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Effects of Planetary Wave-breaking on the Seasonal Variation of Total Column Ozone

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Abstract. The effects of planetary wave breaking on the seasonal variation of total column ozone are investigated using a zonally averaged chemical-radiative-transport model of the atmosphere. The planetary wave breaking effects of zonal wavenumbers k=1 and k=2 are significant in the middle latitude stratosphere during Northern Hemisphere (NH) winter, whereas only wave k=1 is important during Southern Hemisphere (SH) winter. The mixing and induced meridional circulation due to the planetary wave breaking increases the seasonal variation of total column ozone in NH (SH) middle latitudes by ~20% (~10%).

Introduction

Because stratospheric ozone plays a vital role in Earth's radiation balance, atmospheric general circulation, and climate, considerable effort has been directed toward detecting, simulating and understanding naturally and anthropogenically induced changes in its spatial and temporal distribution. Here we examine the seasonal variation of total column ozone (TCO) due to planetary wave breaking using a two-dimensional chemical-radiative-transport model of the atmosphere.

Figure 1a displays the climatological monthly and zonally averaged (TCO) distribution obtained from Total Ozone Mapping Spectrometer (TOMS) data averaged between 1988-1992. This data shows significant seasonal variation of TCO between the two hemispheres. Because the highest ozone concentrations are found at altitudes between about 10 km and 35 km, a region where the ratio of dynamical to chemical time scales is $\geq O(1)$, dynamical processes, such as planetary wave breaking (Leovy et al. 1985), are crucial for determining the observed inter-hemispheric differences in the seasonal variation of TCO.

One of the most important, and certainly among the most striking, dynamical processes in the stratosphere is the eddy mixing associated with planetary wave breaking. This process is characterized by 1) the rapid and irreversible deformation of material contours (McIntyre and Palmer 1984), and 2) strong seasonal variations (Baldwin and Holton 1988). Because planetary wave breaking plays a vital role in the driving of the zonal mean circulation and the mixing of trace gases, recent modeling efforts have sought to quantify its importance. However, most of these modeling efforts have considered the wave breaking effects of only a *single* planetary wave, despite observations (e.g., Randel 1987) showing that the two gravest zonal modes dominate the quasi-stationary planetary wave spectrum in the stratosphere.

To more closely align modeling efforts with observations, Li et al. (1995) used a quasigeostrophic, two-dimensional model of the stratosphere to examine the effects of topographically forced planetary wave breaking on eddy transport for zonal wavenumbers k=1 and k=2. Here we extend Li et al.'s study by examining the effects of two-mode topographically forced planetary wave breaking on the inter-hemispheric differences in the seasonal variation of TCO using a zonally averaged chemical-radiative-transport model of the atmosphere. The central question addressed here is how much of the seasonal variation in TCO is caused by the seasonal variation of topographically forced planetary wave breaking?

The Model

The effects of topographically forced planetary wave breaking on the seasonal variation of TCO are examined using the Lawrence Livermore National Laboratory (LLNL) two-dimensional chemical-radiative-transport (CRT) model. Because the model is described in detail in Patten et al. (1994), only a brief summary is provided here. The model domain extends from the surface to 84 km and from pole to pole; the vertical and meridional grid spacing are, respectively, 1.5 km and 5°. The model chemistry includes 43 transported species, 4 species for which abundance is determined based on the assumption of instantaneous equilibrium, 106 thermal reactions, and 47 photolytic reactions. Radiative transfer processes are based on a two-stream multiple-layer UV-visible model. Algorithms for calculating radiative scattering and the bulk optical properties of clouds and aerosols are also included in the model.

The transport due to sub-grid scale processes resulting from gravity wave breaking is based on the parameterization developed by Lindzen (1981). The transport due to planetary wave breaking is based on the parameterization of Garcia (1991) and is described

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in detail in Li et al. (1995). Briefly, a quasigeostrophic model is used to solve for planetary waves k=1 and k=2, which are forced at the lower boundary by realistic bottom topography. The wave breaking is assumed to occur in those regions where the potential vorticity gradient vanishes, a necessary condition for instability of the flow. The parameterization of the wave breaking is based on the assumption that there exists a balance between the flux of wave activity and its dissipation by nonlinear processes, where the latter is represented as a linear damping of the primary wave field.

Total column ozone distributions are obtained by integrating the model forward in time until the chemical species reach a quasi-equilibrium state, which typically occurs within three model-years. The model data from the last (third) year is then used for the analysis.

