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OZONE REDUCTION IN THE 1980's: A MODEL SIMULATION OF ANTHROPOGENIC AND SOLAR PERTURBATIONS

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Abstract. An interpretation of global ozone changes deduced from satellite data obtained since 1979 is presented, based on two–dimensional model simulations. The study shows that a depletion in total ozone of the order of 2 percent and a reduction in ozone density near 40 km of 7 to 12 percent over the 1979–1986 period are consistent with the observed increase in trace gas densities (chlorofluorocarbons, methane, nitrous oxide, carbon dioxide) and the simultaneous decrease in solar activity during this period. The model also suggests that ozone variations of solar and anthropogenic origins between 1979 and 1986 were of similar magnitude but that the ozone response to trace gas emissions increases substantially with latitude while the solar signal in ozone is present lower in the atmosphere and is nearly independent of latitude.

Introduction

Total ozone, as well as the ozone density in the stratosphere, have been measured routinely since 1979 by means of space–borne instruments such as TOMS and SBUV (both on Nimbus 7), the UV and IR spectrometers on board the Solar Mesosphere Explorer (SME) or SAGE and SAGE II. The abundance of ozone in the stratosphere is believed to have been changing over the last decade as a result of increasing emissions of trace gases such as the chlorofluorocarbons (CFCs), methane, nitrous oxide and carbon dioxide. These perturbations are essentially of anthropogenic origin and are superimposed on natural variations related to dynamical fluctuations (e.g., quasi–biennial oscillation, El Niño, interannual variability, etc.), volcanic activity (e.g., El Chichon eruption in 1983), or solar activity (e.g., 11–year solar cycle).

Careful analyses of ozone measurements have revealed that satellite and Dobson data are in disagreement due to the degradation of space-borne instruments [NASA, 1988; Reinsel et al., 1988]. Moreover the uncertainties in the ozone variations derived from instruments based on backscattered radiation techniques are larger than those associated with the self-calibrated solar occultation measurements (SAGE and SAGE II). By applying to the TOMS data a correction to make these consistent with the measurements from the ground–based Dobson instruments (which are periodically recalibrated), it appears that, during the 1979–1986 period [NASA, 1988], total ozone from 53°S to 53°N has decreased from October 1978 to October 1985 by 2.5 percent (with the range being 1.1 to 3.7 percent). A larger reduction is detected at high latitude, especially in the Southern Hemisphere, where the dramatic Antarctic ozone depletion observed during spring [Farman et al., 1985; Stolarski et al., 1986] since the mid 1970's seems now to affect a significant fraction of the hemisphere throughout the year.

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Model Simulation of Ozone Decline

Numerical models of the middle atmosphere provide a means of interpreting observations and estimating the relative contribution of different types of atmospheric perturbations. The two–dimensional model [Brasseur et al., 1988], which is used in the present study, extends from pole to pole and from the Earth's surface to 85 km altitude. The equations for the conservation of mass, angular momentum, thermodynamic energy and mixing ratio of chemically active gases are treated interactively. The meridional transport is formulated through the transformed Eulerian mean circulation [Edmon et al., 1980; Dunkerton, 1981] which is forced by momentum deposition associated with Rossby and gravity wave absorption. This torque as well as the eddy diffusion resulting from transience and dissipation of these waves are parameterized according to Hitchman and Brasseur [1988] and Brasseur and Hitchman [1987]. Radiative heating/cooling is treated using the NCAR CCM1 radiative code [Kiehl et al., 1987], which includes the effects of solar radiation on ozone, molecular oxygen, water vapor and carbon dioxide and the effects of terrestrial radiation on carbon dioxide, water vapor and ozone. The chemical scheme includes all reactions of importance for the oxygen, hydrogen, nitrogen and chlorine species in the middle atmosphere. It does not consider the specific action of atmospheric particles which are believed to affect the chemistry in the cold regions of the lower stratosphere and to play an essential

TABLE 1. Mixing Ratios of the trace species in 1979 and 1986.

