NUMERICAL EXPERIMENTS ON NH SUBTROPICAL UPPER TROPOSPHERIC QUASI-STATIONARY VORTICES IN SUMMER

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ABSTRACT

To reveal the possible factors affecting the maintenance and interannual variations of the subtropical planetary-scale vortices such as the south Asian anticyclone and the mid-oceanic troughs, a series of numerical experiments are conducted with a quasi-geostrophic low-resolution spectral model. Firstly, a simulation experiment is performed in which the realistic thermal and topographic forcing are incorporated. The results of simulation show a certain similarity to the actual subtropical flow field in July. On the basis of simulation experiment a series of contrast experiments are performed. It is found that the topographic boundary forcing is less important than the thermal forcing in the dynamics of these systems, and that the anomaly of heating field may cause significant change in position and intensity of the south Asian high and the other systems. It is speculated that the response of the subtropical large-scale systems to heating anomaly is an important cause for the interannual variations of circulation, especially the monsoon circulation.

I. INTRODUCTION

There exist some planetary-scale quasi-stationary vortices in the Northern Hemisphere subtropics in summer, such as the south Asian and Mexican anticyclones and mid-oceanic troughs on the upper troposphere. Among them the South Asian high is the most strong and stable one, and it is also an important member of the summer monsoon circulation system. Tao and Zhu (1964) have studied the regularity of its variation and the relation with variations of the Pacific subtropical high. Yeh and Chang (1974), Krishnamurti (1973), and recently Huang (1986) have studied its dynamic causes. Their works confirm that the thermal forcing plays an important role in the dynamics. Besides the forcing, however, we think that the nonlinear advection may be also an important factor since it is such a large vortex with considerable amplitude and the zonal wind in summer is weak. Recently, using a highly truncated spectral model, Zhu (1987) found that there exists a sort of stable equilibrium state under the mutual effects of thermal forcing and nonlinearity of the flow. The features of the upper level flow field of this state possess some typical characteristics of the actual systems such as the south Asian high and the mid-oceanic troughs. Furthermore, some interesting conclusions are drawn from the analytical model. For example, the high will be weaker and further to south if the zonal heating difference is weak or the meridional heating difference is strong, and vice versa. To verify these conclusions, Zhu et al. (1986) calculated the monthly mean height departures at 500 and 100 hPa level for six El Nino years and six anti-El Nino years respectively. It is found that on average the South Asian high is weak and further to south in El Nino years, and vice versa in anti-El Nino years. We suggest that the difference between the two kinds of years may be caused mainly by the heating anomaly. For instance, it is speculated that the zonal heating difference is weaker than normal in El Nino years, so that the south Asian high is weak and further to south. If this is true, the observational facts are coincident with the conclusions of the theoretical study mentioned above. Since the theoretical model is highly simplified and idealized, whereas the observational study can only offer a suggestion for the role of heating anomaly, *it is necessary to verify the conclusions by numerical experiments. This is* the main goal of the present work.

II. MODEL

The model used is a quasi-geostrophic two level spectral model analogous to the highly truncated spectral model, but different in the following aspects: it incorporates much more wave and zonal components than the theoretical model: the heating field adopted is realistic rather than idealized; the topographic boundary forcing is included through the vertical velocity at the lower boundary. The basic equations are

$$\frac{\partial}{\partial t}\nabla^2\psi = -J(\psi,\nabla^2\psi) - J(\eta,\nabla^2\eta) - \bar{u}\frac{\partial}{\partial x}\nabla^2\psi - \bar{u}_T\nabla^2\eta - \left(\beta - \frac{\partial^2\bar{u}}{\partial y^2}\right)\frac{\partial\psi}{\partial x} - r\nabla^2(\psi - 2\eta)$$

$$- \frac{cf_0}{H}J(\psi - 2\eta, h) - (\bar{u} - 2\bar{u}_T)\frac{cf_0}{H}\frac{\partial h}{\partial x} + A\nabla^4\psi, \tag{1}$$

$$\frac{\partial}{\partial t}(\nabla^2 - \lambda)\eta = -J(\psi,\nabla^2\eta) - J(\eta,\nabla^2\psi) + \lambda J(\psi,\eta) - \bar{u}\lambda\frac{\partial\eta}{\partial x} - \bar{u}_T\lambda\frac{\partial\psi}{\partial x} - \bar{u}\frac{\partial}{\partial x}\nabla^2\eta$$

