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The Propagation and Transport Effect of Planetary Waves in the Northern Hemisphere Winter

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ABSTRACT

Based on the transformed Eulerian–mean equations, the dynamics of planetary waves are discussed. Both observations and simulations indicate that in the Northern Hemisphere winter there are two waveguides for the meridional propagation of quasi–stationary planetary waves. One is the high latitude waveguide, and the other is the low latitude waveguide. These results are in good agreement with theoretical analysis. Moreover, the convergence of EP flux indicates that the stratospheric sudden warming is the result of anomalous planetary wave propagation along the high latitude waveguide and its interaction with mean flows. The tropical quasi–biennial oscillation (QBO) winds, which represent one significant variation of zonal flow in the lower stratosphere at low latitudes, can influence the low latitude waveguide of planetary wave propagation. Our results of the wave–mean flow coupled model show that these tropical winds can also modulate the high latitude waveguide significantly in the case of wave–mean flow interaction.

The transport effect of planetary waves on ozone is also analyzed. The residual mean circulation forced by planetary waves indicates that there is strong transport circulation for the dissipative planetary waves. Under the forcing of northward eddy heat transport, a positive transport circulation can result which rises at low latitudes and sinks at high latitudes. At the same time, the modification of planetary wave propagation by the equatorial QBO winds is shown to have an important impact on the transport circulation. The model results indicate that the meridional transport is amplified during the easterly phase of the QBO. This mechanism may explain the interannual variability of ozone in the stratosphere at high latitudes.

Key words: quasi–stationary planetary waves, wave propagation, planetary wave–mean flow interaction, transport effect

1. Introduction

It is well known that the concept of Rossby wave energy dispersion proposed by Rossby (1945) and Yeh (1949) has been widely used in the dynamical studies of weather and atmospheric large–scale disturbances for more than forty years. This theory can explain the propagation of atmospheric large–scale disturbances and has been regarded as one of the most important classical theories in atmospheric dynamics. The energy of waves is dependent upon their frequency and is propagated with the group velocity of the waves. Yeh (1949) used this principle to explain the dynamical effect of a large–scale disturbance on its upper and lower reaches in a uniform flow. At the same time, Charney (1947) and Eady (1949) put forward the theory of baroclinic instability of long waves, and Kuo (1949) proposed the theory of barotropical instability of long waves. After that, these theories were widely used to explain

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the evolution and propagation of perturbations in a uniform basic flow and laid a foundation for modern atmospheric dynamics.

From the 1960s, many meteorologists paid attention to the energy dispersion of waves in the vertical direction. For example, Charney and Drazin (1961) and Eliassen and Palm (1961) independently investigated the vertical propagation of quasi-stationary planetary waves in basic flow with vertical shear. Matsuno (1970, 1971) simulated the vertical propagation of quasi-stationary planetary waves from the troposphere to the stratosphere with a basic flow quite similar with the real one, and proposed the mechanism of stratospheric sudden warming. However, these investigations discussed only the propagation and evolution of waves in the zonal and vertical directions, not in the meridional direction. In recent decades, due to the discovery of many observational facts, much attention has been given to the propagation of large-scale disturbances in a non-uniform atmosphere and their interaction with the zonal flow, especially in the three-dimensional spherical atmosphere. In the early 1980s, Huang and Gambo (1982, 1983a, 1983b) investigated the characteristics of three-dimensional propagation of quasi-stationary planetary waves during the Northern Hemisphere winter and summer. They proposed theoretically that in the Northern Hemisphere winter there are two waveguides for the propagation of quasi-stationary planetary waves.

As is well known, planetary waves are the dominant wave structure in the stratosphere (Andrews et al. 1987). They may exert significant influences on the distribution of trace species, such as ozone, in the middle atmosphere. Ozone is formed mainly in the tropical regions, while the observed total ozone and its variations are the largest at high latitudes. So there should be a dynamical transport of ozone from the tropical regions to the middle and high latitudes. On the basis of observed ozone data, Dobson (1956) pointed out that a poleward transport circulation ascending at low latitudes and descending at middle and high latitudes was needed to account for the increase of ozone from the equator to high latitudes. Murgatroyd and Singleton (1961) obtained a similar circulation from the results of a radiative heat budget calculation with neglect of eddy terms. Nevertheless, the eddy transport neglected by Murgatroyd and Singleton is important (Vincent 1968) and it was shown that the cancellation between the transport by mean meridional circulation and eddy transport holds exactly for steady and conservative waves (Andrews and McIntyre 1976, 1978). Therefore, in the past, most studies assumed that waves were steady and conservative, and so they could be carried out using the Eulerian mean approach. Matsuno (1980) explained that the mean meridional circulation contained, to a large extent, a component that was forced by eddy transport. This part of the mean circulation would be cancelled naturally by the eddy transport and the net transport circulation would be the residual mean meridional circulation. So the effects of planetary wave transport are closely related to the interactions between wave and mean flow.

In this paper, based on the transformed Eulerian-mean equations, we will first investigate the meridional propagation of planetary waves in the Northern Hemisphere winter. Then we shall discuss the effect of planetary wave-mean flow interaction on the phenomena of stratospheric sudden warming and extratropical QBO from the viewpoint of waveguides for planetary wave propagation in sections 2 and 3 respectively. We shall analyze further the transport effect of planetary waves on ozone in section 4. Finally, summaries are given in section 5.

