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SIMULATIONS OF ARCTIC OZONE DEPLETION WITH CURRENT AND DOUBLED LEVELS OF CO_2

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ABSTRACT

Results from idealised 3-D simulations of a dynamical-radiative-photochemical model of the stratosphere are presented for the northern hemisphere winter and spring. For a simulation of a quiescent winter, it is found that with current levels of CO_2 only modest polar ozone depletion occurs, consistent with observations. For a second simulation with the same planetary wave amplitudes in the upper troposphere but with doubled CO_2 the model predicts a northern hemisphere ozone hole comparable to that observed in Antarctica with almost complete ozone destruction at 20 km. Reasons for the marked difference between the simulations are identified.

1. INTRODUCTION

An essential component for the formation of the Antarctic ozone hole (Farman et al., 1985) is the occurrences of Polar Stratospheric Clouds (PSCs) which "chemically process" the air for ozone destruction (Solomon, 1990). The PSCs form in winter time in the extremely cold regions of the lower stratosphere in the Antarctic, and to a lesser extent the Arctic. The frequency and extent of PSCs is, however, rather temperature dependent. Consequently, destruction of ozone over the polar regions could be somewhat perturbed by changes in climate. In particular, the cooling of the lower stratosphere associated with increases in CO_2 (Fels et al., 1980; Rind et al., 1990) may trigger significant ozone destruction in the Arctic, in addition to that already observed in the Antarctic.

The effect of doubled CO_2 amounts on Arctic ozone has been investigated by Pitari et al. (1992) and Austin et al. (1992) using 3-dimensional models. Pitari et al. used a general circulation model and found only small differences (~10 Dobson Units (DU)) in the spring time total ozone over the Arctic when the amount of CO_2 was doubled. However, their conclusions were based on a single model winter using a low resolution model which simulated higher temperatures in the polar lower stratosphere than are typically observed. In contrast, Austin et al. used a mechanistic model of the stratosphere which allowed a more comprehensive treatment of the radiative-dynamical-photochemical couplings at the expense of representing the tropospheric behaviour by a prescribed lower boundary condition at 316 mbar. Results from this model provided the first direct evidence of a possible future Arctic "ozone hole", in which almost all the ozone at 20 km is destroyed over a significant area.

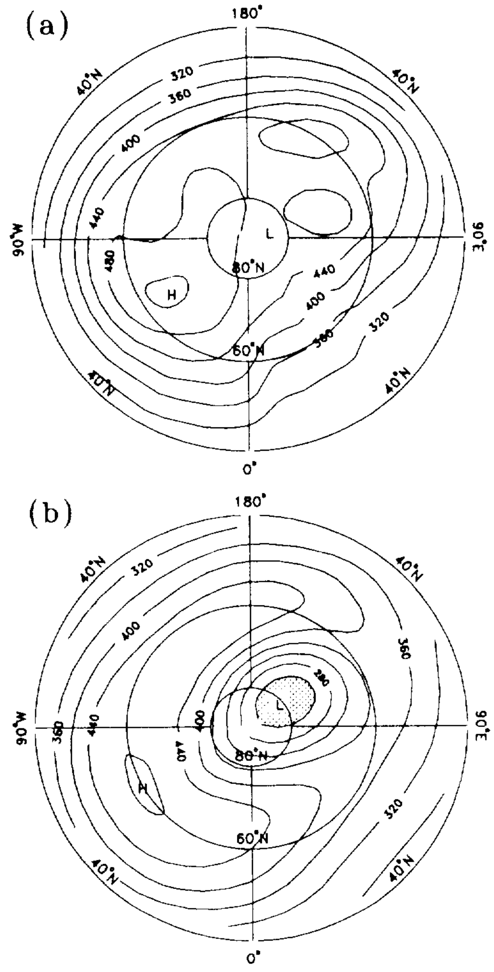

Fig. 1. Total ozone (Dobson Units, including an estimated tropospheric component) on 14 April for the model simulations with (a) present day levels of CO_2, and (b) doubled CO_2. Shading denotes where the ozone column is under 240 DU.