$$- \bar{u}_T\frac{\partial}{\partial x}\nabla^2\psi - \left(\beta - \frac{\partial^2\bar{u}_T}{\partial y^2}\right)\frac{\partial\eta}{\partial x} + r\nabla^2(\psi - 2\eta) + \frac{cf_0}{H}J(\psi - 2\eta, h)$$

$$+ \frac{cf_0}{H}(\bar{u} - 2\bar{u}_T)\frac{\partial h}{\partial x} + A(\nabla^2 - \lambda)\nabla^2\eta - SQ, \tag{2}$$

where ψ, η are stream function and thermal wind stream function at 400 hPa, $\bar{u}$, u_T the basic zonal wind and thermal wind which vary with latitudes, Q is diabatic heating rate, h topographic height, λ a parameter relating to static instability, $r = \frac{g}{RT_s}\sqrt{\frac{\nu}{2f_0}}$, ν is eddy friction coefficient, C,H and S are all constants, and A is a horizontal diffusion coefficient.

The domain of the model is a narrow channel on the β-plane, with width as πD and length as $2\pi L$, where $L = 5.5\times10^6$ m, $D = 1.4\times10^6$ m. This channel approximately corresponds to a latitudinal belt from 10° to 50°N. The basic harmonic functions for expanding ψ, η, Q, h are as follows.

$$\begin{aligned} F_{Am} &= \sqrt{2}\cos(mD^{-1}y) \\ F_{Knm} &= 2\cos(nL^{-1}x)\sin(mD^{-1}y) \\ F_{Lnm} &= 2\sin(nL^{-1}x)\sin(mD^{-1}y). \end{aligned} \tag{3}$$

The heating field is expanded into

$$Q = \sum_{m=1}^{M} Q_{Am}F_{Am} + \sum_{n=1}^{N}\sum_{m=1}^{M}[Q_{Knm}F_{Knm} + Q_{Lnm}F_{Lnm}], \tag{4}$$

where the two terms at *right side of* (4) represent meridional and zonal heating differences respectively, the latter is caused mainly by sea-land contrast. The diabatic heating field in

July 1979 calculated by Johnson (1985) is adopted. The topography is also realistic. Analogous to the theoretical model, the basic zonal wind and thermal wind are specified as quadratic polynomials of Y, i.e.

$$\bar u(y) = a_1 + b_1 y + c_1 y^2$$
$$\bar u_T(y) = a_2 + b_2 y + c_2 y^2 \qquad (5)$$

By choosing appropriate values of a_1—c_2, the basic zonal wind can be roughly coincident with the distribution of actual zonal wind. Using a spectral method similar to that used in the theoretical model, we have the spectral equations,

$$-\varepsilon_i^2 \dot{\psi}_i = \sum_{j=1}^{N_0}\sum_{k=1}^{N_0} c_{ijk}\varepsilon_k^2(\psi_j\psi_k+\eta_j\eta_k) + \sum_{j=1}^{N_0} b_{ji}\left[\varepsilon_j^2(\bar u\psi_j+\bar u_T\eta_j)\right] - \frac{cf_0}{H}(\bar u-2\bar u_T)h_i$$
$$-(\beta-2c_1)\psi_i + r\varepsilon_i^2(\psi_i-2\eta_i) - \frac{cf_0}{H}\sum_{j=1}^{N_0}\sum_{k=1}^{N_0} c_{ijk}(\psi_j-2\eta_j)h_k - A\varepsilon_i^4\psi_i, \qquad (6)$$

$$-(\varepsilon_i^2+\lambda)\dot{\eta}_i = \sum_{j=1}^{N_0}\sum_{k=1}^{N_0} c_{ijk}\left[(\varepsilon_k^2+\lambda)\psi_j\eta_k+\varepsilon_k^2\eta_j\psi_k\right] + \sum_{j=1}^{N_0} b_{ji}\left[\varepsilon_j^2(\bar u\eta_j+\bar u_T\psi_j) + \frac{cf_0}{H}(\bar u\right.$$
$$\left.-2\bar u_T)h_j - (\beta-2c_2)\eta_j\right] - \bar u_T\lambda\sum_{j=1}^{N_0} b_{ji}\psi_j + \bar u\lambda\sum_{j=1}^{N} b_{ji}\eta_j - r\varepsilon_i^2(\psi_i-2\eta_i)$$
$$+\frac{cf_0}{H}\sum_{j=1}^{N_0}\sum_{k=1}^{N_0} c_{ijk}(\psi_j-2\eta_j)h_k + A(\varepsilon_i^4+\varepsilon_i^2\lambda)\eta_i - SQ_i, \qquad (7)$$

where c_{ijk} is nonlinear interaction coefficient, ε_i^2 the eigenvalue of the basic function, $\bar u = a_1 + \frac{1}{2} b_1\pi D + \frac{c_1}{3}\pi^2 D^2 - \frac{1}{2}c_1 D^2$, and $\bar u_T = a_2 + \frac{1}{2} b_2\pi D + \frac{c_2}{3}\pi^2 D^2 - \frac{1}{2}c_2 D^2$. The zonal and meridional wavenumbers truncated are 1–5 and 1–3 respectively, so this is a low resolution model. The aim of the numerical experiments by using this model is to study the dynamics, other than to simulate the realistic systems at length.

