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Relationship between the Interannual Variations of Total Ozone in the Northern Hemisphere and the QBO of Basic Flow in the Tropical Stratosphere

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ABSTRACT

The harmonic analyses of monthly mean total ozone in the atmosphere over the Northern Hemisphere for 26 years (1960–1985) are made by using the Fourier expansion. The analysed results show that there is obviously a quasi–biennial oscillation (QBO) in the interannual variations of the amplitudes of total ozone. Generally, the amplitudes of wavenumber 1 and 2 during the westerly of the equatorial QBO are larger than those during the easterly. In the early winter, the amplitude of wavenumber 1 during the easterly phase is larger, and in the late winter, it is larger during the westerly phase. These are in good agreement with the observational distributions.

I. INTRODUCTION

Although the total ozone is very small in the atmosphere, it is one of the important compositions of atmosphere. It absorbs ultraviolet radiation in short wave radiation from the sun. The ultraviolet radiation is largely related to the human life, and is directly related to the cancer of human skin. On the other hand, since a photochemical reaction can be caused in the ozone due to absorption of ultraviolet, the heating sources in the middle atmosphere may be affected. Thus, it would play an important role for the circulation of middle atmosphere and for the climatic change.

Owing to the Dobson's observational stations of the total ozone increase continuously, a global Dobson's observational network of the ozone has been set up. Therefore, a good monitoring of interannual and intraseasonal variation of the total ozone in an air column can be made on the globe. Dutch (1971) analysed the seasonal variation of the total ozone in the atmosphere by using the data of global Dobson's observational network. The analysed results show that there is an obvious seasonal variation of total ozone either in the Southern Hemisphere or in the Northern Hemisphere. London et al. (1976) also analysed the variation of total ozone with the help of the observational data of satellite. His results show that the zonal mean features of total ozone obtained from the data of satellite are analogous to that from the data of global Dobson's observational network.

As far back as 1940's, it was found that ozone is a tracer, which can be used to trace the variation of the atmospheric circulation. Thus, recently, more investigations focus attention on the relationship between the variation of the total ozone and the atmospheric circulation. For example, Gushein (1976) analysed the relationship between the circulation at 100 hPa and the variation of total ozone. He pointed out that when a zonal circulation is prevailing in the Northern Hemisphere, the zonal circulation can cause large total ozone in high latitudes to be separated from small total ozone in low latitudes, and the poleward meridional transfer of ozone may be blocked. Therefore, the variation of total ozone is not obvious; however, a meridional circulation is prevailing, the poleward meridional transfer becomes evident, in this case, total ozone tends to have obvious variation. Recently, Tung et al. (1986) investigated the causes of ozone home over the Antarctica. Their investigations show that because large part of the Southern Hemisphere is covered by ocean, the quasi–stationary planetary waves forced by the large–scale topography and the difference between ocean and land, are weak, the polar vortex surrounding the Antarctica is much stable than that in the Northern Hemisphere. Therefore, the transfer to the Antarctica due to disturbance is weak, the ozone home is easily formed over the Antarctica. All these can explain that atmospheric circulation may play an important role in the distribution of ozone. Thus, the distribution of ozone would in turn well reflect the variation of atmospheric circulation.

In this paper, the interannual and seasonal variations of total ozone in the Northern Hemisphere for every wavenumber are analysed by using the Fourier expansion with observational data of monthly mean total ozone for 26 years from 1960 to 1985 (from Ozone Data for the World, January, 1960–December, 1985, Atmospheric Environment Service, Canada).

A quasi–geostrophic, 34–level, 2–dimensional model with Rayleigh friction, Newtonian cooling and horizontal eddy thermal diffusion is used to calculate forced quasi–stationary planetary waves during different phases of the equatorial QBO in late winter. The relationship between the interannual variation of total ozone and the QBO of basic flow in the tropical stratosphere is explained.