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By appropriately choosing the lower boundary condition Austin et al. simulated the evolution of polar ozone in the northern hemisphere from mid-December through to April for an idealized winter situation in which prolonged and extensive PSC formation was most likely. With current CO_2 amounts the modelled ozone distribution evolved in a manner broadly consistent with observations. With doubled CO_2 amounts and when proper account was taken of the ozone radiative feedbacks the model produced an Arctic ozone hole in April, though this result neglected any concomitant changes in the tropospheric behaviour resulting from the doubling of CO_2. The modelled Arctic ozone hole occurred because of a change in the stratospheric circulation. However, because of the interannual variability of the northern hemisphere stratosphere it was not possible for Austin et al. to say whether similar circulation changes are likely to be a ubiquitous feature of the winter stratosphere when the concentration of CO_2 is increased and, therefore, whether the large ozone depletion would only be a feature of relatively undisturbed winters. In order to address this question it will first be necessary to obtain a better understanding of the causes of the differences in the simulations described by Austin et al. and compare how the modelled Arctic ozone hole develops in contrast to the Antarctic ozone hole.

2. OZONE DEPLETION

Maps of the simulated column ozone amounts on 14 April obtained by Austin et al. (1992) with current and doubled CO_2 amounts are presented in Figure 1. With current levels of CO_2 (Figure 1a) the maximum total ozone amount is 527 DU near 70°N and there is no clearly defined minimum in high latitudes. The results for doubled CO_2 shown in Figure 1b contrast markedly with Figure 1a. Apart from a clearly defined minimum in high latitudes, approaching 200 DU, the maximum ozone amount is also about 10% lower. The reduction in the mid-latitude ozone maximum has also been noted for the Antarctic (Schoeberl et al., 1989) while the overall figure is very reminiscent of southern hemisphere springtime total ozone distributions (Schoeberl et al.,1989), albeit with an ozone hole of smaller total area.

Figure 2 shows the vertical ozone profile where the total column is a minimum for the two simulations on 5 March and 14 April in comparison with the initial ozone profile at the pole. The results for current levels of CO_2 (Figure 2a) show only a small change by 5 March but by April some local depletion has occurred near 100 mbar. When allowance is made for transport, the chemical depletion is similar in magnitude to that noted by Proffitt et al. (1990) and Koike et al. (1991) for the winters of 1989 and 1990, respectively. For doubled CO_2 (Figure 2b), again little change has occurred by 5 March but by April complete ozone destruction has occurred at the 56 mbar level. The results for doubled CO_2 are very similar to the vertical ozone profile reported by Gardiner (1988) during the 1987 Antarctic ozone hole. In particular the ozone destruction in the model occurs over the same altitude range, though is less extensive than observed in Antarctica.

In an analysis of the simulation with doubled CO_2 Austin et al. (1992) examined the chemical behaviour associated with the formation the modelled ozone hole. It was found that with the doubling of CO_2 the period of PSC formation was extended well into spring, similar to the situation currently observed in

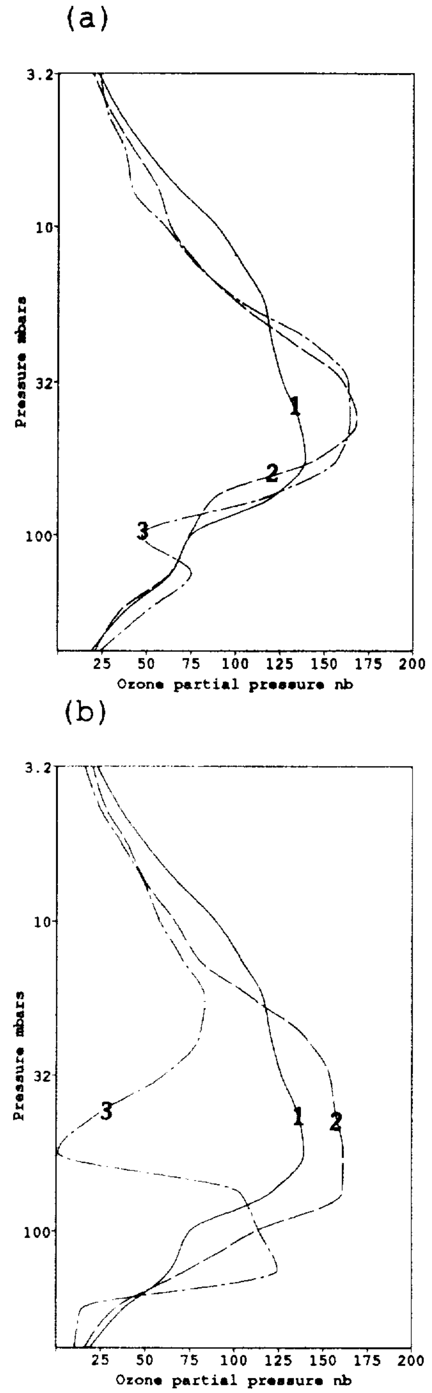

Fig. 2. Vertical profile at the position of the ozone minimum column for the model simulations with (a) present day levels of CO_2, and (b) doubled CO_2. Curve 1 shows the initial conditions (340 DU); curve 2 shows the results for 5 March (329 and 353 DU for simulations (a) and (b) respectively); curve 3 shows the results for 14 April (339 and 208 DU respectively).

