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MODELLING STRATOSPHERIC POLAR OZONE USING OBJECTIVE ANALYSIS

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Abstract

We have studied the development of the austral ozone hole using a 3–D spectral chemical transport model at R15 resolution for the period 15th September to 15th October, 1991. The model is driven by objectively analyzed wind fields obtained from the Canadian Meteorological Centre and uses the chemical module developed by Kaminski (1992). Although extensive processing of NO_y and Cl_x occurs within the model the ozone hole that develops appears shallow and ephemeral. Analysis of the results indicate that the meridional transport of ozone is sufficient to overwhelm the substantial chemical depletion that does occurs. We suggest that the low resolution objectively analyzed data used is unable to capture the essential isolated nature of the vortex.

Introduction

The formation of the Antarctic polar ozone hole in the austral spring is a complex process involving temperatures sufficiently cold for polar stratospheric clouds (PSCs) to form, and dynamics that lead to the chemical isolation of the polar vortex (eg. Solomon, 1990). PSCs provide the surfaces upon which heterogeneous chemistry proceeds to produce the precursors of ozone destruction. Due to this complex interaction of chemistry and dynamics, we have used a three dimensional model to study the evolution of ozone during this period.

This study uses the York University global spectral stratospheric chemical transport model (CTM) (Kamiński, 1992) with a R15 truncation (corresponding to 48 longitudes by 40 latitudes in grid space). It uses objectively analyzed wind fields as the source of the driving meteorology to solve the continuity equation

$$\frac{\partial \chi_i}{\partial t} = -\vec{V} \cdot \nabla \chi_i + \nabla(K \cdot \nabla)\chi_i + \frac{P_i}{m} - L_i \chi_i \quad (1)$$

where χ_i is the mixing ratio of the i'th species, P_i is the chemical production term, L_i is the chemical loss frequency, $-\vec{V} \cdot \nabla \chi_i$ is the advection term, $\nabla(K \cdot \nabla \chi_i)$ is the diffusion term, and m is the number density of the atmosphere.

The version of the model used for this experiment has been reduced from the previous 26 vertical levels to 15 extending from the surface to 10 mb, the height at which the objective analysis stops. A leapfrog numerical scheme in spectral space, and a finite difference scheme in the vertical are employed to integrate the model's continuity equation forward in time. The chemistry in the model consists of 49 reactions (which include gas phase, heterogeneous and photochemical reactions) and 21 species. Seven tracers are used: O_x, Cl_x, NO_z, CH_4, N_2O, H_2O, and O_3–passive. The passive tracer undergoes no chemistry, just transport. Note that the chemistry has no brominated species included, which means that the model will underestimate ozone destruction. This will be added to the chemistry at a later time. A 30 minute dynamical time step and a 1.5 hour chemical time step are used to calculate the species future concentrations.

Objectively analyzed meteorological fields are obtained from the Canadian Meteorological Centre (CMC) and are the source of the meteorology for the model. Fields included in the objective analysis are divergence, vorticity, temperature and surface pressure at 00, 06, 12, and 18Z. The CMC operational global spectral model (Ritchie, 1991) was run at R15 resolution in the Analysis Cycle and the zero hour forecast was used. These objective analysis fields are then interpolated to the model dynamical time step.

The CTM was integrated over the 30 day period, from September 15 to October 15, 1991 to study the conversion of HCl and $ClNO_3$ to active chlorine and the denitrification of the polar stratosphere using the following heterogeneous reactions

