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A 3-D MODEL STUDY OF OZONE EDDY TRANSPORT IN THE WINTER STRATOSPHERE

N. C. Hsu[1] and D. M. Cunnold[2]

[1] Science Application International Corp., Hampton, VA 23666

[2]School of Earth and Atmospheric Sciences,Georgia Institute of Technology, Atlanta, Ga 30332

Abstract

Calculations of the Northward eddy fluxes of stratospheric ozone in a three-dimensional chemical-dynamical model are discussed. It is shown that, although approximately 50% of the zonal mean flux is produced by stationary planetary wavenumbers 1 and 2, the wintertime flux due to the chemical eddies is substantially underestimated when a quasi-linear representation is used.

Introduction

The problem of modeling ozone of the middle atmosphere has been considered to be complex because of the coupling between radiation, dynamics and photochemistry. The eddy transport of ozone plays an important role in determining the stratospheric ozone distribution, especially in the winter. Based upon the linear wave theory, Hartmann and Garcia (1979) and Garcia and Solomon (1983) argued that the net eddy transport is significant only in the region where advective and photochemical time scales are comparable and that the zonal mean eddy flux might be approximated by including just the contribution by stationary wavenumber 1 based upon quasi-linear mathematics. On the other hand, using the LIMS satellite data, Leovy et al. (1985) showed that the ozone distribution is strongly influenced by irreversible deformation associated with planetary wave breaking, which is a highly nonlinear process. The purpose of this work is to study the effect of the nonlinear wave-wave interactions on ozone eddy fluxes using the results of a spectral global 3-D model.

Model Description

The model used in this study is an improved version of the 3-D GCM model by Cunnold et al. (1975). This model utilizes quasi-geostrophic governing equations (see Cunnold et al., 1975 for details). The vertical domain of integration extends from the ground to approximately 85 km in log-pressure altitude. In the horizontal plane, truncated series of spherical harmonics are used to represent the zonal and meridional structures up to wavenumber 18. This self-consistent 3-D model allows for full interaction between radiative heating, dynamics and photochemistry without much ad-hoc parameterization in either the dynamical or the chemical schemes.

Results

The model has been integrated for 18 months starting from December 1. The results discussed in this section are based upon the model output of the second January.

Figure 1 shows the calculated January monthly mean ozone map at 10 mb. A distinct region of strong ozone gradient spiraled westward and outward from the vortex between 50° and 60° N to the tropical region. Between the edge of the vortex and the tropical branch of the spiral a prominent tongue of high ozone stretches inward toward the polar region near 60° N, 210° E. These features are consistent with the LIMS data analyzed by Leovy et al. (1985).

Figure 2 shows the model-generated amplitude and phase of the geopotential height of wavenumber one in January. Compared to the satellite observations analyzed by Labitzke et al. (1985), the location of the maximum amplitude of the model geopotential height disturbance is at a slightly lower altitude than the observed which is at about 65 degree north and 7 mb, and the measured magnitudes are underestimated by approximately 10% in the stratosphere and the polar night region. The phases of the model geopotential heights are generally in good agreement with the satellite data, which exhibit decreasing phase with increasing altitude and increasing phase with increase of latitude toward the north pole.

The comparison of the model temperature disturbances of wavenumber one with the satellite measurements by Labitzke et al. (not shown here) also indicates that the observed amplitude of temperature disturbance is characterized by a major maximum located at 62° N and 40 mb, which is about the same amplitude and location as the model predicted, and a minor maximum at 58° N and 2 mb, which is overestimated by approximately 40% in the model. The constant phase lines in both the model and the observations tilt equatorward and downward with magnitudes decreasing with height.

There are large interannual fluctuations of planetary wave activities from year to year. Although the model-predicted amplitudes of geopotential height and temperature of wavenumber 1 and 2 do not agree exactly with the multi-year averaged satellite measurements reported by Labitzke et al., they are within the range of the interannual variations given in the four-year NOAA/NMC observations (Geller et al., 1984). Therefore the perturbations of the winter middle atmosphere generated by the model are representative of the real atmosphere and can be used to study the ozone eddy tranport in the stratosphere.

The Importance of The Nonlinear Terms In The Mass Continuity Equation

The complete Eulerian ozone eddy continuity equation can be written as follow:

$$\frac{\partial \chi'}{\partial t} + (\bar{u} + u')\frac{\partial \chi'}{\partial x} + v'\left(\frac{\partial \bar{\chi}}{\partial y} + \frac{\partial \chi'}{\partial y}\right) + w'\frac{\partial \chi_0}{\partial z} = S' \quad (1)$$

where χ is the ozone mixing ratio; S denotes the ozone production/loss rate; (u,v,w) are zonal, meridional and vertical velocities, respectively; overbars represent the zonal means of quantities and primes denote the departures from zonal averages.