III. SIMULATION EXPERIMENT

The basic zonal wind and thermal wind profiles specified are shown in Fig. 1. The profiles are somewhat similar to reality in July, with easterly in southern area and westerly in northern area and a maximum westerly at middle latitudes. Fig. 2 is the heating field adopted from Johnson. It is seen that a strong heat source is situated in southern Asia and a weak source in North America, and two cooling centers are situated in eastern Pacific and Atlantic respectively. The zonally asymmetric heating is apparently due to the strong sea-land contrast in the Northern Hemisphere subtropics during summer.

The initial state is taken as an unperturbed zonal flow, i.e. only the basic zonal flow exists, whereas all of the Fourier components of the flow approach zero. In the first model day of the simulation, weak highs on 200 hPa level occur over the east coast of Asia and North America, and extend rapidly and shift to WNW direction. Fig. 3a shows the 200 hPa flow field on the third day. After day 3 the high over south Asia continues to intensify and moves westwards, whereas the high over the North America becomes weaker than before. Finally the flow field gradually reaches a quasi-steady state after day 8, with the intensity and

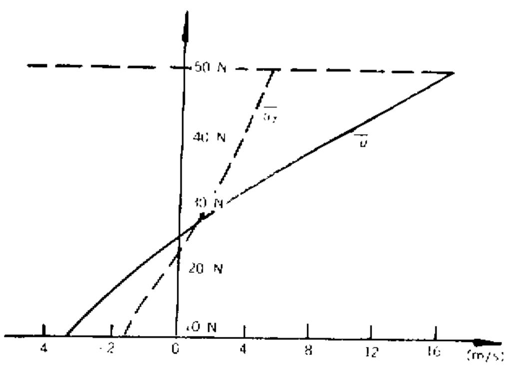

Fig. 1. Profiles of basic zonal wind and thermal wind.

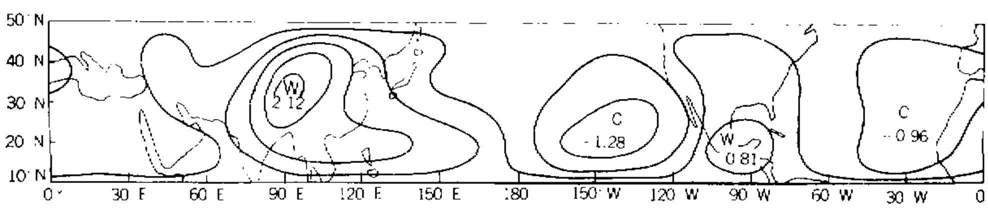

Fig. 2. Diabatic heating field in July 1979 (from Johnson, 1985), contour interval is 0.5 k/day.

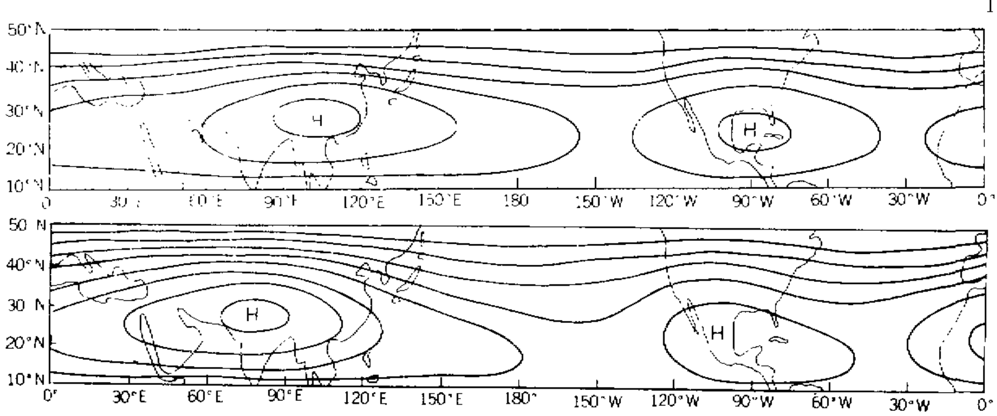

Fig. 3. 200 hPa flow field of the simulation, (a) for day 3, and (b) for day 10, contour interval is 0.5×10^{7} m^2/s

