3 FORCED PLANETARY WAVES, STRATOSPHERIC OZONE AND PSEUDO-CRITICAL LEVELS: INGREDIENTS FOR THE STRATOSPHERIC FORCING OF THE TROPOSPHERE

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1. INTRODUCTION

Forced planetary-scale waves generally extend throughout the troposphere and stratosphere and thus provide an important connection between these two regions of the atmosphere. Because these planetary waves originate from mechanical and thermal forcing in the troposphere, planetary wave energy propagates upward into the stratosphere where momentum deposition via wave damping drives the zonal-mean stratospheric circulation. Here we present striking evidence showing that the interactions between stratospheric ozone and planetary-scale waves affect the wave damping rate and thus the planetary wave structure. In some cases, the changes in planetary wave structure radiates downward into the troposphere.

Using analytical (WKB) and one-dimensional numerical modeling approaches, we show that there is an intimate connection between the zonal-mean background flow, ozone field, and forced planetary wave field in the stratosphere, a connection that in some cases leads to significant changes in the tropospheric wave fluxes. We find that this stratosphere-troposphere connection, which hinges on the interactions between the wave and ozone fields, is dramatically strengthened in the presence of pseudo-critical levels, i.e., at those levels where the Doppler shifted frequency and potential vorticity gradient vanish.

2. THE MODEL

We consider a stratified atmosphere on a periodic β -plane centered at 45^oN in which the quasigeostrophic flow is linearized about a steady, zonally averaged basic state that is in radiative-photochemical equilibrium. The *steady*, *linear* response of this model atmosphere to Newtonian cooling and ozone heating is described by coupled perturbation equations for the quasigeostrophic (QG) potential vorticity and ozone volume mixing ratio, which in log-pressure coordinates take the form (Nathan and Li 1991):

$$\frac{\overline{u}}{\partial x} \left[\nabla^2 \phi' + \frac{I}{\rho} \frac{\partial}{\partial z} \left(\frac{\rho f_o^2}{N^2} \frac{\partial \phi'}{\partial z} \right) \right] + \beta_e \frac{\partial \phi'}{\partial x} \\
= \kappa \frac{f_o}{\rho} \frac{I}{H} \frac{\partial}{\partial z} \left(\frac{\rho}{N^2} Q' \right)$$
(1)

$$\overline{u}\frac{\partial}{\partial x}\gamma' + \frac{\partial\phi'}{\partial x}\frac{\partial\overline{\gamma}}{\partial y} + w'\frac{\partial\overline{\gamma}}{\partial z} = S'.$$
 (2)

where the QG potential vorticity, q', diabatic heating rate per unit

mass, Q', net ozone production/destruction, S', and vertical motion, w', are given by

$$q' = \nabla^2 \phi' + \frac{1}{\rho} \frac{\partial}{\partial z} \left(\frac{\rho f_o^2}{N^2} \frac{\partial \phi'}{\partial z} \right), \tag{3}$$

$$\mathcal{Q}' = \Gamma_1 \gamma' - \Gamma_2 \int_{z}^{\infty} \frac{\rho(\zeta)}{\rho_0} \gamma' d\zeta - f_0 \frac{H}{\kappa} \Gamma_T \frac{\partial \phi'}{\partial z}, \qquad (4)$$

$$S' = -\xi_1 \gamma' + \xi_2 \int_{z}^{\infty} \frac{\rho(\zeta)}{\rho_0} \gamma' d\zeta - \frac{f_0 H}{R} \xi_T \frac{\partial \phi'}{\partial z}, \qquad (5)$$

$$w' = \frac{f_o}{N^2} \left[-\frac{u}{u} \frac{\partial}{\partial x} \frac{\partial \phi'}{\partial z} + \frac{du}{dz} \frac{\partial \phi'}{\partial x} + \frac{\kappa}{H} \frac{Q}{f_o} \right].$$
 (6)

At the upper boundary we require that the disturbance field be bounded. At the lower boundary the disturbance field is forced by sinusoidal bottom topography, h', which produces the vertical motion

$$w' = \frac{-\partial h'}{\partial x}$$
 at z=0. (7)