Results

The TCO model simulations have been carried out for two general cases. The first case examines the inter-hemispheric differences and seasonal variation of TCO due to the *combined* planetary wave breaking effects of zonal waves k=1 and k=2. The second case examines the relative importance of the two waves to the distribution of TCO.

Figure 1 displays as a function of latitude and season the observed climatological monthly and zonally averaged TCO distribution (Fig. 1a), the model-simulated TCO distribution without planetary waves (Fig. 1b), and the model-simulated TCO distribution with planetary waves (Fig. 1c). The observed and model-simulated TCO distributions are in qualitative agreement between 15°N and 15°S. Within this latitude belt the seasonal variation of TCO is relatively small, generally <5%. Differences between the observed and simulated TCO distributions are greatest at middle and high latitudes. As discussed below, these differences are significantly reduced when the two-wave planetary wave breaking is included in the model simulations.

Consider first the no-wave case shown in Fig. 1b. The NH simulated TCO maximum occurs about a half month later (March/April), is ~15° south of and is ~9% smaller than observed. The simulated TCO minimum occurs about a month later (September), is more localized to high latitudes, and is about 6% smaller than observed. Inclusion of the planetary scale wave breaking effects (Fig. 1c) yields results that are significantly different from the no-wave case and, more importantly, are in closer agreement with observations, particularly regarding the timing and amplitude of the TCO extrema. For example, the TCO maximum (minimum) is only about ~5% (3%) smaller than observed. At NH middle latitudes, the topographically forced planetary wave breaking significantly enhances the seasonal variation of TCO, producing model simulations that are in closer agreement with observations. For example, at 45°N, differences in the TCO between the spring maximum and fall minimum without waves, with waves, and observed is 60 DU (Dobson units), 90 DU, and 80 DU, respectively.

It is interesting to note that at northern mid-latitudes in winter/spring, the TCO field is larger without the planetary wave breaking effects, meaning the contribution of direct horizontal and vertical eddy transport by the wave fields (term V in eq. 2) is negative. This can be explained as follows. In the upper troposphere and lower stratosphere of the subtropics during northern winter, the eddy diffusion is large (see Li et al. 1995). Thus, the wave breaking at these locations transports ozone-poor air from the tropical upper troposphere to the midlatitude lowermost stratosphere, leading to a reduction in the ozone column there.

In the SH, the TCO maximum (minimum) occurs in October (March). Although the simulations show that the timing of the extrema is consistent with observations, the observed October maximum centered near 55°S is not well simulated in the no-wave case. However, in the simulation with wave breaking, the October maximum in TCO is in much closer agreement with observations. However, because our model does not contain polar chemistry, which is believed to be responsible for the SH springtime loss of ozone (e.g., heterogeneous chemistry on polar stratospheric clouds), there exist large differences between the model and observations during October in high southern latitudes. Although the model simulated TCO at middle latitudes is on average about

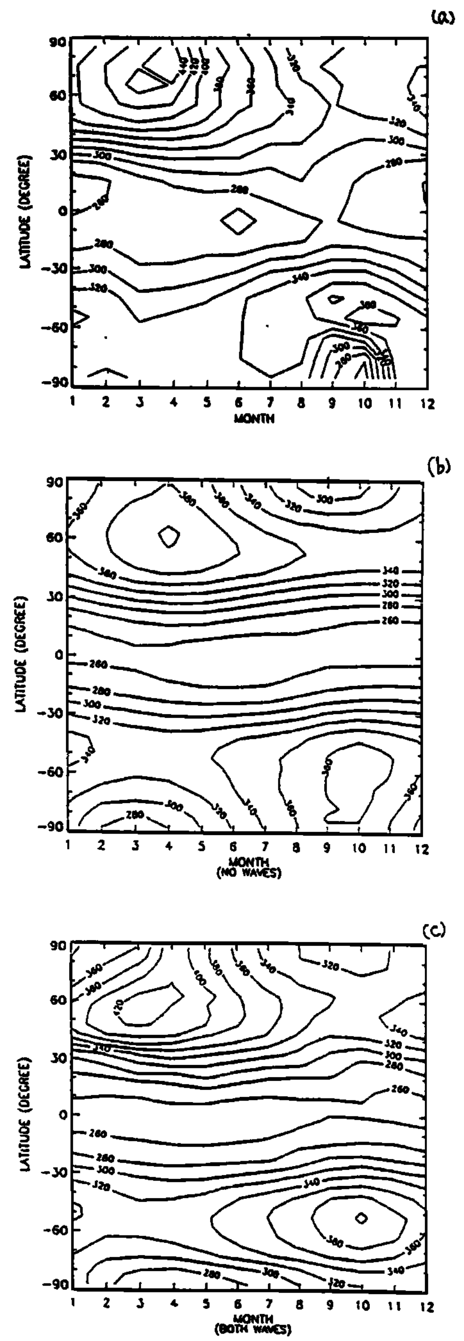

Figure 1. The zonally averaged total column ozone distribution (Dobson units) as a function of latitude and season based on (a) observations (TOMS data averaged between 1988-1992), (b) a model simulation without planetary wave breaking, and (c) a model simulation that includes the effects of planetary wave breaking by zonal waves 1 and 2.