II. THE INTERANNUAL VARIATION OF AMPLITUDE OF TOTAL OZONE FOR VARIOUS WAVENUMBERS

The interannual variation of the atmospheric circulation in the equatorial lower stratosphere exhibits a quasi–biennial oscillation. This phenomenon was discovered by Reed et al. (1961), Vergand and Ebdon (1961) from the observational data. Recently, Holton and Tan (1982) have pointed out from the analyses of observational data that in late winter, the amplitudes of planetary waves for wavenumbers 1 and 2 in high and middle latitudes are larger during the westerly phase of the equatorial QBO; while in early winter, they are smaller. Angell (1980) investigated the interannual variation of ozone at Resolute station near the North Pole, and pointed out that there is an obvious quasi–biennial oscillation in the amount of total ozone. Moreover, Kulbarni (1980) analysed the variation of ozone at some stations in the Northern Hemisphere, and also discovered that there is a quasi–biennial oscillation in total ozone. However, the variations from those investigations are analysed by using the data only at one station. Hasebe (1980) studied the interannual variations of the zonal and meridional mean total ozone using the data of total ozone for 14 years from 1962 to 1976. He discussed mainly the interannual variation of phase of total ozone in the Northern Hemisphere for various wavenumbers and not the interannual and seasonal variations of amplitude of total ozone. Thus, it is a significant subject to study how the interannual variations of amplitude of total ozone in the Northern Hemisphere for various wavenumbers would be.

Fig.1 shows the interannual variation of amplitude of annual mean total ozone in the Northern Hemisphere for wavenumber 1 during 1960–1985. We can see from Fig.1 that there is a distinct difference of the interannual variation of amplitude for wavenumber 1 between in the south of 30°N and in the north of 30°N. In the south of 30°N, the amplitude of total ozone for wavenumber 1 decreases obviously from 1960's to the present. The amplitude of total ozone for wavenumber 1 is larger in the early and middle 1960's, while in the late 1960's, it decreases suddenly. It seems to experience a catastrophic event.

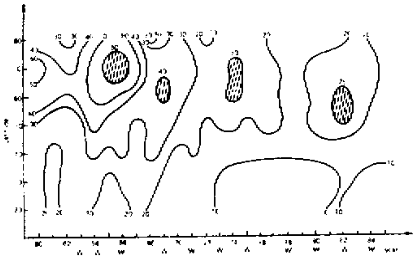

Fig.1. Interannual variation of amplitude of annual-mean total ozone in the Northern Hemisphere for wavenumber 1 during 1960–1985 (Unit in Dobson). W indicates the westerly phase of basic flow in the tropics.

We also see from Fig.1 that in the north of 40°N, especially in the area of 60°–70°N, there is an obvious quasi–biennial oscillation in the distribution of amplitudes of total ozone for wavenumber 1. Generally, during the westerly phase of the equatorial QBO, the amplitude of total ozone for wavenumber 1 is larger.

We have also analysed the interannual variation of amplitude of total ozone for wavenumber 2 for 26 years from 1960 to 1985. As shown in Fig.2, there is a distinct difference of the interannual variation of amplitude of total ozone for wavenumber 2 between in the south of 30°N and in the north of 30°N. In the south of 30°N, the amplitude of total ozone for wavenumber 2 is larger in 1960's, while in the period from the late 1960's to the present, the amplitude of total ozone for wavenumber 2 decreases obviouly. This is analogous to the variation of amplitude for wavenumber 1. In the north of 30°N, especially in the area of 40°–50°N, there is a quasi–biennial oscillation in the distribution of amplitude of wavenumber 2. Generally, during the westerly phase of the equatorial QBO, the amplitude of wavenumber 2 is slightly larger.

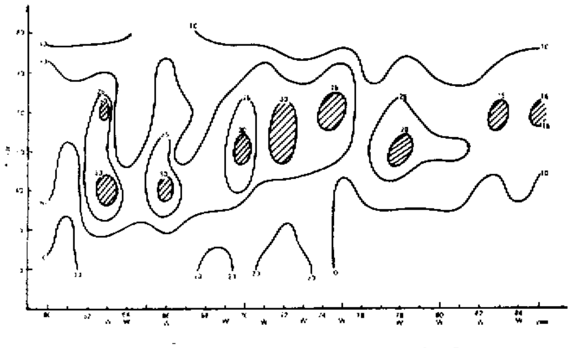

Fig.2. As in Fig.1 except for wavenumber 2.