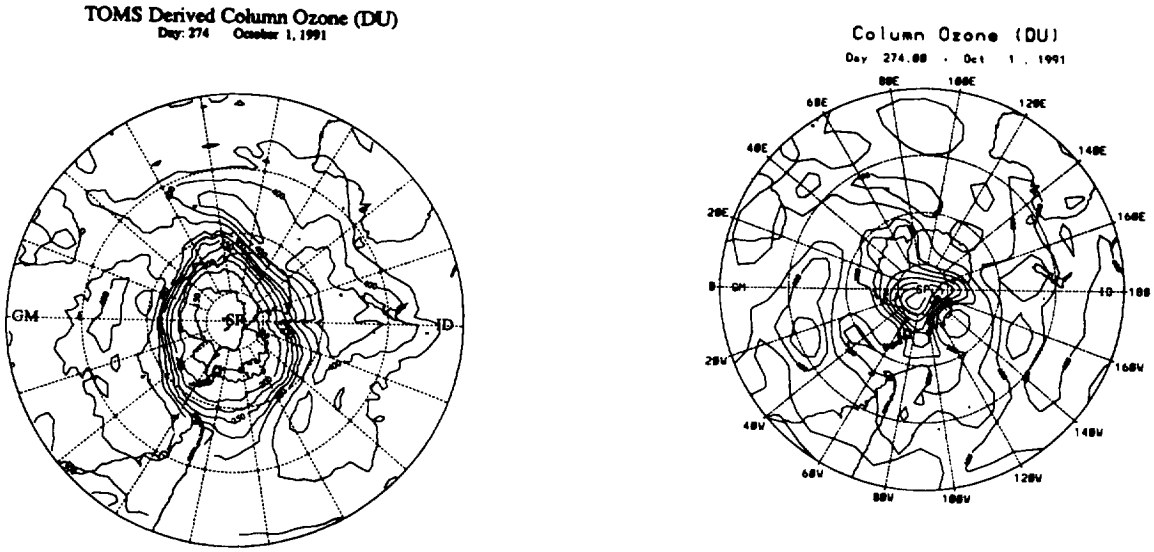

Figure 1. Column ozone amounts for October 1, 1991 for TOMS and the model at OOZ.

$$ClONO_2(g) + HCl(s) \rightarrow Cl_2 + HNO_3(s)$$

$$N_2O_5(g) + HCl(s) \rightarrow ClNO_2(g) + HNO_3(s)$$

$$ClONO_2(g) + H_2O(s) \rightarrow HOCl(g) + HNO_3(s)$$

$$N_2O_5(g) + H_2O(s) \rightarrow 2HNO_3(s)$$

In the model, heterogeneous chemistry proceeds when the temperatures are sufficiently cold (< 195K for type I PSCs and < 190 for type II) for the production of PSCs. The initial conditions for the chemistry were taken from a previous experiment run on the 26 level CTM (Kamiński, 1992) that used the two-dimensional fields of Garcia and Solomon (1983). The initial ozone fields applied did not exhibit an ozone hole at the beginning of the model run. Due to the large volume of data generated over the course of one model month, October 1st, 1991 has been chosen as the one day concentrated on for the analysis, given the brief nature of this communication.

Analysis

Figure 1 compares the model column O_3 with the TOMS data for October 1, 1991. Many of the features observed in the collar surrounding the ozone hole are reproduced with the model's wind fields. However, the depth of the hole is far from being reproduced. The lowest amount during the first 3 days of October is 134 DUs compared to the 122 DU for the TOMS minimum. However, the model ozone depletion has neither the temporal nor spatial extent that is usually associated with an "ozone hole". At the end of the model run on October 15 the lowest total column ozone value is 227 DUs while the TOMS value for the same period is 139 DUs. Interestingly enough, the model stratosphere experiences two warmings, one on Sept. 25th and another on October 10th, suggesting that the polar vortex is breaking down. Indeed, a time series of total column ozone over the pole shows the hole decreasing in size as ozone rich air from lower latitudes replaces it due to meridional transport into the vortex.

Figure 2 shows the major zonally averaged individual components of production and loss of odd oxygen for both inside (73° S) and outside (51° S) the vortex. The two production terms considered for O_x are $O_2+h\nu$, and HO_2+NO. There are six loss terms: $O+O_3$, $O+NO_2$, O+ClO, O_3+OH, O_3+HO_2, and $Cl_2O_2+h\nu$. Because of the presence of heterogeneous reactions in the vortex, we would expect to see the conversion of unreactive forms of chlorine to more reactive forms, and denitrification of the stratosphere, and this is indeed the case. Outside the vortex there is approximate photochemical steady state (PCSS) down to about 30 mb and extensive production of ozone via photolysis of O_2. The major odd-oxygen loss processes are due to NO_2 + O, O + ClO, and O + O_3. Within the vortex, O_2 photolysis is greatly reduced as is the loss due to O + NO_2 due to denitrification. Below 30 mb the main ozone losses are due to $h\nu$ + Cl_2O_2, O