Species	1979	1986
CO_2	333.5 ppmv	344.0 ppmv
CH_4	1.62 ppmv	1.70 ppmv
N_2O	305 ppbv	310 ppbv
$CFCl_3$ (F-11)	170 pptv	220 pptv
CF_2Cl_2 (F-12)	290 pptv	418 pptv
CH_3CCl_3	110 pptv	174 pptv
CCl_4	120 pptv	120 pptv

role in the formation of the springtime ozone hole over Antarctica. The temperature dependent chemical rate constants and the absorption cross sections are adopted from DeMore et al. [1985]. The spectrum of the solar irradiance at the top of the atmosphere is taken from Brasseur and Simon [1981].

In order to help interpret the trend of ozone deduced from observations over the last 10 years, the response of the atmosphere to changes in the trace gas abundance and to variations in solar activity between 1979 and 1986 has been simulated with the model. The mixing ratios of these source gases reflecting the strength of the anthropogenic perturbations are given in Table 1 for the years 1979 and 1986, respectively. The percentage reduction in the solar irradiance between the beginning and the end of the period under consideration is specified for spectral intervals in Table 2. It should be remembered that, because of possible instrument drift, there are substantial uncertainties in the measured amplitude of the variations of the solar emission over the 11-year cycle. The values quoted in Table 2, based on the Mg II solar line variations deduced from an analysis of the SBUV data [Heath and Schlesinger, 1986] and used as an index for long-term solar variations, should probably be considered as upper limits since they are higher than the amplitude derived from SME observations between 1982 and 1987, especially near and below 200 nm.

Model Results and Discussion

Figure 1 shows a time-latitude representation of ozone changes calculated for the 1979-1986 period, resulting from the simultaneous effects of increased densities in perturbing trace gases and decreased solar activity. The globally averaged ozone decline over this period is estimated to be 2.1 percent. This value is close to the average reduction deduced from the recent data analysis. A seasonal variation in the ozone reduction is visible at high latitudes, the largest depletion being found in winter, particularly in the Southern Hemisphere The decline in the column abundance observed in winter at mid- and high-latitudes (larger than 3 percent) however is higher than predicted by the model. The reason for this discrepancy, which is common to most models [NASA, 1988], could be attributed to the effects of heterogeneous reactions on particles, which are not taken account in the model.

Figure 2a and b show the changes in the meridional

TABLE 2. Ratio between maximum and minimum solar irradiance at different wavelengths used in the model calculation

Wavelength	Factor
Lyman α (121.6 nm)	2
170 nm	1.25
180 nm	1.16
190 nm	1.10
200 nm	1.10
205 nm	1.09
210 nm	1.04
220 nm	1.04
250 nm	1.04
300 nm	1.01

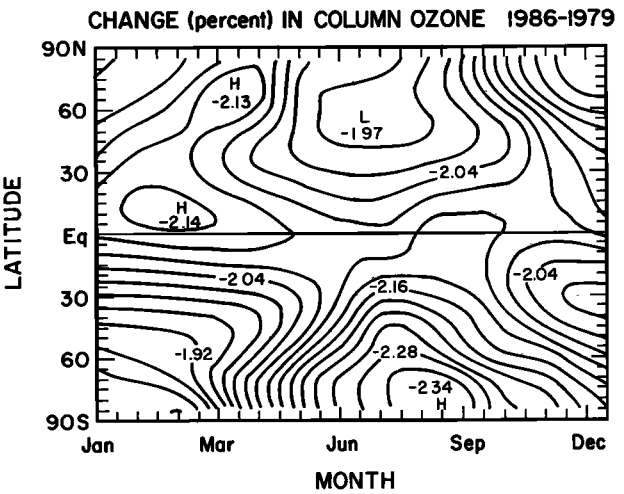

Fig. 1. Relative variation (percent) in the ozone column amount between 1979 and 1986 as a function of latitude and season.