2. The transformed Eulerian-mean equations and stratospheric sudden warming

In the 1940s, Rossby (1941) pointed out that eddies are necessary for the maintenance of zonal flow. Starr (1948) and Yeh and Chu (1958) stated that the maintenance of zonal flow is due to the angular momentum transfer by eddies. Lorenz (1967) showed that eddies could not only accelerate zonal–mean flow but also induce mean meridional circulation. Therefore, the dispersion or propagation of waves can cause the variation of zonal mean flow and meridional mean flow. This can be described more conveniently with the transformed Eulerian–mean equations (Andrews et al. 1987). The transformed Eulerian–mean equations can be written as follows,

$$\frac{\partial \bar{u}}{\partial t} - f\bar{v}^* - \bar{D} = \frac{1}{a\cos\varphi} \nabla \cdot \boldsymbol{F} , \tag{1}$$

$$f\bar{u}_p - \frac{R}{a}\bar{\theta}_\varphi = 0 , \tag{2}$$

$$\frac{1}{a\cos\varphi}(\bar{v}^* \cos\varphi)_\varphi + \bar{\omega}_p^* = 0 , \tag{3}$$

$$\frac{\partial \bar{\theta}}{\partial t} + \bar{\theta}_p \bar{\omega}^* - \bar{S} = 0 , \tag{4}$$

where $(\bar{v}^*, \bar{\omega}^*)$ is the residual meridional circulation, i. e.,

$$\bar{v}^* = \bar{v} - \frac{\partial}{\partial p}\left(\frac{\overline{\theta' v'}}{\bar{\theta}_p}\right) , \tag{5}$$

$$\bar{\omega}^* = \bar{\omega} + \frac{1}{a\cos\varphi}\frac{\partial}{\partial \varphi}\left(\frac{\overline{\theta' v'}\cos\varphi}{\bar{\theta}_p}\right) , \tag{6}$$

The vector $\boldsymbol{F}$ is the Eliassen–Palm flux (EP flux), introduced by Eliassen and Palm (1961) and extended by Andrews and McIntyre (1976). However, Andrews and McIntyre demonstrated the conservative properties of wave activity only in the case of a β–plane approximation. Obviously, the β–plane approximation does not hold for planetary–scale waves because the meridional wavelength of these waves extends from high to low latitudes. Therefore, it is necessary to investigate the wave–action conservation equation and the wave–action flux in a spherical atmosphere. Edmon et al. (1980) extended the wave–action conservation from a β–plane approximation case to a spherical atmosphere under the assumption of the smallness of $\Delta f / f$, where f is the Coriolis parameter and Δf is its meridional change. It is evident that this assumption does not hold for the planetary waves in low latitudes, because there the change of Coriolis parameter is large and the Coriolis parameter is small. Thus, it is necessary to reasonably derive the wave–activity conservation. In this way, it is possible to obtain the accurate relationship between the EP flux divergence and the evolution of basic flow.

Huang (1984) derived the potential vorticity equation with the influence of the divergent component of motion on the meridional advection of potential vorticity. From this, the wave–action conservation in a spherical atmosphere is demonstrated using the WKBJ method, i. e.,

$$\frac{\partial A_m}{\partial t} + \nabla \cdot \boldsymbol{F} = 0 , \tag{7}$$

where A_m is the wave action and $\boldsymbol{F}$ is the EP flux, i. e.,

$$\boldsymbol{F} = (-a\cos\varphi\overline{u'v'},\ fa\cos\varphi\overline{\theta' v'}/\bar{\theta}_p) . \tag{8}$$

Moreover, it is also demonstrated that in a spherical atmosphere, EP flux is parallel to the local group velocity of the wave. With a primitive equations model for describing planetary

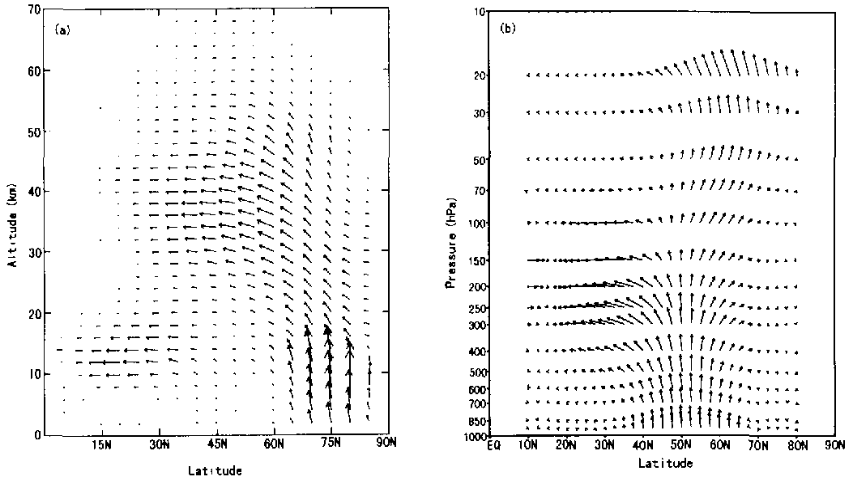

Fig. 1. (a) The modeled meridional distribution of EP fluxes in the Northern Hemisphere. (b) The observed mean EP fluxes in the Northern Hemisphere winter from 1958 / 1959—1997 / 1998.

waves, Chen and Huang (1999) investigated the propagation of quasi–stationary waves in a three–dimensional atmosphere with EP flux of waves. Fig. 1a presents the simulated meridional distribution of the EP fluxes in the Northern Hemisphere. The distributions of EP flux vectors show vividly that there are two waveguides for the quasi–stationary planetary wave propagation in winter. One is from the lower troposphere into the stratosphere in high latitudes. The other is from the troposphere in middle latitudes to the upper troposphere in low latitudes. These are in good agreement with the theoretical analysis of Huang and Gambo (1983b). Using NCEP reanalysis data, we computed the 40 years averaged EP fluxes in the Northern Hemisphere winter from 1958 / 1959—1997 / 1998 (Fig. 1b). The NCEP reanalysis data includes the lower stratosphere. So we see that the observations confirm the results of both the theory and the model by showing the quite similar two waveguides.