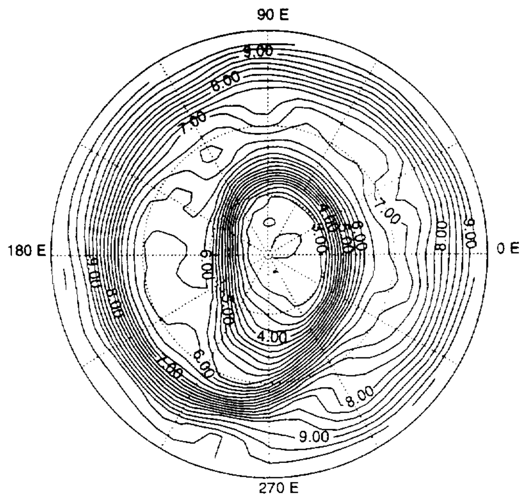

Figure1 January monthly mean ozone (in ppmv) map at 10 mb

The nonlinear terms in equation (1) have been neglected in a number of studies concerning ozone eddy transport. The rationale for the neglect of the nonlinear transport depends on the validity of the linear wave theory which assumes that the wave amplitudes are small and thus the linear terms would be much larger than the nonlinear terms in the tracer eddy continuity equation. Using the satellite measurements, Douglass et al. (1985), however, pointed out that the nonlinear terms could be an important part of the net dynamical forcing in the winter stratosphere and the inclusion of these terms improved the agreement between the calculated ozone mixing ratios and the observations. To investigate the importance of the nonlinear terms in the net dynamical forcing, the nonlinear terms have been calculated at each timestep of the 3-D model and averaged over the simulated month of January.

Figure 3 (a) and (b) show the comparisons of the nonlinear terms against the linear terms at the Gaussian longitudes at 60^{o} N and 42^{o} N for wavenumber 1. For both wavenumber 1 and 2 (not shown) the nonlinear terms are small compared to the linear terms between 1 and 10 mb at 60^{o} N, while at 42^{o} N the nonlinear terms are comparable to or even larger than the linear terms in the altitudes between 1 and 10 mb.

Generally speaking, the region where the nonlinear terms are significant in the eddy ozone budget takes place at a lower latitude for wavenumber 2 than for wavenumber 1. The nonlinear terms are more important to the net dynamical forcing at midlatitudes than at high latitudes, implying that the ozone distribution is greatly influenced by the nonlinear wave interaction at some distance from the core of the polar night jet stream. This is consistent with the idea that wave breaking (i.e. strong nonlinear interaction) occurs in winter outside the polar vortex (e.g. McIntyre and Palmer, 1984).

The Roles of The Transient and The Nonlinear Terms on The Net Ozone Eddy Fluxes Due To Stationary Rossby Waves

Model calculation indicates that in the winter stratosphere about 50% of the model net ozone eddy fluxes are attributed to the contributions of stationary waves, while the contributions of planetary wavenumber 1 and 2 account for 90% of the model net ozone transport due to stationary waves. Therefore approximately half of the net ozone eddy transports result from the transports by stationary planetary wavenumber 1 and 2. The importance of wavenumber 1 has been noted observationally by Wu et al. (1987). In this section, we will discuss the significance of the transient and nonlinear effects in calculating the net ozone eddy transport due to stationary wavenumber 1 and 2 using the output of the 3-D model.

Time averaging equation (1) and following Garcia and Solomon's procedures (1983), the net ozone eddy fluxes due to stationary waves can be represented as

$$\begin{pmatrix} \overline{[v'][\chi']}^{NET} \\ \overline{[w'][\chi']}^{NET} \end{pmatrix} = \begin{pmatrix} \overline{[v'][\chi']} - \dfrac{\overline{[v'][T']}}{\sigma}\dfrac{\partial \chi_0}{\partial z} \\ \overline{[w'][\chi']} + \dfrac{\overline{[v'][T']}}{\sigma}\dfrac{\partial \bar{\chi}}{\partial y} \end{pmatrix}$$