~12% higher than observed values, inclusion of the mixing due to the forced planetary wave breaking produces significant changes in its spatial and seasonal distribution, changes that are in closer agreement with observations. In particular, the wave breaking increases the seasonal variation of TCO in the NH (SH) on average by ~20% (~10%) in middle latitudes and ~6% (~15%) poleward of 60°N (60°S).

The processes that affect the TCO distribution are most clearly illuminated by considering the zonal-mean meridional circulation equation and the transformed Eulerian-mean continuity equation for TCO. These equations can be written as (Andrews et al. 1987):

$$\mathcal{L}_1 \bar{w}^* = \underbrace{\mathcal{L}_2(\nabla \bullet \mathbf{F})}_{I} + \underbrace{\mathcal{L}_3 \bar{X}}_{II} + \underbrace{\mathcal{L}_4 \bar{Q}}_{III}, \qquad (1)$$

and

$$\frac{\partial \bar{\chi}}{\partial t} = \underbrace{-\bar{V}^* \bullet \nabla \bar{\chi}}_{IV} + \underbrace{\bar{D}}_{V} + \underbrace{\bar{S}}_{VI}, \qquad (2)$$

where the $\mathcal{L}_j$ (j=1-4) are linear spatial operators.

Equation (1) states that the zonal-mean residual vertical motion field, w^*, is driven by i) the divergence of Eliassen-Palm (EP) flux, **F**, due to planetary waves (term I), ii) mechanical drag effects due to gravity waves and other small-scale eddies (term II), and iii) diabatic effects (term III). Once w^* is determined, the zonal-mean residual meridional motion field, v^*, can be calculated directly from mass continuity.

Equation (2) states that local time changes in zonal mean TCO, χ, are due to i) advection by the zonal-mean meridional circulation (term IV), where $V^* = (v^*, w^*)$, ii) horizontal and vertical eddy transport by the wave fields, D (term V), and iii) net chemical sources/sinks, S (term VI).

Holton (1986) demonstrated that the equilibrium meridional slope of tracer mixing ratio surfaces is determined primarily by the competition between two processes: i) the mean meridional mass circulation (term IV), which has a slope steepening effect, and ii) eddy transport (term V) and photochemical loss (term VI), which have a slope flattening effect. It is important to note that because the mean meridional mass circulation itself is driven in part by the eddies (terms I and II), the steepening and flattening processes are not independent. However, to better isolate the relative importance of these two processes in affecting the TCO distribution, simulations have been carried out with and without the planetary wave driving of the mean meridional circulation, corresponding to $I \neq 0$ and $I = 0$ in (1), respectively. When the planetary wave EP flux divergence is zero ($I=0$), the planetary wave breaking affects the TCO distribution only through transport (term V).

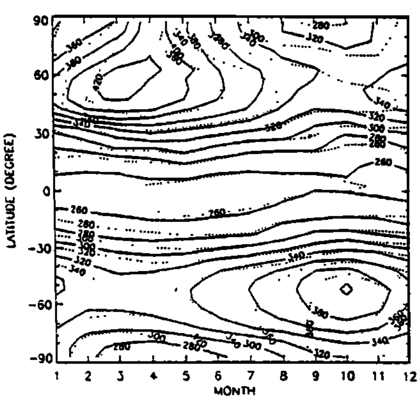

Figure 2. The model-simulated total column ozone distribution as a function of latitude and season with the planetary wave Eliassen-Palm (EP) flux (I≠0 in eq. 1; solid curves) and without the planetary wave EP flux (I=0 in eq. 1; dotted curves).

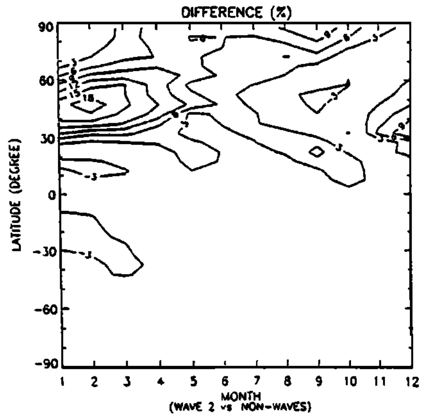

Figure 3. Percent difference in the TCO distribution between the wave 2 and no-wave cases.