position of the highs and troughs changed little. Fig. 3b depicts the 200 hPa flow field on the tenth day, which shows that the south Asian high is centered over the Tibetan Plateau with strong intensity and covers almost half of the latitudinal circle, and that a weak high is centered over the Mexico, and two mid-oceanic troughs are over the two oceans. The simulated flow field is generally coincident with the observed 200 hPa subtropical flow field in July except that the intensity of the systems is weaker and the position of the south Asian high is slightly further southeast. These discrepancies are probably brought about mainly by the undue simplicity of the model and the idealized initial condition. However, the main features of these systems are reproduced after all. It is proved that this model is capable of simulating the realistic flow field in general.

The results of the simulation confirm the idea that the large-scale quasi-stationary vortices such as the South Asian high are a sort of equilibrium state of the flow forced by asymmetric heating and topography. It is apparent that no such vortices will exist if the forcing is not incorporated. For instance, there are no such vortices in the Southern Hemisphere since the sea-land contrast there is much weaker than in the Northern Hemisphere.

IV. RELATIVE IMPORTANCE OF THERMAL AND TOPOGRAPHIC FORCING

On the basis of the simulation, two sets of contrast experiments are performed in order to reveal the role of the forcing in the dynamics of these vortices. The goal of the first set of contrast experiments is to find out the relative importance of the two kinds of forcing. This can be easily examined by omitting either the thermal or topographic forcing and then comparing the results with the simulation experiment. Firstly the thermal forcing is omitted so that only the mechanical forcing of topography is retained. Other parameters and initial condition are the same as in the simulation experiment. The experiment is performed until the 75th day and the perturbations of the flow are very small all the time. Secondly only the thermal forcing is retained. In this case the flow field evolves in a way similar to the simulation experiment, and finally comes into a similar equilibrium state (figures omitted).

This set of experiments demonstrates that the thermal forcing is far more important than the mechanical forcing of topography in the dynamics of the subtropical large scale eddies. This conclusion is similar to that by Huang (1986) whose model is a linear one. But the perturbations of the flow in the case of topographic forcing seem to be too small, which may be due to the very small parameter of topographic forcing adopted in our model.

It seems reasonable that the mechanical forcing of topography is not very important in summer since the zonal flow is weak. However, this conclusion does not mean that all the effects of topography are not important, because besides its mechanical forcing it also has a significant influence on the heating distribution, through sensible heat transfer from the plateau surface and through its indirect influence on latent heat release and radiation processes due to its effects on the circulation. In the present model the influence of topography on heating distribution has been included in the so-called realistic heating field. This is the reason that the results without topographic forcing are still consistent with those in consideration of the two kinds of forcing.

From this set of contrast experiments it can be concluded that the thermal forcing plays a main role in the formation and maintenance of the South Asian high and other subtropical systems. However, the heating distribution is in turn dependent on the atmospheric circulation. Therefore it is necessary to profoundly study the interaction processes between heating and circulation.

V. RESPONSE OF SUBTROPICAL SYSTEMS TO HEATING ANOMALIES

The Asian summer monsoon circulation has significant interannual variations, which have been recognized to correlate with the sea-surface temperature anomalies in eastern equatorial Pacific. In El Nino years the monsoon precipitation is generally less than normal, whereas the South Asian high is weak and further to the south. Zhu et al. (1986) suggested that this might be caused mainly by the large scale heating anomalies in these years. In order to study the response of the subtropical systems to heating anomalies, the following set of contrast experiments are conducted.

The first experiment aims at the influence of zonally asymmetric heating anomalies. In this experiment some of the Fourier components of heating field used in the simulation experiment are changed. i.e. Q_{K11}, Q_{L11}, Q_{K12}, and Q_{L12} are multiplied by 1.5. The changed heating field is shown in Fig. 4a. Comparing with Fig. 2 we see that the value of South Asian heating center increases from 2.12 to 2.43 k/day, the cooling center value in eastern Pacific changes from −1.08 to −1.45 k/day, and another heat source in North America slightly weakens. Other parameters and initial condition are all the same as in the simulation experiment. Fig. 4b depicts the flow field of this experiment on the tenth day. A comparison of this figure with Fig. 3b shows that the South Asian high significantly strengthens where as the Mexican high slightly weakens. It is noticeable that the result of this contrast experiment is consistent with that of the theoretical study mentioned before, i.e. the South Asian high intensifies when zonal heating difference increases, and vice versa.