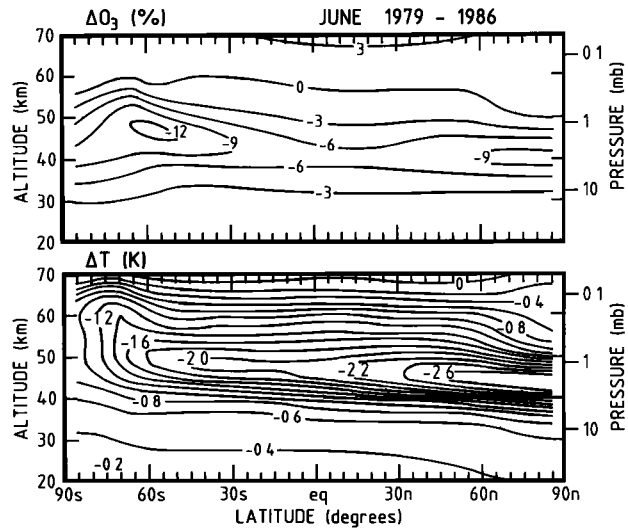

Fig. 2. (a) Relative variation of the ozone density between June 1979 and June 1986 presented in percent as a function of latitude and altitude. (b) Temperature change (in Kelvin) between June 1979 and June 1986 as a function of latitude and altitude.

distribution of ozone and temperature at the solstice, calculated for the same conditions. The largest relative reduction in the ozone density is found in the upper stratosphere near 40–45 km altitude, with the most pronounced effects at high latitude (12.7 percent in winter and 9.7 percent in summer). This latitudinal dependence results from the low sequestering rate of chlorine atoms as inactive HCl molecules by methane at high latitudes and consequently to the high destruction rate of ozone by active chlorine in these regions. Methane is less abundant in the polar stratosphere because of its destruction by OH while transported from the tropics to the pole by the general circulation. The ozone reduction at 32 km is estimated to be of the order of 3 percent at all latitudes. A slight increase of ozone is calculated above 58 km as a result of reduced photolysis of water vapor during the declining phase of the solar cycle and consequently reduced destruction of odd oxygen (O and O_3) by hydrogen radicals.

The cooling of the stratosphere resulting essentially from the decreased ozone and enhanced carbon dioxide densities reaches a maximum near 45-50 km altitude. The model predicts a temperature reduction at the stratopause varying from 1 K at the winter pole to 2.8 K at the summer pole. The average temperature decrease is about 0.5 K at 30 km, 1 K at 40 km, 2 K at 45 and 48 km, 1.2 K at 55 km, 1 K at 60 km and 0.5 K at 65 km. These values are consistent with the trends derived from available temperature data [NASA, 1988].

Figure 3 shows the calculated ozone decline between 1979 and 1986, averaged over all latitudes and seasons. It is found to be 1.3 percent at 25 km, 2.5 at 30 km, 4.3 at 35 km, 7.0 at 40 km, 6.5 at 45 km, 3.2 at 50 km, and 1.5 percent at 55 km. The ozone reduction derived from observations at 40 km (3 percent from the SAGE data between 1979/80 and 1984/85 and 9 percent from the ground-based Umkehr measurements between 1976 and 1986) are not inconsistent with the model prediction in the middle stratosphere. The SAGE data [NASA, 1988] however, suggest very little ozone change at 45 km, a 2-3 percent increase near 50 km, and a reduction of about 4 percent at 25 km. This latter decrease is larger than predicted in the model.