In order to see clearly the differences between the amplitude of total ozone for various wavenumbers for different phase of the equatorial QBO, the latitude–time cross sections of amplitude of total ozone for wavenumbers 1 and 2 in easterly and westerly categories of the equatorial QBO in the early and late winter are shown in Figs. 3a,b, and Figs. 4a,b. From Figs.3 and 4 it can be seen that the amplitude of total ozone for wavenumber 1 is larger in the easterly category than that in the westerly category for the early winter. Moreover, the total ozone for wavenumber 2 exhibits slightly stronger amplitudes in the easterly category for the early winter, but the difference between categories is not statistically significant. However, As shown in Figs. 4a,b, in the late winter, the amplitude of wavenumber 1 is obviously stronger in the westerly category, and the amplitude of wavenumber 2 seems to be slightly larger.

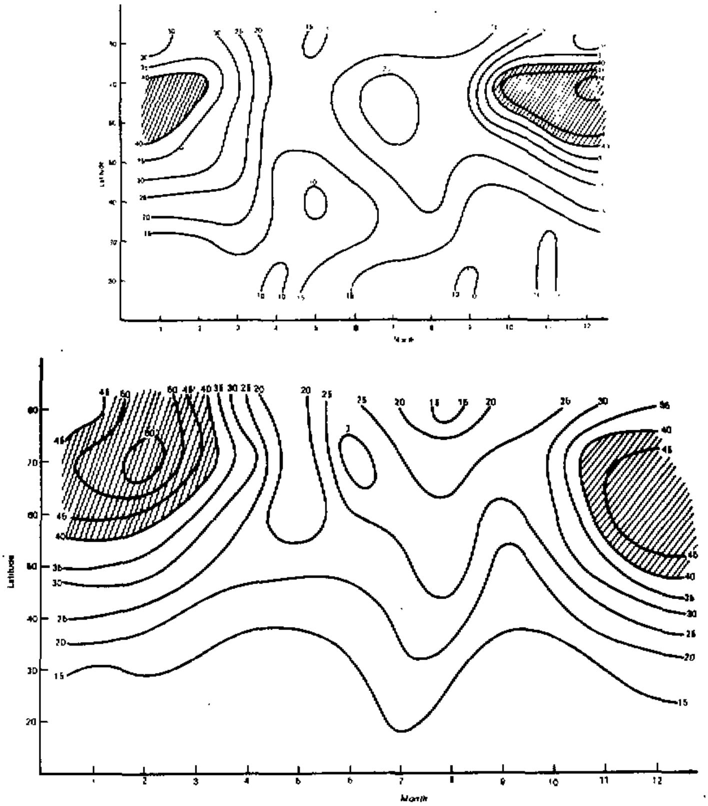

Fig.3. Latitude–time sections of the amplitude (unit in Dobson) of the total ozone for wavenumber 1 (a) in the easterly category; (b) in the westerly category.

From the above–mentioned harmonic analyses of the total ozone, we can see that there is an obvious quasi–biennial oscillation in the interannual variation of the amplitudes of wavenumbers 1 and 2. Generally, when the basic flow is westerly in the tropical stratosphere, their amplitudes are larger for the late winter. This is in good agreement with the distribution of amplitudes of planetary wavenumbers 1 and 2 obtained by Halton and Tan (1982).