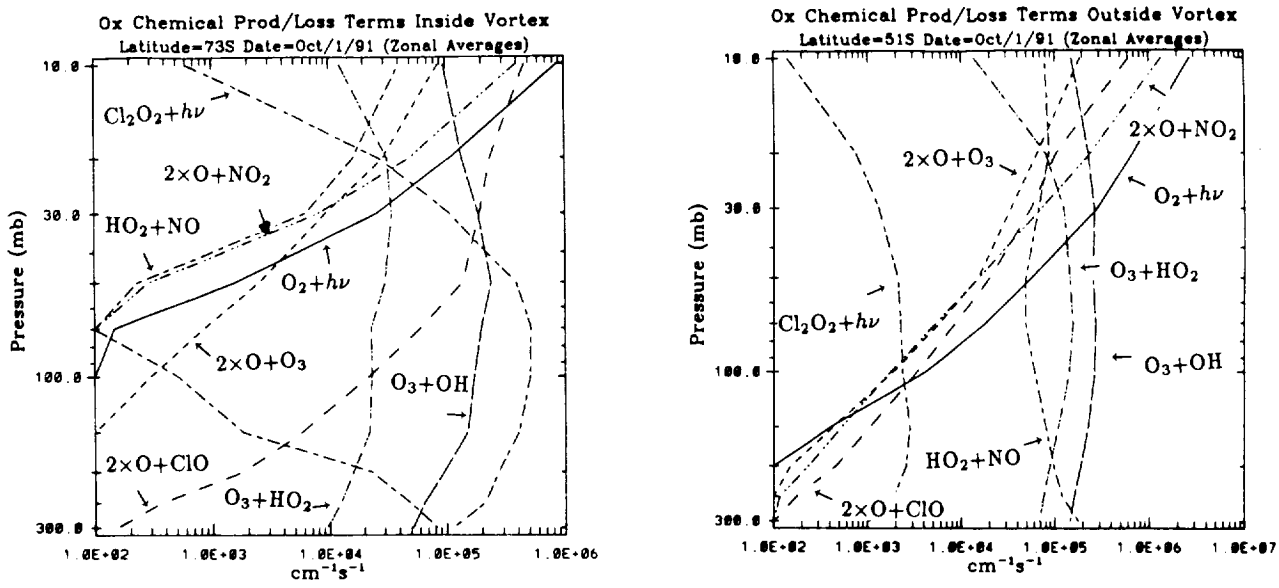

Figure 2. Twenty four hour averaged odd-oxygen production and loss rates (cm^{-3} s^{-1}) for (a) inside (73° S) and (b) outside (51° S) the vortex.