In the above equations primes denote perturbation quantities and over-bars denote zonal-mean basic state quantities. The ozone volume mixing ratio is $\gamma(x, y, z)$ and the streamfunction is $\phi(x, y, z)$. The radiative-photochemical parameterizations for Q' and S' are described in detail in Nathan and Li (1991). Briefly, the diabatic heating rate (4) is due to three effects: the local ozone heating rate, the heating rate arising from variations in perturbation column ozone above a given level, termed the shielding effect, and Newtonian cooling (NC). The net ozone production/destruction (5) also is due to three effects: local ozone perturbations, the shielding effect, and temperature variations.

The basic state fields as well as the radiative-photochemical coefficients vary only with height and are identical to those in Nathan and Li (1991). These fields and coefficients were constructed from observational data representative of the respective seasons.

Figure 1 shows the basic state distributions of zonal wind and meridional gradient of potential vorticity (PV). Of particular note are the spring distributions of zonal wind and PV, which vanish at about the same level. The level where the zonal wind and PV gradient both vanish is called a pseudo-critical level. Pseudo-critical levels possess several interesting properties (Harlander 2002). For example, in the presence of a local wavemaker, wave energy can accumulate within the pseudocritical level. In the present study, we find that basic states that possess a pseudocritical level, such as the spring basic state shown in Fig. 1, the wave-ozone feedbacks can have a strong effect on the planetary wave structure and associated wave fluxes.

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Figure 1. The basic state distributions of zonal wind and meridional gradient of potential vorticity at 45 N are shown for months representative of each season [January (solid), March (dash-dot), July (dash), September (dot)].

3. ANALYTICAL ANALYSIS

If normal mode solutions are assumed for the streamfunction and ozone fields and if the shielding terms are neglected, (1)-(6) can be combined into a single equation for the vertical structure of the streamfunction,

$$F_{zz} + m^2 (z)F = 0, (8)$$

where $m^2(z)$ is a complex index of refraction; $m^2(z)$ is a complicated function of the basic state distributions of wind, temperature and ozone, as well as the radiative-photochemical coefficients. If the basic state is slowly varying, we can immediately write down the WKB solution,

$$F(z) = \frac{F_0}{\sqrt{m}} e^{-i \int m dz} .$$
⁽⁹⁾

A preliminary analysis of (9) indeed shows that in the vicinity of the pseudocritical level, the response of the disturbance vertical structure to wave-ozone feedbacks is quite strong. This is borne out in our numerical calculations (see Fig. 2).

4. NUMERICAL RESULTS

Figure 1 shows the vertical distribution of disturbance northward heat flux for Newtonian cooling (NC) alone (solid line) and for NC and ozone heating (OH) combined (dotted line). The calculations are based on the spring basic state and zonal wavenumber k=2. Below ~20 km there are two local maxima and one local minimum in the northward heat flux. The primary and secondary maxima as well as the local minimum are at about the

same level with and without the OH. The local amplitude extrema, however, are sharply different between the NC alone and NC plus OH combined cases. For example, the local minimum in the northward heat flux at about 5 km increases by about 25% when the wave-ozone interactions are included. The vertical heat flux change (not shown) also increases by about 25%; the change in potential vorticity flux (not shown) is smaller (about 8%).



Figure 2: The vertical distribution of the zonally averaged northward heat flux for Newtonian cooling alone (solid) and Newtonian cooling and ozone heating combined (dotted) for the spring basic state.

4. CONCLUSION

Using analytical (WKB) and one-dimensional numerical modeling approaches, we show that there is an intimate connection between the zonal-mean background flow, ozone field, and forced planetary wave field in the stratosphere, a connection that in some cases leads to significant changes in the tropospheric wave fluxes. We find that this stratosphere-troposphere connection, which hinges on the interactions between the wave and ozone fields, is dramatically strengthened in the presence of pseudo-critical levels, i.e., at those levels where the Doppler shifted frequency and potential vorticity gradient vanish. Such conditions are most often met during Northern Hemisphere spring and summer.

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