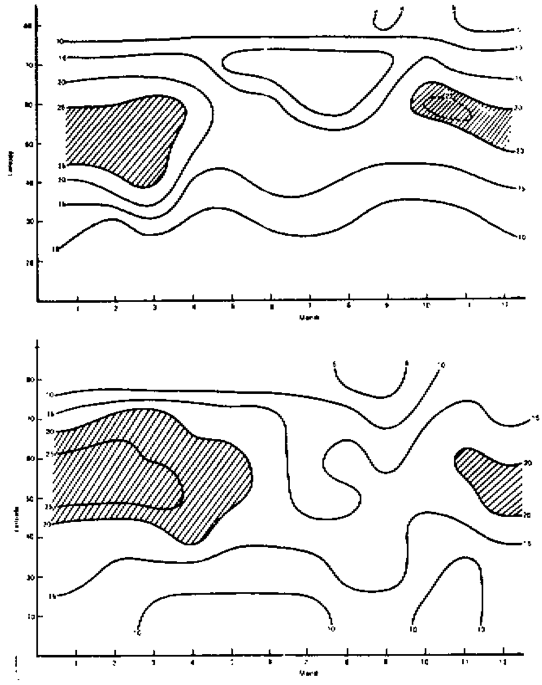

Fig.4. As in Fig.3 except for wavenumber 2.

III. MODEL AND PARAMETERS

Above, we have analysed the relationship between the distribution of the amplitude of total ozone and the QBO of basic flow in the tropical stratosphere in winter from the observational facts. In order to make this relationship much clear, a quasi– geostrophic, 34–level, two–dimensional model with the Rayleigh friction, the Newtonian cooling and the horizontal eddy thermal diffusion is used to make numerical simulation of this problem.

1. *Model*

As described in Huang and Gambo's (1982) paper, the model equations used in this paper are

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

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

$$\left.+\frac{1}{\cos^2\varphi}\frac{\partial^2\varphi'}{\partial\lambda^2}\right]_{n-\frac{1}{2}}, \tag{1}$$

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

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

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

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

$$\left. + \frac{1}{\cos^2\varphi}\frac{\partial^2 \varphi'}{\partial \lambda^2}\right]_{n+\frac{1}{2}} , \tag{3}$$

where $\hat{\Omega} = \frac{U}{a\cos\varphi}$ is the angle velocity of basic flow. H is diabatic heating per unit time and unit mass. R is gas constant (0.287KJ / Kg · K), C_p is specific heat at constant pressure (1.004KJ / Kg · K), α_R is Newtonian cooling coefficient, K_T is horizontal eddy thermal diffusion, R_f stands for Rayleigh friction coefficient of perturbation, n represents level in the model, and is expressed:

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

is derived from the 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.

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

$$\omega = 0, \quad \text{at} \quad p = p_t \qquad (\text{ or } \quad Z = Z_t). \tag{4}$$

For the lower boundary condition, we assume p–velocity at P_s is caused by surface topography and by Ekman pumping resulting from the viscosity in the Ekman layer:

$$\omega = \vec{V}_s \cdot \nabla P_G - \frac{P_s F}{2f}\zeta'_s , \quad \text{at} \quad P = P_s \quad (\text{ or } \quad Z = 0), \tag{5}$$

where $\vec{V}_s$ is horizontal velocity vector at $P = P_s$ and $P_s = 1000$ hPa, for simplicity. F is friction coefficient and will be treated as a constant ($4 \times 10^{-6}\ \mathrm{s}^{-1}$), ζ'_s is vorticity of perturbation at the surface. P_G is height of topography.

The vertical finite difference scheme used in this model is the same as that discussed in the paper of plane approximate model (See Huang and Gambo (1981)), i. e., we divide the atmosphere into 34 layers from the earth's surface to the top of this model atmosphere, the finite–difference scheme with an interval $\Delta\varphi = 5^0$ is used in latitudinal direction.

Since the relaxation methods are not, generally, applicable for the model equations obtained above, the method proposed by Lindzen and Kuo (1969) is used to solve the model equations.

In order to solve those algebraic equations, we assume

$$\varphi'(\lambda,\varphi,p) = Re\sum_{k=1}^{k}\Phi_R(\varphi,p)e^{ik\lambda}, \qquad k = 1,2,\ldots\ldots K \tag{6}$$

and assume

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

that $\Phi_k(\varphi,p)$ should vanish at the pole and equator.