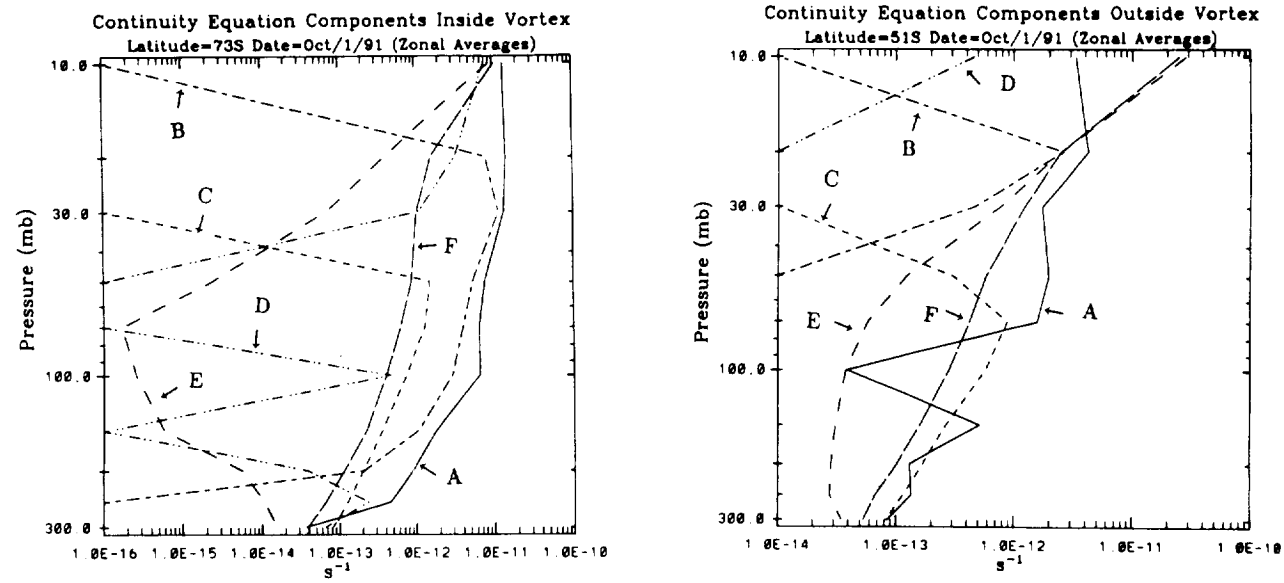

Figure 3. The zonally averaged dynamical and net chemical components for O_x for the version of the continuity equation described in the text for (a) inside (73°) and (b) outside (51°) the vortex. Units are s^{-1} and averaged over one day. The terms A, B, C, D, E, and F, are described in the text.

+ ClO and OH + O_3 with a combined loss rate of approximately 6.25×10^5 cm^{-3} s^{-1} at 50 mb which is about 6.25×10^{10} ozone molecules cm^{-3} day^{-1} or about 1.2% per day. Thus, if this persisted for a period of about a month, we might expect a 30–40% decrease in the ozone column (even if bromine chemistry were added this would only add an additional 10% (cf Henderson et al., 1990)). However, the net loss is much less than this as can be seen in Figure 1.

The reason for the lack of decrease of ozone is shown in Figure 3 which shows the various dynamical and net chemical components of the continuity equation. The labelled curves of the figure are as follows. A is the negative of horizontal advection term, B is the vertical advection term, C is the horizontal diffusion term, D is the total mixing ratio tendency, E is the total O_x chemical production term, and F is the total O_x chemical loss term. Outside the vortex at 10 mb the chemistry terms are larger than the dynamical terms. But in the 30–100 mb region the dynamical terms dominate the chemistry. Inside the vortex the dynamical terms are between 5 to 10 times larger than the chemical terms at all heights. At these latitudes the main terms are the horizontal and vertical advection terms which are in approximate balance: the chemical loss is superimposed on this dynamically active situation. Thus, in spite of extensive ozone loss the transport from lower latitudes in the model dominates the vortex ozone budget. This excessive transport may be a consequence of the inadequacies of the low resolution CMC objectively analyzed data in being unable to correctly provide a description of the important vortex dynamics during the period (cf. Kaminski et al., 1992). In particular, the transport resulting from the two previously mentioned model warmings needs to be more critically examined to assess the accuracy of the CMC data in describing the temperature and wind evolution during these events.

Conclusions

At the Symposium we had anticipated that the problem resided in the temperature fields being too warm. Even though we have found that there was indeed a temperature error with the CMC stratospheric temperatures this is clearly not directly (in terms of heterogeneous chemistry) the major problem. The problem in simulating the generation of the ozone hole lies with the excessive transport of ozone which may in part be due to the temperature field (which is used to provide the forecast field at 6 and 18Z, when radiosonde data is not available).

The zonal average temperatures near the beginning and at the end of the run suggest that the temperatures from the objective analysis might be too warm by as much as 5 degrees (Dr. H. Ritchie, private communication, 1992). This implies that the winds are also effected, as they are derived from the temperature. As an aside, the temperature problems in the stratosphere have since been investigated and fixed by CMC. Also the warming rates might be too high, as at 10 mb over the south pole there is a warming of almost 40K in 25 days. These points seem to suggest that the objective analysis itself doesn't accurately reflect the dynamical processes over the southern hemisphere. The major problem may be the low resolution at which the CMC objectively analyzed data have been used and further work will investigate this effect.

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