The EP flux is not only a useful measure of wave propagation, but also a useful tool for diagnosing wave–mean flow interaction. The EP flux has been widely applied to the investigation of acceleration or deceleration of zonal mean flow. For example, Palmer (1981a, 1981b), Kanzawa (1980, 1984), O'Neill and Youngblut (1982) performed an analysis on stratospheric sudden warming using EP flux diagnosis. Huang and Zou (1989) discussed the formation and maintenance of blocking in the troposphere and stratospheric sudden warming in the Northern Hemisphere during 14–28 February 1979 with the EP flux. Here we give the evolution of zonal wind and divergence of EP flux at 75°N. As shown in Fig. 2, the convergence of the EP flux appears in the upper troposphere in high latitudes due to the upward propagation of the planetary wave. At the same time, the basic flow is decelerated and the warming occurs. Therefore, the stratospheric sudden warming is the result of anomalous planetary wave propagation along the high latitude waveguide and its interaction with mean flows.

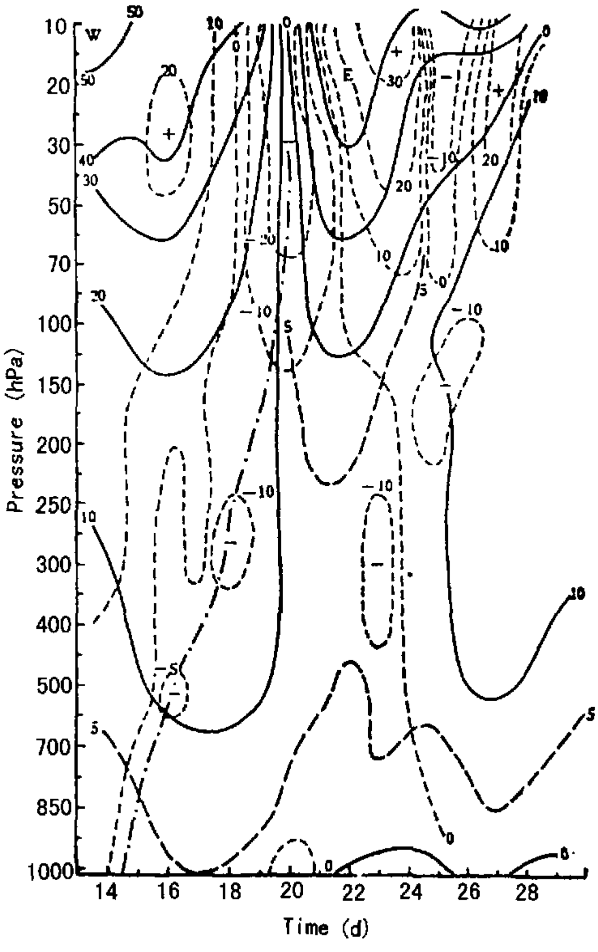

Fig. 2. Relationship between the zonal-mean wind (solid curves) and the divergence of EP flux (dashed curves) at 75°N. (Units for wind: m s^{-1}, Units for divergence: 10^{14} m^3).

3. The modulation of planetary wave propagation by tropical QBO zonal winds

The presence of a quasi-biennial oscillation (QBO) in zonal winds in the equatorial stratosphere is well known (Reed et al. 1961). The generally accepted theory of the QBO was developed by Lindzen and Holton (1968) and Holton and Lindzen (1972). Quasi-biennial variations have also been detected in middle and high latitudes in both dynamical and tracer fields, including ozone (Holton and Tan 1982; Hasebe 1983; Labitzke and van Loon 1988). The basic mechanism responsible for the ozone QBO near the equator appears to be well understood (Andrews et al. 1987). However, the mechanism for the extratropical QBO signal