Antarctica. The denitrification of the model atmosphere and elevated levels of ClO were therefore still present in the simulation when the photochemical processes began operating in polar latitudes. Ozone was then destroyed over the Arctic in the model simulation by the same catalytical cycle involving the chlorine dimer (Molina and Molina, 1987) as is principally responsible for the Antarctic ozone hole (Solomon, 1990).

3. CHANGES IN DYNAMICS

In addition to the modelled Arctic ozone hole being similar in many respects to the observed Antarctic ozone hole, Austin et al. (1992) found that with the doubling of CO_2 the modelled stratospheric circulation in the northern hemisphere spring became more like the observed southern hemisphere spring. Although the same northern hemisphere planetary wave amplitudes were prescribed at the model lower boundary the simulation with doubled CO_2 no longer produced a stratospheric warming before the end of the simulation on 24 April. Austin et al. identified the absence of a warming in the simulated winter as a contributory cause of the modelled Arctic ozone hole and this most likely resulted from a change in the wave amplitudes in the lower stratosphere.

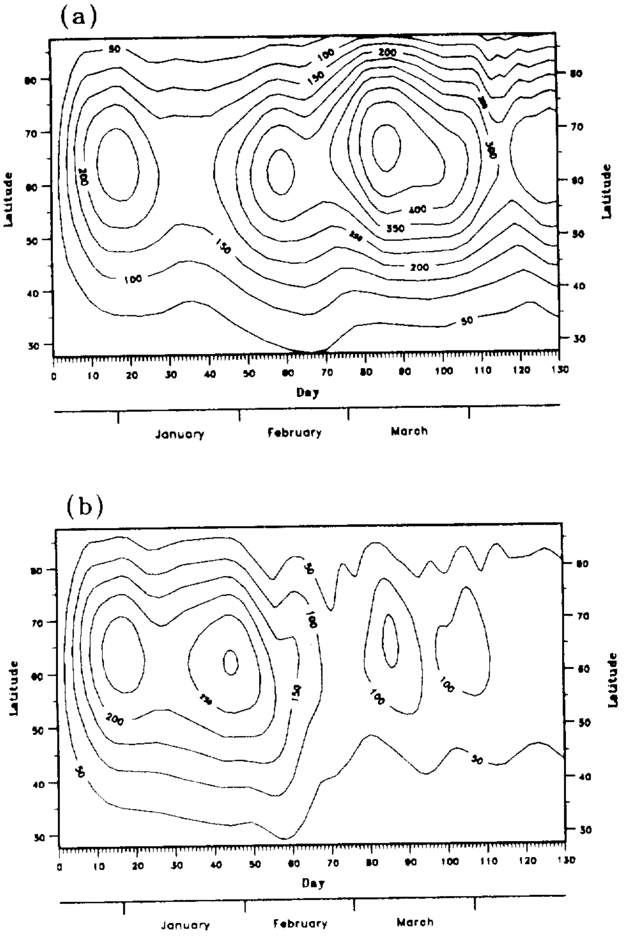

Fig. 3. Amplitude of the wavenumber one component of the geopotential height field at 100 mbar for the model simulations with (a) present day levels of CO_2, and (b) doubled CO_2.

Figure 3 shows the evolution of the wavenumber one amplitudes at 100 mbar for the two simulations. Differences in the wave amplitudes at this level are relatively small until late January when the two simulations begin to diverge. With current levels of CO_2 (Figure 3a) there is growth in the wave amplitude throughout February and early March and this can be linked to the occurrence of the stratospheric warming in that simulation. On the other hand, with doubled CO_2 (Figure 3b) there is a substantial reduction in the wave amplitudes despite identical wave amplitudes at the model lower boundary (316 mbar). A further analysis of the results also showed that by early February the polar night jet in the doubled CO_2 simulation was slightly weaker and narrower, and this rather subtle difference in the zonal mean wind gave rise to a significantly different refractive index. This substantially altered the propagation characteristics for wavenumber one, as confirmed by smaller EP Fluxes (see e.g. Butchart et al. (1982) for the definition and interpretation of these diagnostics) in the doubled CO_2 simulation. In a model simulation of an observed stratospheric warming, Butchart et al. also found that the precise details of the refractive index were critical to whether or not the warming occurred.