$$= -\widehat{S_1}\begin{pmatrix} [\dfrac{\partial \bar{\chi}}{\partial y}] \\ [\dfrac{\partial \bar{\chi}}{\partial z}] \end{pmatrix} - \widehat{S_2}\begin{pmatrix} [\dfrac{\partial \bar{T}}{\partial y}] \\ \sigma \end{pmatrix} - \widehat{S_3} + \widehat{S_4} \qquad (2)$$

where

$$\widehat{S_1} = \begin{pmatrix} C_1 & A+B \\ A-B & C_2 \end{pmatrix}$$

$$\widehat{S_2} = \begin{pmatrix} \gamma\phi_2\overline{[\eta']^2} & \gamma(\phi_2\overline{[\eta'][\zeta']} - \phi_1 i\overline{[\eta'][\zeta']}) \\ \gamma(\phi_2\overline{[\eta'][\zeta']} + \phi_1 i\overline{[\eta'][\zeta']}) & \gamma\phi_2\overline{[\zeta']^2} \end{pmatrix}$$

$$\widehat{S_3} = \begin{pmatrix} \tau_D(\phi_1\overline{[v'][D_x']} - \phi_2 i\overline{[v'][D_x']}) \\ \tau_D(\phi_1\overline{[w'][D_x']} - \phi_2 i\overline{[w'][D_x']}) \end{pmatrix}$$

$$\widehat{S_4} = \begin{pmatrix} \gamma\tau_D^2(\phi_2\overline{[v'][D_T']} + \phi_1 i\overline{[v'][D_T']}) \\ \gamma\tau_D^2(\phi_2\overline{[w'][D_T']} + \phi_1 i\overline{[w'][D_T']}) \end{pmatrix}$$

$$A = \frac{\phi_1}{\tau_D}\overline{[\eta'][\zeta']}\,;\ B = \frac{(\phi_2-1)}{\tau_D} i\overline{[\eta'][\zeta']} - \frac{\tau_D}{\sigma} i\overline{[v'][D_T']}\,;$$

$$C_1 = \frac{\phi_1}{\tau_D}\overline{[\eta']^2}\,;\ C_1 = \frac{\phi_1}{\tau_D}\overline{[\zeta']^2}\,;$$

$$\phi_1 = \frac{(\bar{\tau}_c/\tau_D)}{1+(\bar{\tau}_c/\tau_D)^2}\ ;\ \phi_2 = \frac{(\bar{\tau}_c/\tau_D)^2}{1+(\bar{\tau}_c/\tau_D)^2}\ ;$$

$$D_x' = u'\frac{\partial \chi'}{\partial x} + v'\frac{\partial \chi'}{\partial y} + \bar{u}^{*}\frac{\partial \chi'^{*}}{\partial x} + v'^{*}\frac{\partial \bar{\chi}^{*}}{\partial y} + w'^{*}\frac{\partial \chi_0^{*}}{\partial z}$$

$$D_T' = q' - u'\frac{\partial T'}{\partial x} - v'\frac{\partial T'}{\partial y} - \bar{u}^{*}\frac{\partial T'^{*}}{\partial x} - v'^{*}\frac{\partial \bar{T}^{*}}{\partial y}$$

bracket [ ] denotes the time average, star * represents the deviation from the time average, τ_c is the chemical time

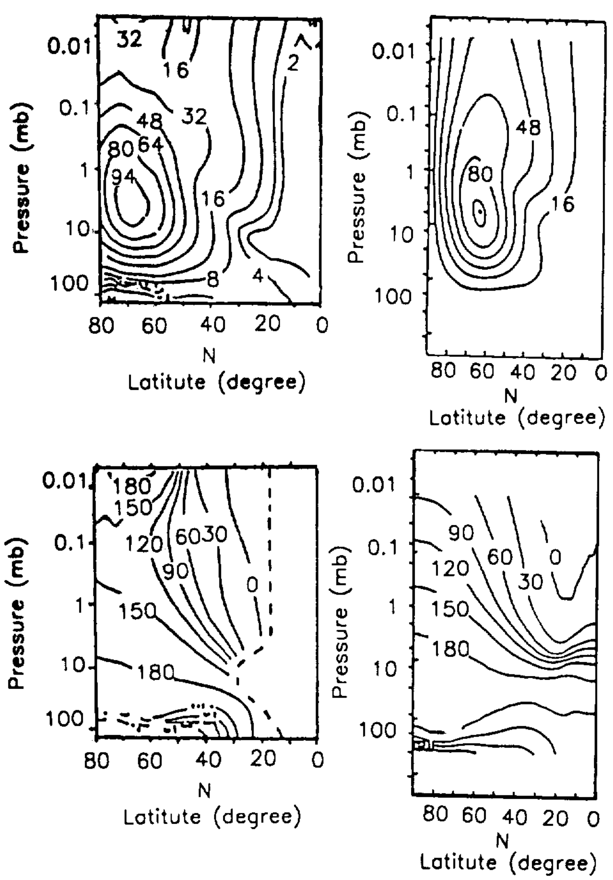

Figure2 The monthly mean amplitude and phase of the model geopotential height of wavenumber one (on the right) for January with the observations analyzed by Labitzke et al. (1985) (on the left).