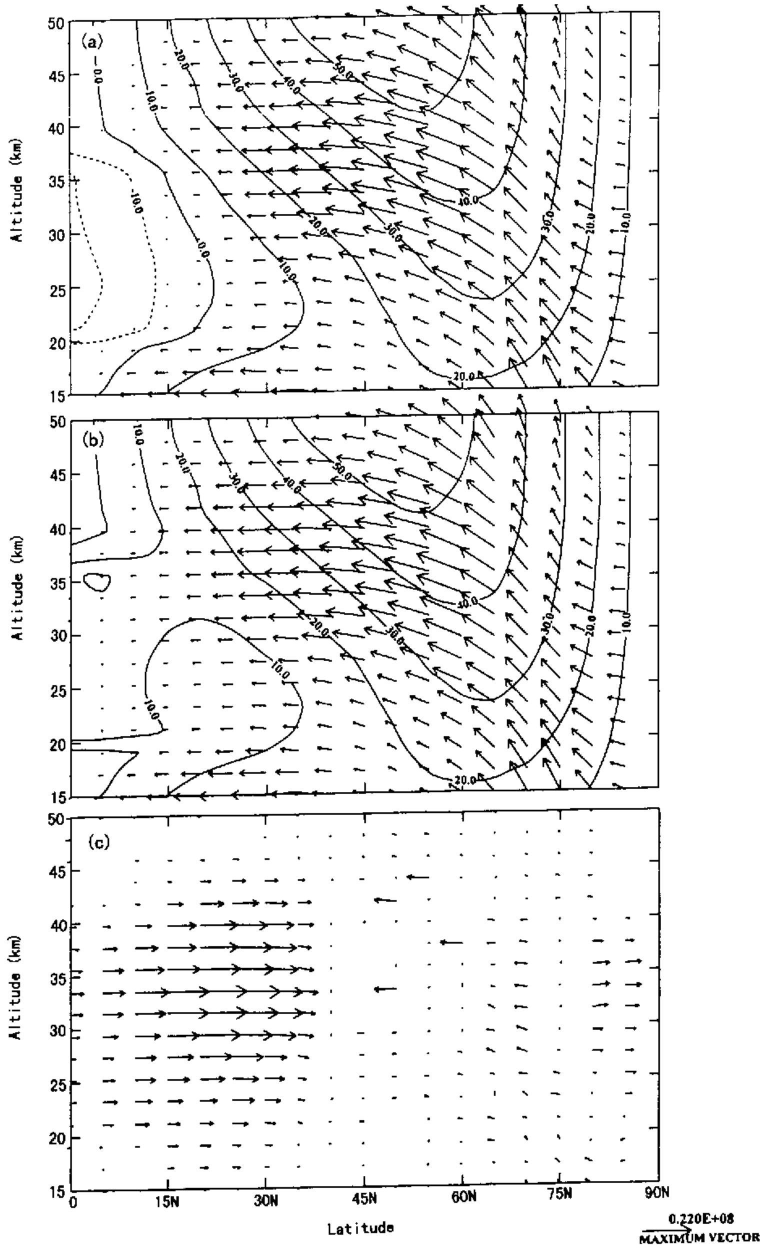

Fig. 3. (a) The EP fluxes and zonal winds for the easterly phase of the QBO in the stratosphere of the Northern Hemisphere. (b) For the westerly phase. (c) The difference of EP fluxes with easterly–minus–westerly.

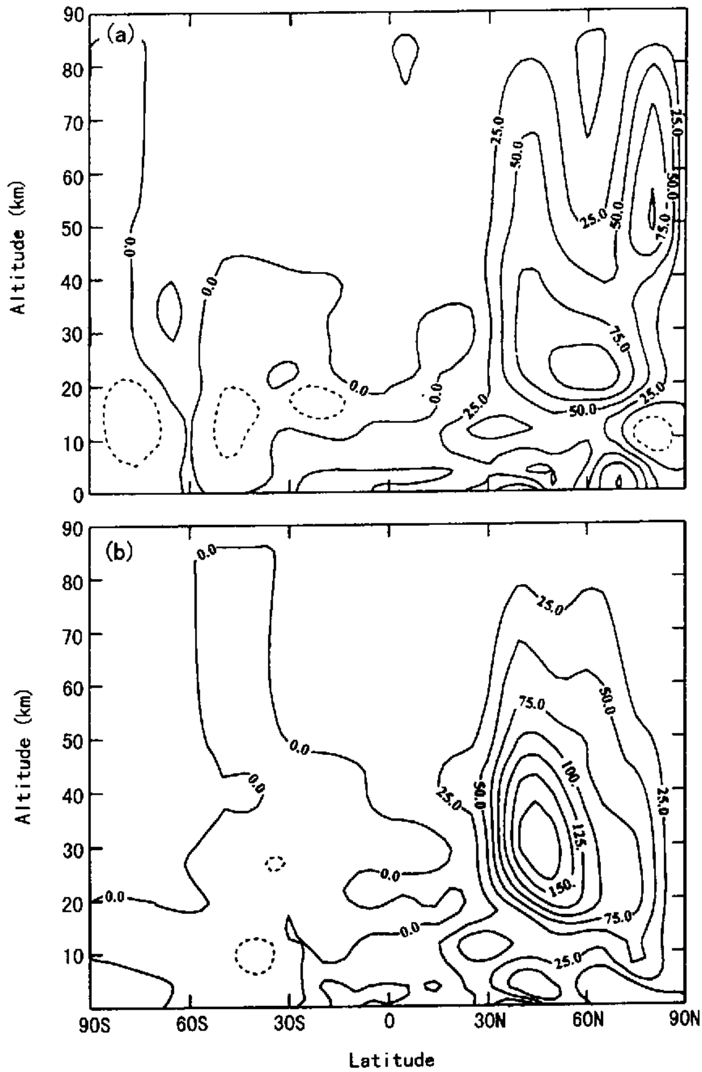

Fig. 4. (a) The difference of amplitudes with easterly–minus–westerly for wavenumber 1. (b) For wavenumber 2. (Units: m).

in the zonal wind, temperature, and ozone distributions is not well understood. Quasi–stationary planetary waves are produced in the troposphere by the forcing of topography and diabatic heating. And as shown in section 2, quasi–stationary planetary waves can propagate into the stratosphere along the high latitude waveguide and propagate to the lower stratosphere via the low latitude waveguide in the Northern Hemisphere winter. As we know, the planetary wave propagation varies with the different structure of zonal flow. Since the tropical QBO wind is one significant variation of zonal flow in the stratosphere, it may influence