2. *Parameters*

(1) Static stability parameter: 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 assume that the static stability parameter does not change with latitude.

(2) The vertical profile of the basic zonal–mean wind: In order to calculate the relationship between amplitude of planetary waves and basic flow in the tropical stratosphere, two different profiles of basic zonal–mean wind are used in this paper. One is easterly in the middle and lower stratosphere of the tropics; another is westerly. Moreover, these two profiles of basic flows are the same in areas of middle and high latitudes and tropical troposphere. They may represent the two categories of the equatorial QBO for the late winter.

(3) The coefficients of Rayleigh friction R_f and Newtonian cooling α_R and coefficients of horizontal eddy diffusion K_T are the same as those in Huang and Gambo's (1982) paper.

IV. RELATIONSHIP BETWEEN THE FORCED QUASI–STATIONARY PLANETARY WAVES AND THE BASIC FLOW IN THE TROPICAL STRATOSPHERE

The model equations (1)–(3) are used to compute the distribution of quasi–stationary planetary waves forced by topography and heat sources in the easterly and westerly categories of the equatorial QBO.

Fig.5a is the distribution of amplitude and phase of planetary wavenumber 1 forced by the Northern Hemispheric topography and heat sources in the easterly category, while Fig.5b is the same as Fig. 5a but in the westerly category. Figs. 6a,b, are the distributions of amplitude and phase of quasi–stationary planetary wave for wavenumber 2 forced by the Northern Hemispheric topography and heat source in the easterly and westerly categories, respectively. Comparing Fig.5 with Fig.6, we can find that the amplitudes of planetary waves for wavenumbers 1 and 2 forced by topography and heat sources are larger in the westerly category than in the easterly category.

In order to see clearly the influence of the basic flow in the tropical stratosphere on the quasi–stationary planetary waves in middle and high latitudes, we calculate the quasi–stationary disturbance pattern at isobaric levels by synthesizing the components of zonal wavenumbers 1–3. Fig.7a is the stationary disturbance pattern at 30 Km height forced by the topography and heat sources in the easterly category. The disturbance pattern exhibits disturbance about wavenumber 1. The Aleutian high is located over the Aleutian islands and the polar vortex is located over Europe. Fig.7b is the same as Fig.7a but in the westerly category. We can find from Fig.7b that the Aleutian high located over the Aleutian area intensifies and the polar vortex located over Europe also intensifies.

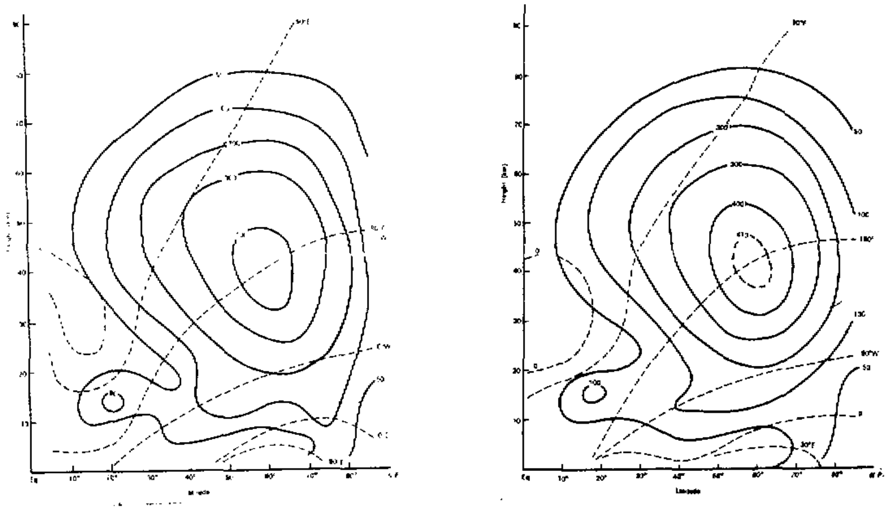

Fig.5. The distribution of quasi-stationary planetary wave for wavenumber 1 forced by the Northern Hemispheric topography and heat sources in the different categories of the equatorial QBO. The solid curves denote amplitude (Unit in m), the dashed curves denote phase. (a) in the easterly category; (b) in the westerly category.