Figure 2 displays the latitudinal-seasonal distribution of TCO with and without the planetary wave EP flux. Between 30°N and 40°S, although the planetary wave induced EP flux does influence the meridional circulation, the distribution of TCO is largely unchanged. In sharp contrast, at high-latitudes in the NH, the EP flux produces enhanced downward motion, resulting in higher values of TCO, particularly during winter and spring when the planetary waves are strongest (Randel 1987). For example, at 60°N during March, inclusion of the planetary wave EP flux in (1) yields a TCO amount of ~420 DU, which is ~12% higher than without the EP flux, and ~8% higher than without both the EP flux and wave-induced meridional circulation. In the SH spring, the EP flux generates a meridional circulation pattern that produces enhanced downward motion near 50°S, and less downward motion in the higher latitudes. In both hemispheres, the influence of planetary wave induced EP flux on the meridional circulation produces a TCO distribution that is closer to the observed distribution than would be obtained without the planetary waves.

As demonstrated by Li et al. (1995), the altitude and latitude where a planetary wave "breaks" depends crucially on its zonal scale. We now present results showing the relative importance of the breaking effects of planetary waves 1 and 2 in affecting the distribution of TCO.

Figure 3 depicts the percent difference in the TCO distribution between the wave 2 alone and no-wave cases. The changes of TCO by wave 2 alone are significant in the NH and negligible in SH. In the NH, the most significant changes occur at middle latitudes in winter, where the TCO increases by ~18% in the absence of wave 1. This increase results from the combined effects of the planetary wave mixing by wave 2 [term V in eq. (2)] and the downward motion induced by its EP flux divergence [term I in eq. (1)]. At high latitudes, the TCO increases throughout most of the year, primarily due to the driving of the zonal-mean meridional circulation by wave 2. Moderate decreases of TCO occur at middle latitudes during summer and fall. The "breaking" of wave 2 has little impact on the TCO distribution at lowlatitudes (south of 20°N) and in the SH. In these regions, topographically forced wave 1 has the dominant amplitude (see Li et al. 1995, their Fig. 1) and thus a stronger effect on the TCO distribution there.

Finally, compared with the winter geopotential amplitude of wave 2 shown in Li et al. (1995), the wave 2 geopotential amplitude for spring and fall are relatively weak; wave 2 is slightly stronger and propagates to a slightly higher altitude in fall than in spring, consistent with observations.

Conclusions

The seasonal variation of total column ozone (TCO) due to topographically forced planetary wave breaking of zonal waves k=1 and k=2 was investigated using a zonally averaged chemical-radiative-transport model of the atmosphere. The planetary wave breaking can affect the ozone distribution by two processes: directly via transport and indirectly by inducing changes in the mean meridional circulation. The relative importance of these two processes as well as the relative importance of waves 1 and 2 in affecting the TCO distribution have been examined numerically.

Our study shows that the seasonal variation of planetary wave breaking plays an important role in the seasonal distribution of TCO. Specifically, we find the following:

- The mixing associated with the "breaking" of topographically forced planetary waves 1 and 2 has a significant effect on the TCO during Northern Hemisphere (NH) winter, whereas only wave 1 is important during Southern Hemisphere (SH) winter.
- The combined effects of transport and changes in the mean meridional circulation due to the forced planetary wave breaking increases the seasonal variation of TCO in NH (SH) middle latitudes by ~20% (~10%). Wave 2 (1) contributes as much as ~18% (3%) to these variations in the NH (SH) middle latitudes.
- The TCO distribution at mid-latitudes is determined primarily by direct transport associated with the planetary wave breaking; the indirect transport effects associated with the wave-induced mean meridional circulation has little effect there. However, at high latitudes (e.g., 60°N), the wave-induced meridional circulation produces a TCO amount that is as much as ~14% higher than would be obtained in its absence.

The above results not only underscore the importance of topographically forced planetary wave breaking in affecting the distribution of TCO, the inclusion of the wave breaking in the model yields a TCO distribution that is in greater agreement with observations than would otherwise be obtained. Thus, explicit representation of the dominant, topographically forced planetary wave activity in two-dimensional models is important if better simulations of the observed inter-hemispheric and seasonal variations of ozone and other long-lived chemical species are to be produced.

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