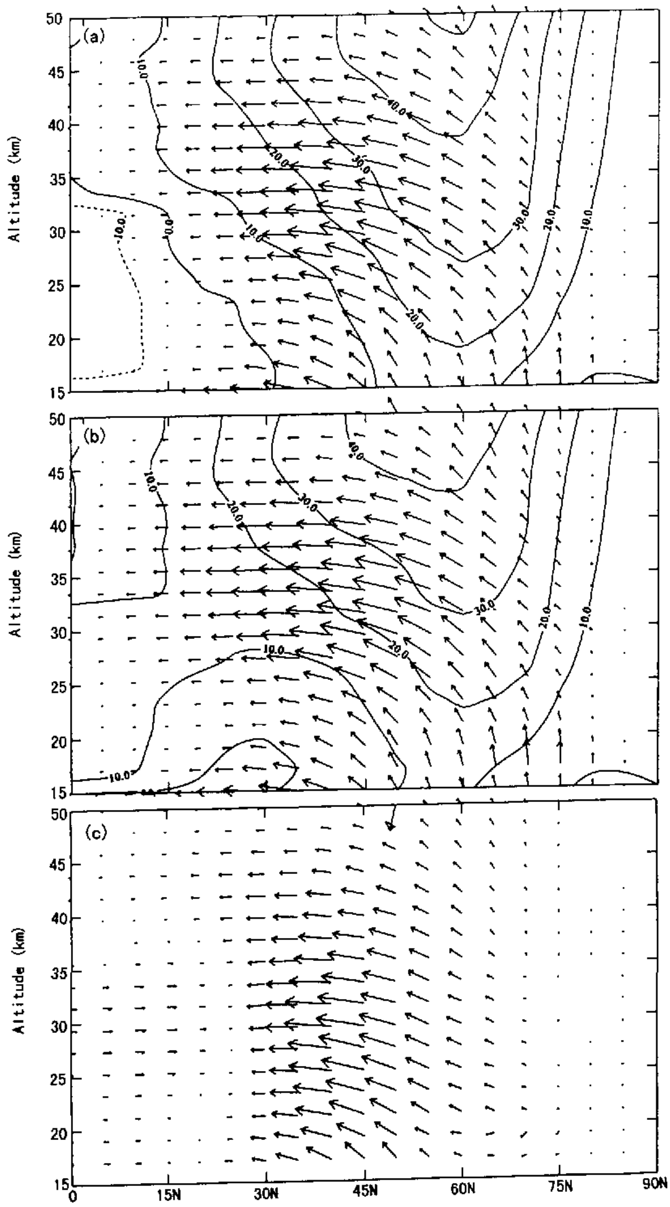

Fig. 5. Same as Fig. 3, but for the case of wave–mean flow interaction.

the propagation of planetary waves. Chen and Huang (1996a, 1996b, 1999) investigated the interannual variation of planetary waves with a coupled wave–mean flow model in both the steady flow case and the non–steady flow case. In the following, we will show the influence of tropical QBO winds on planetary wave propagation.

The wave–mean flow coupled model is a primitive equation model with the log–pressure altitude as the vertical coordinate. The model details can be seen in Chen and Huang (1999). We integrated the model in the case of steady flow and in the case of wave–mean flow interaction. In the linear case of steady flows, the difference of dissipative planetary wave propagation between easterly and westerly phases of the QBO is apparent, but is confined chiefly to low latitudes with a weak difference at high latitudes. Fig. 3 presents the modeled 35–day mean EP fluxes and zonal winds in the linear case of steady flows for the easterly and the westerly phases of QBO in the stratosphere of Northern Hemisphere winter. Both Figs. 3a and 3b display upward and equatorward refraction of the EP fluxes. However it can be discerned that the planetary waves can propagate into lower latitudes when the tropical winds are westerly, because in this case the zero wind line is shifted into the summer (southern) hemisphere. When the tropical winds are easterly, the zero wind line is shifted further north. Therefore the easterly winds confine the planetary waves to more further north. The difference of the easterly phase minus the westerly phase is shown in Fig. 3c. From this diagram, it is clear that the main difference is confined around the shifting area of the zero wind line of the tropical QBO winds. A westerly over the tropics lets the planetary waves propagate across the equator, while in the phase of the easterly, the planetary waves are prevented from propagating into low latitudes. Under these conditions, the differences of planetary wave amplitudes with easterly–minus–westerly present a dipole pattern with increasing values at high latitudes (figure not shown).

The situation is quite different when the planetary waves are coupled with the zonal mean flows. The differences of planetary wave amplitudes between the easterly phase and the westerly phase of the QBO are shown in Fig. 4. It can be seen that the planetary waves are stronger at middle–high latitudes of the Northern Hemisphere in the easterly phase winter than in the westerly phase winter. Eliassen–Palm cross sections for the easterly and the westerly phase winters are shown in Fig. 5. Although it is similar that the planetary waves are blocke d near the zero wind surface in the easterly phase winter (Fig. 5a) and propagate into lower latitudes in the westerly phase winter (Fig. 5b), their difference (easterly–minus–westerly) presents a prominent feature with larger upward and equatorward fluxes at middle and high latitudes (Fig. 5c). Comparing this with Fig. 3, it is clear that in this quasi–linear case of wave–mean flow interaction, the tropical QBO winds can significantly modulate the planetary wave propagation at middle–high latitudes.

Therefore, in the linear case of steady flows, the tropical QBO winds mainly influence the low latitude waveguide since the variation of zonal flow appears in the lower stratosphere at low latitudes. However, in the case of wave–mean flow interaction, the tropical QBO winds can modulate the high latitude waveguide significantly. The impact of this modification on the transport effect of planetary waves will be discussed in section 4.

4. The transport effect of planetary waves on ozone in the atmosphere

It is well known that ozone forms mainly in the tropical regions, but the total ozone and its variations are the largest in high latitudes. So there must be a dynamical transport of ozone from the tropical regions to the middle and high latitudes. The study on this dynamical transport has been one of the significant works of scientific research in the middle atmosphere for a long time (Andrews et al. 1987). Since the traditional Eulerian mean circulation is not suitable for studying the transport of ozone in the stratosphere, the generalized Lagrangian mean, which is made along the trajectory of fluid parcels, was suggested for the investigation of the transport circulation (Andrews and McIntyre 1978). Furthermore, the residual mean circulation may be regarded as an approximation to the Lagrangian advective motion projected onto the meridional plane (Plumb and Mahlman 1987).

Using the log–pressure coordinate as the vertical coordinate, we obtain a set of equations in the β–plane from Equations (1)—(6), as in Chen and Huang (1995). Then the equation for the stream function Ψ^* of residual mean circulation can be obtained with the assumption of $\bar{D}=\bar{S}=0$,

$$\frac{f_0^2}{N^2}\left(\frac{\partial^2\Psi^*}{\partial z^2}+\frac{1}{H}\frac{\partial\Psi^*}{\partial z}\right)+\frac{\partial^2\Psi^*}{\partial y^2}=\frac{\rho_0 f_0}{N^2}\frac{\partial}{\partial z}(\rho_0\nabla\cdot F) . \tag{9}$$

From Eq.(9), the following results can be obtained.