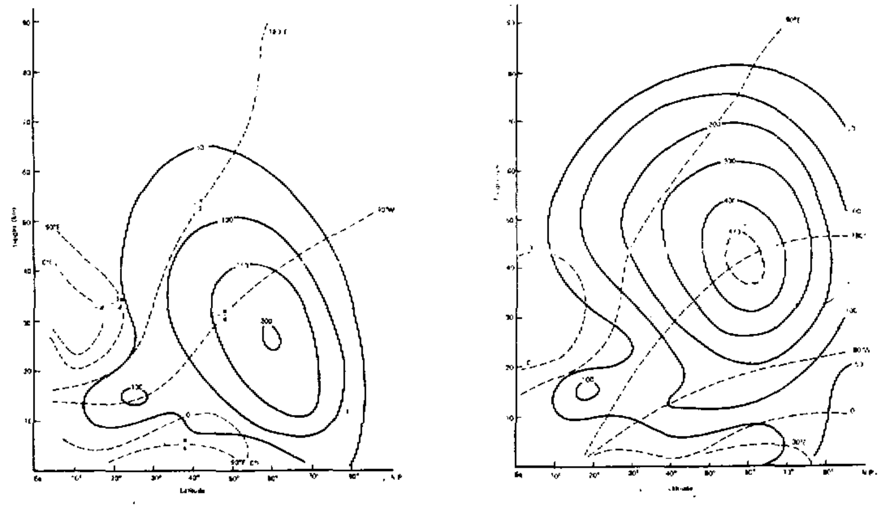

Fig.6. As in Fig.5 except for wavenumber 2.

As mentioned in the introduction, ozone is a tracer of the atmospheric circulation in the stratosphere. Variations of the stratospheric circulation, especially the planetary-scale circulation, would influence greatly on the distribution of ozone. As a result, the larger amplitude planetary-scale disturbances, forced by topography and heat sources, may cause larger amplitudes of total ozone distribution during the westerly category of the equatorial QBO.

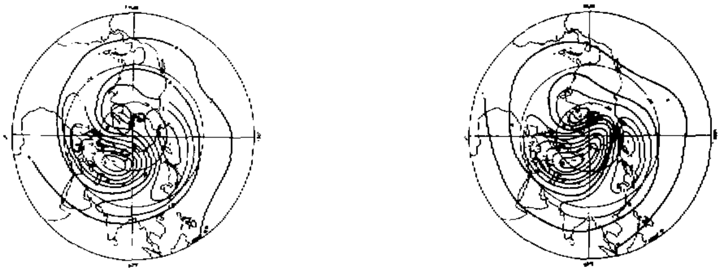

Fig.7. The disturbance patterns (Unit in 100 m) at 30 Km height forced by topography and heat sources in the different categories. (a) in the easterly category; (b) in the westerly category.

V. CONCLUSIONS

The harmonic analyses of monthly mean total ozone in the Northern Hemisphere for 26 years during 1960–1985 are made by using the Fourier expansion in this paper. The analysed results show that there is an obvious quasi–biennial oscillation in the interannual variation of amplitude for wavenumbers 1 and 2 in the north of 30°N. Amplitudes of total ozone for wavenumbers 1 and 2 are larger in the westerly category of the equatorial QBO during the late winter. These are in good argreement with the observational distributions of planetary waves.

In this paper, a quasi–geostrophic 34–level, two–dimensional model with the Rayleigh friction, the Newtonian cooling and the horizontal eddy thermal diffusion is used to calcutate the forced planetary waves for the late winter during the different categories of the equatorial QBO. The results show that the amplitudes of wavenumbers 1 and 2 in the westerly category are larger than that in the easterly category. This can demonstrate that the planetary–scale disturbances forced by topography and heat sources may cause larger amplitudes of total ozone distribution during the westerly category of the equatorial QBO.

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