4. RADIATIVE HEATING RATES

Although the detailed characteristics of the wave propagation produced the marked differences between the dynamical behaviour of the simulations, the differences in the radiative heating must have ultimately been responsible. The impact of the changes in composition on radiative heating rates is illustrated in Figure 4. The temperature profile is taken from the simulation with current levels of CO_2 on 4 April at the grid point at which minimum ozone occurs on that day in the doubled CO_2 simulation. The effect of doubling CO_2 is to increase the radiative cooling of the lower stratosphere. The small scale struc-

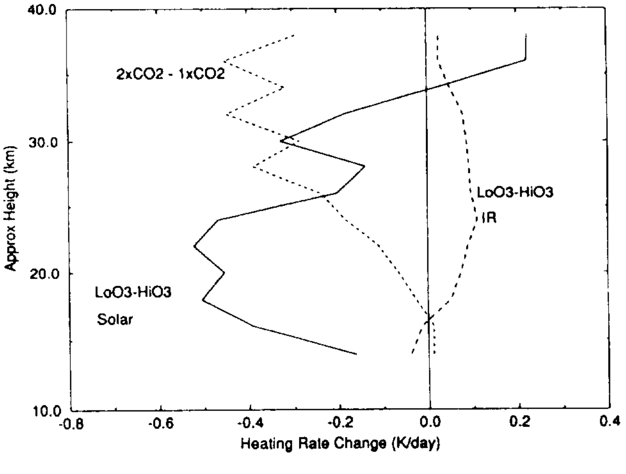

Fig. 4. Effect of changes in ozone and carbon dioxide on heating rates. A temperature profile from the present day CO_2 simulation on 4 April is chosen, and the effect of doubling CO_2 and depleting ozone (separated into solar and thermal infrared effects) are shown. The depleted ozone profile corresponds to the grid point of minimum ozone on 4 April of the double CO2 simulation.

ture in the mid-stratosphere is due to small amplitude 2-grid length waves present in the model. The impact of the model predicted changes in ozone column are also shown. Using the ozone column from the doubled CO_2 simulation and that from the current CO_2 simulation the change in the heating rate is dominated by the contribution from the solar heating, which produced a decrease of up to about 0.5 Kd^{-1}. It is this decrease which cools the lower stratosphere and maintains the low temperatures, both directly, and indirectly via a reduction in the adiabatic heating (see Section 3). The effect in the thermal infrared is much smaller and indeed acts to heat the region above 18 km. This is due to a combination of decreased cooling to space from the ozone depleted regions and an increased penetration of thermal infrared radiation from the warmer troposphere. These results are consistent to those obtained by Shine (1986) in a simpler study.

5. DISCUSSION AND CONCLUSIONS

In the model simulations presented here the effect of doubling CO_2 was to produce an Arctic ozone hole comparable in vertical extent but of slightly smaller area to that observed over Antarctica. The ozone hole occurred because of a change in dynamical circulation resulting in a delay in the final warming. This delay occurred due to the radiative coupling of the dynamics and photochemistry with the solar ozone heating term as the largest contributor. The change in solar heating modified the mean zonal wind fields thereby considerably reducing the propagation of planetary wavenumber one. This enhanced the effects of the direct radiative heating by reducing the adiabatic heating component. Thus, with a cooler stratosphere, PSCs were more extensive and persisted longer so that the ozone destruction was further enhanced and, by a positive feedback mechanism via the radiative heating, the final warming was delayed.

The simulation presented here for current levels of CO_2 was similar to that observed in 1988 and 1989, in which the lower stratosphere remained relatively cool throughout the winter. Under these conditions radiative changes introduced by doubling CO_2 have a more direct influence on the model behaviour and the positive feedback mechanism described above is effective. It is possible, however, that during more active winters the effect of CO_2 increases may be to enhance wave activity (Rind et al., 1990). Under these conditions climate perturbations to the lower stratosphere may be determined more by dynamical processes and less directly by radiative processes. Therefore, although an Arctic ozone hole is a possibility with increased CO_2 amounts it may also be concluded that not all winters will produce ozone holes.

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