constant of ozone, τ_d is the advective time constant $[k\bar{u}]^{-1}$, k is the wavenumber, σ denotes the static stability parameter and q' **is the heating rate** perturbation.

The first two terms on the right hand side of (2) are similar **to those derived** based on a quasi-linear theory by Garcia and Solomon and many others, except that an extra term appears in the anti-symmetric components of the first term, which results from the effect of D_T' on the ozone eddy transport. This is compensated by the transports by the Eulerian mean motion. The last two terms are caused by the inclusion of D_χ' and D_T' which represents the transient and nonlinear terms in the ozone continuity equation and the thermodynamic equation, repectively.

As depicted in figure 4, the chemically induced ozone eddy fluxes predicted by the quasi-linear theory (i.e. $D_\chi' = 0$ and $D_T' = 0$) substantially underestimate the model net ozone eddy fluxes for wavenumber 1 as well as wavenumber 2. Neither the magnitudes of the net ozone eddy fluxes nor their structures have been reproduced.

When the nonlinear terms and the linear transient terms in the ozone eddy continuity equation and the thermodynamic equation are included in the calculation of the net ozone eddy transport, the resulting net ozone eddy fluxes of wavenumber 1 and 2 calculated from (2), shown in Figure 5, are in remarkable agreement with those from the model except in the region south of 40° N, where the model mean zonal wind is weak and the particle trajectories are quite variable. Obviously, the discrepancies between the net model ozone eddy fluxes and those calculated by the linearized formulation of Garcia and Solomon (1983) are caused by the neglect of the nonlinear terms and the linear transient terms.

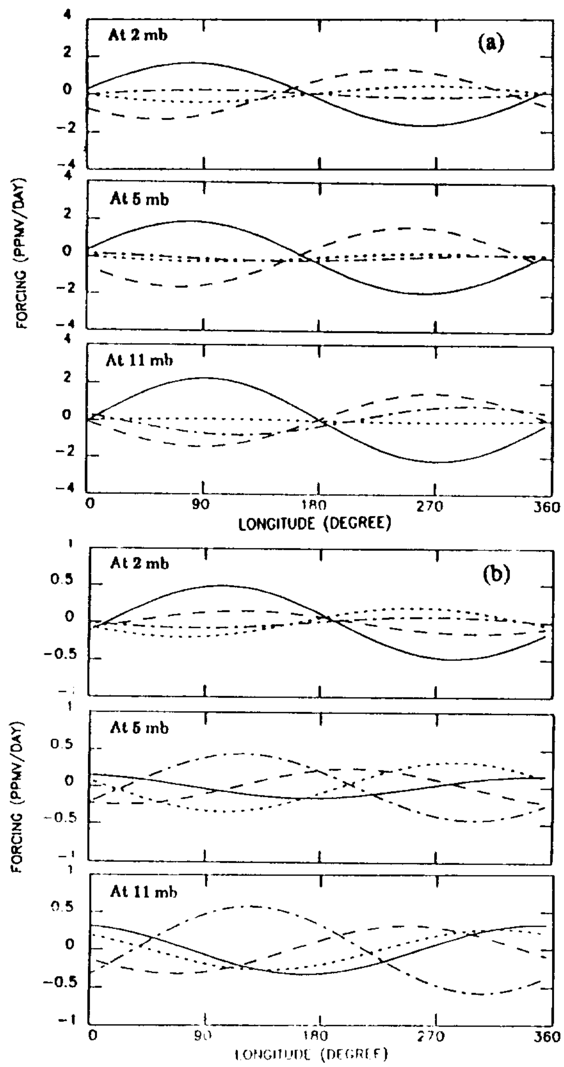

Figure3(a) The comparison of the linear advection terms with the nonlinear advection terms for wavenumber 1 at 60° N for January. The solid line denotes the linear term $\bar{u}\frac{\partial\chi'}{\partial x}$, the short-dashed line the nonlinear term $u'\frac{\partial\chi'}{\partial x}$, the long-dashed line the linear term $v'\frac{\partial\bar{\chi}}{\partial y}$, the dot-dashed line the nonlinear term $v'\frac{\partial\chi'}{\partial y}$.