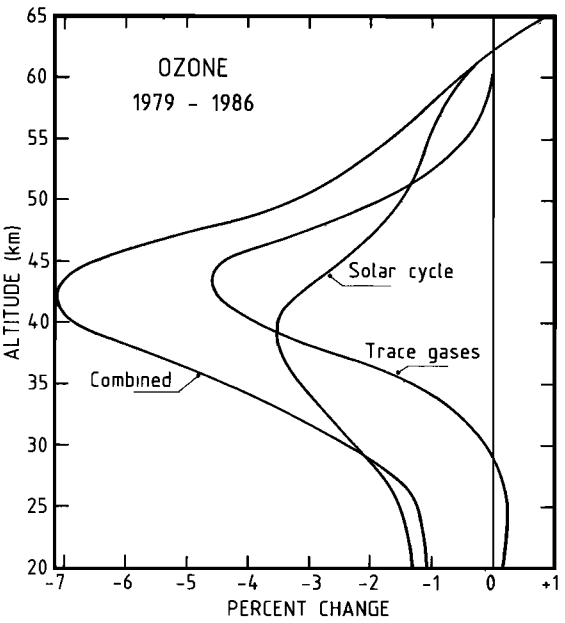

Fig. 3. Relative ozone change between 1979 and 1986 (expressed in percent) averaged over all latitudes and seasons. The contributions of the trace gases and solar effects are shown together with the combined results.

In order to estimate the relative contribution of anthropogenic and solar effects, the vertical distribution of the relative ozone change (averaged over latitude and season) resulting from each of these effects is also shown in Figure 3. The signature of both effects is very similar in shape and magnitude. The peak of the ozone reduction is however 5 km higher and the vertical extent of the ozone perturbation is smaller in the case of the trace gas effect than in the case of the solar perturbation. Furthermore, when only the perturbations by the trace gases are considered, the so-called self-healing effect of the atmosphere (increased ozone formation at low levels due to enhanced penetration of solar UV radiation associated with reduced ozone at higher altitudes) causes the ozone change to be small and even to become positive in the lower stratosphere, where most of the ozone is present. The average reduction in the ozone column determined by the model (due to trace gases changes alone) is of the order of 0.5 percent. The ozone perturbation associated with the solar cycle appears to be significant even in the lower stratosphere and produces a reduction in the ozone column abundance of 1.6 percent over the 1979-1986 period. As indicated earlier, the calculated ozone and temperature responses to solar activity remain highly uncertain [Brasseur et al., 1987] because of difficulties in determining the magnitude of the solar variability, especially in the region between 180 and 210 nm. The calculated sensitivities are therefore commonly expressed relative to the solar variability at 205 nm. The mean ozone sensitivity to a 1 percent change in the 205 nm solar irradiance determined by the model is 0.26 at 30 km, 0.35 at 35 km, 0.39 at 40 km, 0.28 at 45 km and 0.16 at 50 km. In the present model calculations, the solar variability, based on Heath and Schlesinger [1986] is taken to be 9 percent at 205 nm. The SME data [Rottman, 1987] suggests however that this could be overestimated by a factor of 1.5 to 2. In this case, the ozone response should be scaled accordingly.

Finally, the model shows that, while the ozone response in the upper stratosphere to trace gas perturbations increases substantially with latitude, the response of ozone to solar activity is nearly independent of latitude. On this basis, it might be possible to discriminate between natural and anthropogenic variations in measured ozone density.

Conclusions

In summary, the observed changes in stratospheric ozone over the 1979-1986 period are generally consistent

with the variations predicted by a model which takes into account the effects of trace gases of human origin and the decline of the solar cycle during this period. The largest change in the ozone column appears to be due to the solar cycle, if the variation in the solar irradiance is as high as suggested by SBUV. Its magnitude is comparable to the anthropogenic effect if the lower solar variability derived from the SME measurements is adopted. Several discrepancies between observed and calculated trends (e.g., in the Northern hemisphere in winter or in the Southern hemisphere southwards of 60 degrees) need to be explored. Since solar activity is expected to increase between 1987 and 1991, total ozone is predicted to increase slightly in the next 4 years. However, it should be remembered that models do not track the real atmosphere exactly and that unpredicted natural variations of ozone are expected to occur as a result for example of dynamical fluctuations. Substantial variations are calculated in the upper stratosphere with a strong latitude dependence. The importance of resulting changes in the dynamics of the atmosphere needs to be assessed with sophisticated three-dimensional general circulation models.

An adequate monitoring program for both ozone density and solar irradiance has to be implemented in the future. It should provide data with a precision to better than 1 percent, compatible with the expected long-term changes.

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