(1) The case of no waves

When there is no planetary wave in the stratosphere, it is quite evident that the Lagrangian mean circulation is zero.

(2) The case of steady, conservative planetary waves

If the upward–propagating planetary waves are steady and conservative, the amplitudes of the planetary waves do not change with height. Thus, $\nabla\cdot F=0$, and the Lagrangian mean circulation is also zero. In this case, the forced Eulerian mean circulation is cancelled exactly by the effect of the waves, as suggested by Matsuno (1980).

(3) The case of dissipative planetary waves

When the dissipative planetary waves propagate upward, their amplitudes will change with height, as do the eddy heat transports. Therefore, the forcing term of the residual mean circulation is not zero, which may cause the wave–mean flow interaction. We take the eddy heat transport in the form of a function as follows:

$$\overline{v'T'}=\begin{cases}A_0\cdot\sin^2\frac{\pi}{D}(z-z_0)\cdot\sin^2\frac{\pi}{L}y\ , & z_0\leqslant z\leqslant z_0+D\\ 0\ , & z<z_0\quad \text{or}\quad z>z_0+D\end{cases}$$

where A_0 is a constant, z_0 is a specified height, and D is the vertical range of eddy heat transport. Taking the values of the parameters as: $L=5000$ km, $H=7$ km, $D=12$ km, $f_0=10^{-4}\ \mathrm{s}^{-1}$, $N=2\times10^{-2}\ \mathrm{s}^{-1}$, $z_0=14$ km, and $A_0=50\ \mathrm{m\ s^{-1}\ K}$, the solutions of the elliptical equation (9) can be obtained. Fig. 6 shows the forced Eulerian mean circulation and the force d residual mean circulation. The Eulerian mean circulation is an obvious negative circulation at middle latitudes, and two weak positive circulations are distributed in the south and the north respectively. The residual mean circulation, on the other hand, is an obvious one–cell positive circulation. That means the transport is from the low latitudes to the high latitudes when there is a northward eddy heat transport in the stratosphere at middle latitudes. Moreover, this transport due to planetary wave propagation has seasonal variability with a maximum during the Northern Hemisphere winter and a minimum in the summer (see Chen and Huang 1995, 1996a, 1996b).

As discussed in section 3, the planetary wave propagation is influenced by the tropical QBO winds. Fig. 7 presents the result with the residual meridional circulation of the easterly phase winter minus that of the westerly phase winter in the case of wave–mean flow interaction. The difference shows that the meridional transport is amplified during the easterly phase of QBO. Therefore, the modification of planetary wave propagation by the equatorial QBO winds may also explain interannual variability of ozone in the stratosphere at high

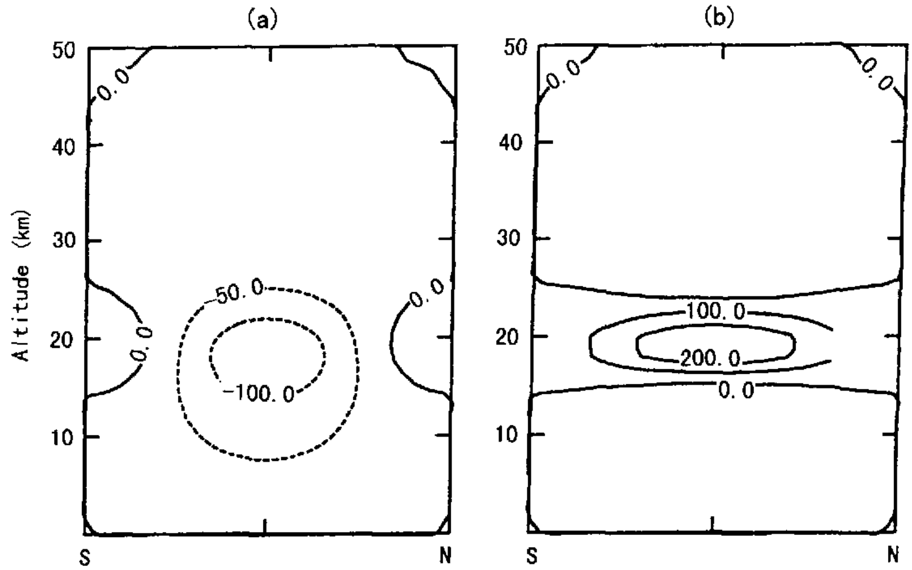

Fig. 6. The forced Eulerian mean circulation (a) and residual mean circulation (b) by the eddy heat transport in the stratosphere. (Units: kg m^{-1} s).

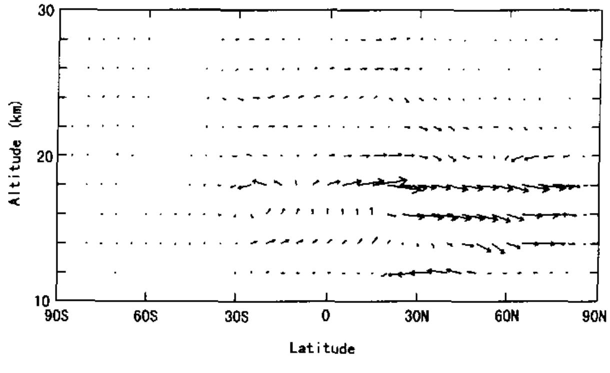

Fig. 7. The distribution with the transport circulation of the easterly phase winter minus the westerly phase winter.

latitudes. In the lower stratosphere, ozone may be considered as a passive tracer of the flow. The photochemical time constant of ozone decreases with increasing altitude as shown by Rood and Schoeberl (1983). Thus the ascending motion should decrease the ozone values, and the descending motion should do the reverse. The enhanced transport during the easterly phase should increase ozone values at middle and high latitudes. This tendency is in agreement with the behavior of total column ozone (Hasebe 1983; Bowman 1989).