Figure 3 (b) As in Figure 3 (a) except for 42° latitude.

The relative importance of the transient linear terms and the nonlinear terms was also investigated by comparing the net ozone eddy fluxes resulting from the nonlinear terms against those arising from the linear transient terms for wavenumber 1 and 2. For wavenumber 1, the linear transient forcings are prominent in the the upper stratosphere, while the effects of the nonlinear terms are dominant in the middle and lower stratosphere. For wavenumber 2, the net ozone eddy

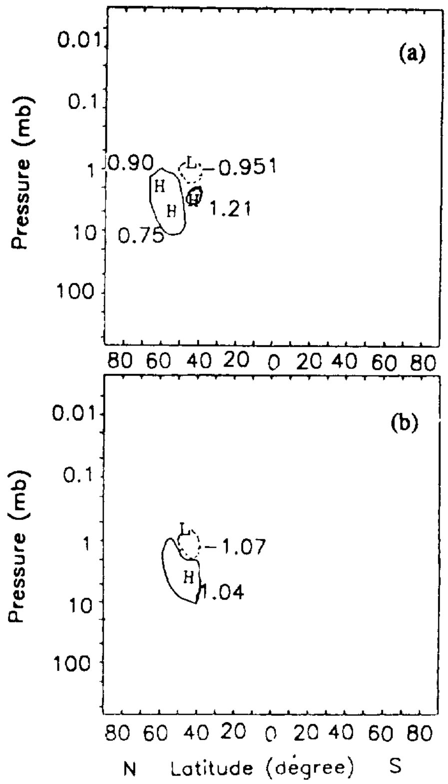

Figure 4 The chemical meridional ozone eddy fluxes, derived from the linear theory, due to (a) standing wavenumber 1; (b) standing wavenumber 2. Contour interval is 0.6 ppmv*m/s.

transports are almost completely controlled by the nonlinear processes.

Therefore the nonlinear process, such as planetary wave breaking, plays an important role in determining the net ozone eddy transport and consequently the mean ozone distribution in the transition region.

Concluding Remarks

The model results suggest that in the winter stratosphere the contribution of stationary waves accounts for more than 50% of the net ozone eddy fluxes and that the net ozone eddy transport contributed by stationary planetary wavenumber 2 may not be ignored, especially in the subtropical region where the nonlinear process is dominant in controlling ozone transport.

Calculations also indicate that the chemical ozone eddy fluxes of stationary wavenumber 1 and 2 estimated by the linearized tracer continuity equation, although significant, do not agree well with the net ozone eddy fluxes evaluated directly from the model for the month of January. The linear chemical transport is important only over a limited area near the edge of the polar vortex and even there it is no larger than the nonlinear contribution.

Acknowledgments

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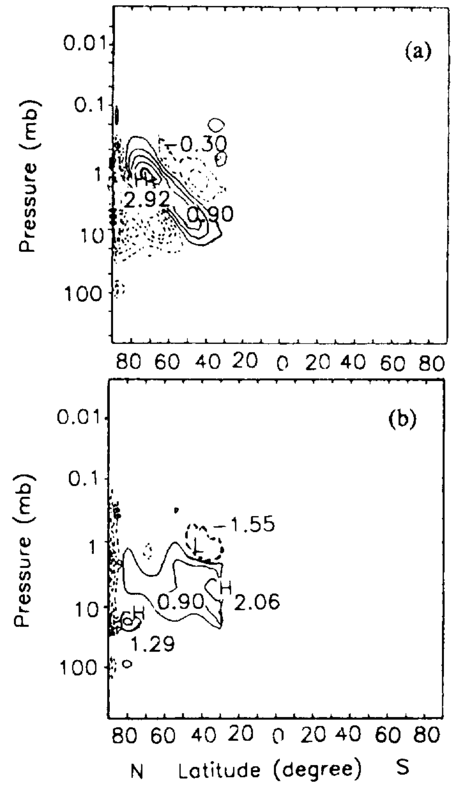

Figure 5 The calculated net meridional ozone eddy fluxes including the effects of the nonlinear terms and the transient terms, due to (a) standing wavenumber 1; (b) standing wavenumber 2. Contour interval is 0.6 ppmv*m/s.

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