The second contrast experiment is performed to study the influence of meridional heating anomaly. The meridional heating difference between the northern and southern boundary changes from 0.08 to 0.8 k/day. The tenth day flow field in this case is shown in Fig. 5. The South Asian high apparently weakens when the meridional heating difference increases. This result also confirms a conclusion of the theoretical study about the control effect of meridional heating.

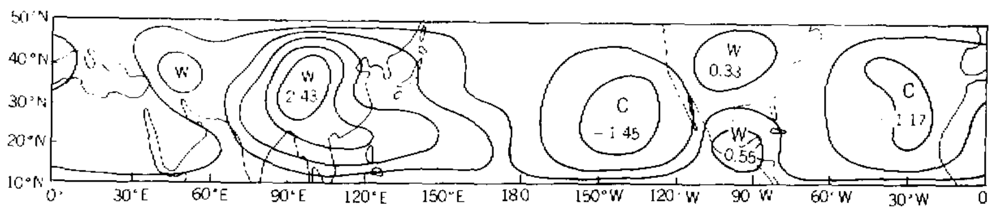

Fig. 4a. Changed heating field with stronger zonally asymmetric heating.

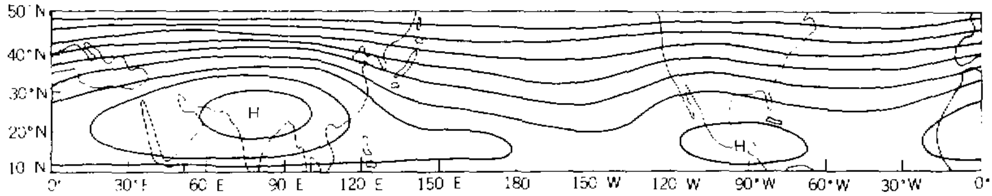

Fig. 4b. The tenth day flow field at 200 hPa corresponding to the changed heating shown in Fig. 4a.

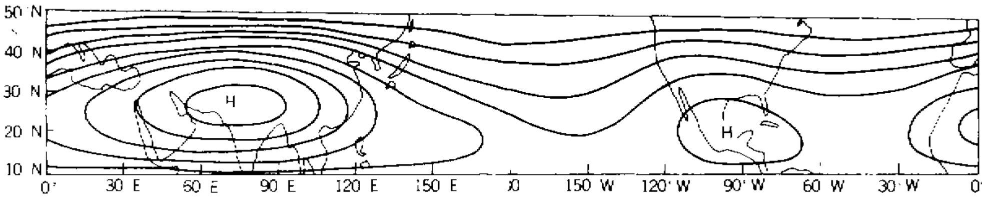

Fig. 5. The tenth day flow field at 200 hPa in the case when meridional heating is stronger.

The above set of contrast experiments confirms that the intensity and position of the South Asian high and other systems will change to respond the anomalies in heating field. This may be an intrinsic cause for the interannual variations of the subtropical systems. The variation of heating field is in turn influenced by some factors, e.g., the SST anomalies in equatorial Pacific. Although there are not any observed data of diabatic heating in El Nino or anti-El Nino years, it is presumable that the heating in these years is abnormal, e.g., the east-west heating difference in El Nino years may be weaker than normal due to the warming of SST and the weakening of the South Asian heat source for the precipitation is less than normal in this area, whereas the meridional heating difference may be abnormally strong due to the positive SST anomaly. Meanwhile the South Asian high, which is a member of monsoon circulation, is generally weak as mentioned by Zhu et al. (1986).

It is conceivable that the thermal forcing plays an important role in the variation of the subtropical circulation, e.g., the interannual variation in the summer monsoon circulation. On the other hand, the heating distribution is relative to the circulation in turn. Therefore it seems that there exists a feedback process between the subtropical circulation and the heating field in northern summer, i.e., warmer (cooler) SST in the eastern equatorial Pacific— decreased (increased) zonal heating difference and increased (decreased) meridional heating difference- weakened (strenthened) monsoon circulation such as the South Asian high— decreased (increased) monsoon precipitation leading to weakened (strengthened) heat source in South Asia — further weakened (intensified) monsoon circulation. It is speculated that this positive feedback process may lead to an amplified response of the monsoon circulation to the SST anomalies in equatorial Pacific. This feedback mechanism may be useful to explain the correlation between the SST anomalies and the interannual variations of monsoon circulation. It will be of significance to further investigate the interaction processes between the subtropical circulation and thermal forcing.

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