5. Summaries

In this paper, we investigate planetary wave dynamics based on the transformed Eulerian–mean equations. Specifically, from the viewpoint of waveguides for planetary wave propagation, we address the effect of planetary wave–mean flow interaction on the phenomena of stratospheric sudden warming and QBO of extratropical ozone. The transport effect of planetary waves on ozone is also analyzed.

The quasi–stationary planetary waves are produced in the troposphere by the forcing of topography and diabatic heating. Both the observations and the simulations show that in the Northern Hemisphere winter there are two waveguides for the propagation of quasi–stationary planetary waves. One is from the middle latitudes to the high latitudes and propagates into the stratosphere. The other is from the lower troposphere in the middle latitudes to the upper troposphere in the low latitudes. These results are in good agreement with theoretical analysis. Moreover, the planetary wave propagation varies with the different structures of zonal flow, and also the waves may interact with the mean flows. The convergence of EP flux indicates that the stratospheric sudden warming is the result of anomalous planetary wave propagation along the high latitude waveguide and its interaction with mean flows. The QBO of tropical winds is one significant variation of zonal flow in the lower stratosphere at low latitudes. These tropical QBO winds should influence the low latitude waveguide of planetary wave propagation. Our results of the wave–mean flow coupled model indicate that these tropical winds can also modulate the high latitude waveguide significantly in the case of wave–mean flow interaction.

The residual mean circulation and the Eulerian–mean circulation forced by planetary waves are analyzed theoretically. The results show that there is no transport effect when the waves are steady and conservative. However, there is strong transport circulation for the dissipative planetary waves. Under the forcing of northward eddy heat transport, a positive transport circulation can occur which rises at low latitudes and sinks at high latitudes. Meanwhile, the modification of planetary wave propagation by the equatorial QBO winds is shown to have an important impact on the transport circulation. The model results indicate that the meridional transport is amplified during the easterly phase of the QBO. This mechanism may explain the interannual variability of ozone in the stratosphere at high latitudes.

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REFERENCES

Andrews, D. G., and M. E. McIntyre, 1976: Planetary waves in horizontal and vertical shear: The generalized Eliassen–Palm relation and the mean zonal acceleration. *J. Atmos. Sci.*, **33**, 2031–2048.

Andrews, D. G., and M. E. McIntyre, 1978: An exact theory for nonlinear waves on a Lagrangian–mean flow. *J. Fluid Mech.*, **89**, 609–646.

Andrews, D. G., J. R. Holton, and C. B. Leovy, 1987: *Middle Atmospheric Dynamics*, Academic Press, 489pp.

Bowman, K. P., 1989: Global patterns of the quasi–biennial oscillation in total ozone. *J. Atmos. Sci.*, **46**, 3328–3343.

Charney, J. G., 1947: The dynamics of long waves in a baroclinic westerly current. *J. Meteor.*, **4**, 135–163.

Charney, J. G., and G. Drazin, 1961: Propagation of planetary–scale disturbances from the lower into the upper atmosphere. *J. Geophys. Res.*, **66**, 83–109.

Chen Wen., and Huang Ronghui, 1995: The dynamical effect of planetary wave transport on ozone in the atmosphere. *Chinese Journal of Atmospheric Sciences*, **19**(3), 219–229.

Chen Wen, and Huang Ronghui, 1996a: Numerical study of seasonal and interannual variabilities of ozone due to planetary wave transport in the middle atmosphere. Part I: The case of steady mean flows. *Chinese Journal of Atmospheric Sciences*, **20**(3), 221–231.

Chen Wen, and Huang Ronghui, 1996b: Numerical study of seasonal and interannual variabilities of ozone due to planetary wave transport in the middle atmosphere. Part II: The case of wave–flow interaction. *Chinese Journal of Atmospheric Sciences*, **20**(4), 318–321.

Chen Wen, and Huang Ronghui, 1999: The modulation of planetary wave propagation by the tropical QBO zonal winds and the associated effects in the residual meridional circulation. *Contrib. Atmos. Phys.*, **72**, 187–204.

Dobson, G. M. B., 1956: Origin and distribution of the polyatomic molecules in the atmosphere. *Proc. Roy. Soc. London*, Ser. A, **236**, 187–193.

Eady, E. T., 1949: Long waves and cyclone waves. *Tellus*, **1**, 33–52.

Edmon, M. J., B. J. Hoskins, and M. E. McIntyre, 1980: Eliassen–Palm sections for the troposphere. *J. Atmos. Sci.*, **37**, 2600–2617.

Eliassen, A., and E. Palm, 1961: On the transfer of energy in stationary mountain waves. *Geophys. Publ.*, **22**, 1–23.

Hasebe, F., 1983: Interannual variations of global ozone revealed from NIMBUS 4 BUV and ground based observations. *J. Geophys. Res.*, **88**, 6819–6834.

Holton, J. R., and R. S. Lindzen, 1972: An updated theory for the quasi–biennial cycle of the tropical stratosphere. *J. Atmos. Sci.*, **29**, 1076–1080.

Holton, J. R., and H.–C. Tan, 1982: The quasi–biennial oscillation in the Northern Hemisphere lower stratosphere. *J. Meteor. Soc. Japan*, **60**, 140–148.

Huang Ronghui, and K. Gambo, 1982: The response of a hemispheric multi–level model atmosphere to forcing by topography and stationary heat sources, Part I, II. *J. Meteor. Soc. Japan*, **60**, 78–108.

Huang Ronghui, and K. Gambo, 1983a: The response of a hemispheric multi–level model atmosphere to forcing by topography and stationary heat sources in summer. *J. Meteor. Soc. Japan*, **61**, 495–509.

Huang Ronghui, and K. Gambo, 1983b: On other wave guide in stationary planetary wave propagations in the winter Northern Hemisphere. *Science in China*, **26**, 940–950.

