model show that when the heat Source is enhanced over the Tibetan Plateau, then,

(1) the Tibetan high over South Asia is enhanced;

(2) a trough will control Northeast China and North Japan, This bring about a cold summer over there;

(3) an anticyclone will be enhanced over the Okhotsk Sea, This may be favourable for the maintenance of plum rains in China;

(4) a trough will develop over Alaska and an anticyclone will be enhanced over the northeast of North America;

(5) the Pacific subtropical high is weakened.

The above-mentioned results are in agreement with the observed facts and can be used in the long-range weather forecasting to some extent.

The results computed by this model also show that the teleconnections in the general circulation during the Northern Hemisphere summer are due to the stationary planetary wave propagations in the Northern Hemisphere.

The anomaly of heat source used in this paper is an idealized case. Therefore, the actual anomaly heat source and the causes resulting in this anomaly need all to be investigated in future.

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