Huang Ronghui, 1984: Wave action conservation equation for planetary wave in a spherical atmosphere and waveguides of stationary planetary wave propagations shown by wave action flux. *Science in China*, **27**, 766–775.

Huang Ronghui, and Zou Han, 1989: Interaction between the upward propagating planetary waves and the zonal mean flow in a spherical baroclinic atmosphere. *Chinese Journal of Atmospheric Sciences*, **9**, 413–422.

Kanzawa, H., 1980: The behavior of mean zonal wind and planetary–scale disturbances in the troposphere and stratosphere during the 1973 sudden warming. *J. Meteor. Soc. Japan*, **58**, 329–356.

Kanzawa, H., 1984: Eliassen–Palm flux diagnostics and the effect of the mean wind on planetary wave propagation for an observed sudden stratospheric warming. *J. Meteor. Soc. Japan*, **60**, 1063–1073.

Kuo, H. L., 1949: Dynamic instability of two–dimensional nondivergent flow in a barotropic atmosphere. *J. Meteor.*, **6**, 105–122.

Labitzke, K., and H. van Loon, 1988: Associations between the 11–year solar cycle, the QBO, and the atmosphere. Part I: The troposphere and stratosphere in the northern hemisphere winter. *J. Atmos. Terr. Phys.*, **50**, 197–206.

Lindzen, R. S., and J. R. Holton, 1968: A theory of the quasi–biennial oscillation. *J. Atmos. Sci.*, **25**, 1095–1107.

Lorenz, E. N., 1967: The nature and theory of the general circulation of the atmosphere, WMO–No. 218, TP. 115, 161pp.

Matsuno, T., 1970: Vertical propagation of stationary planetary waves in the winter Northern Hemisphere. *J. Atmos. Sci.*, **27**, 871–883.

Matsuno, T., 1971: A dynamical model of the stratospheric sudden warming. *J. Atmos. Sci.*, **28**, 1479–1494.

Matsuno, T., 1980: Lagrangian motion of air parcels in the stratosphere in the presence of planetary waves. *Pure Appl. Geophys.*, **118**, 189–216.

Murgatroyd, R. J., and F. Singleton, 1961: Possible meridional circulations in the stratosphere and mesosphere. *Quart. J. Roy. Meteor. Soc.*, **87**, 125–135.

O'Neill, A., and C. E. Youngblut, 1982: Stratospheric warmings diagnosed using the transformed Eulerian mean equation and the effect of the mean state on wave propagation. *J. Atmos. Sci.*, **39**, 1370–1386.

Palmer, T. N., 1981a: Diagnostic study of a wave number 2 stratospheric sudden warming in a transformed Eulerian-mean formalism. *J. Atmos. Sci.*, **38**, 844–855.

Palmer, T. N., 1981b: Aspects of stratospheric sudden warming studied from a transformed Eulerian-mean viewpoint. *J. Geophys. Res.*, **86**, 9679–9687.

Plumb, R. A., and J. D. Mahlman, 1987: The zonally-averaged transport characteristics of the GFDL general circulation / transport model. *J. Atmos. Sci.*, **44**, 298–327.

Rood, R. B., and M. R. Schoeberl, 1983: A mechanistic model of Eulerian, Lagrangian mean, and Lagrangian ozone transport by steady planetary waves. *J. Geophys. Res.*, **88**, 5208–5218.

Reed, R. J., W. J. Campbell, L. A. Rasmusson, and D. G. Rogers, 1961: Evidence of the downward-propagating annual wind reversal in the equatorial stratosphere. *J. Geophys. Res.*, **66**, 813–818.

Rossby, C. G., 1941: The scientific basis of modern meteorology. Yearbook of Agriculture, U. S. Dept. of Agriculture, 599–655.

Rossby, C. G., 1945: On the propagation of frequencies and energy in certain types of oceanic and atmospheric waves. *J. Meteor.*, **2**, 187–204.

Starr, V. P., 1948: An essay on the general circulation of the earth's atmosphere. *J. Meteor.*, **5**, 39–43.

Vincent, D. G., 1968: Mean meridional circulation in the northern hemisphere lower stratosphere during 1964 and 1965. *Quart. J. Roy. Meteor. Soc.*, **94**, 333–349.

Yeh, T. C., 1949: On energy dispersion in the atmosphere. *J. Meteor.*, **6**, 1–16.

Yeh, T. C., and B. Z. Chu, 1958: Some Fundamental Problems of the General Circulation of the Atmosphere, Science Press, Beijing, 159pp (in Chinese).

北半球冬季行星波的传播及其输运作用

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摘 要

利用变换欧拉平均方程讨论了行星波动力学。观测和模拟结果都表明，在北半球冬季准定常行星波的经向传播存在两支波导。一支为高纬度波导，另一支则为低纬度波导。这些结果与理论分析相当一致。通过对 EP 通量进一步的研究表明，平流层爆发性增温是沿高纬度波导传播的异常行星波与平均气流相互作用的结果。而热带风场的准两年周期振荡(QBO)是低纬度平流层下层大气纬向平均流的一个重要年际变化，它可以影响行星波沿低纬度波导的传播；此外，由一个行星波—平均流耦合模式模拟的结果表明，这个热带风场的变化还可以通过波流相互作用调制行星波沿高纬度波导的传播。

行星波对臭氧的输运作用在文中也进行了分析。行星波强迫出的剩余平均环流表明，耗散的行星波有强的输运作用；向北的涡动热量输送可以强迫出一个正的输运环流，其在低纬度上升并在高纬度下沉。同时研究还表明，热带风场的 QBO 对行星波传播的调制对输运环流也有重要影响，模式结果表明，在 QBO 的东风位相期间行星波引起的输运作用明显增强，其结果可用于解释平流层高纬度臭氧的年际变化。

关键词: 准定常行星波，波的传播，波流相互作用，输运作用