Polar Meteorol. Glaciol., **13**, 1-10, 1999

INFLUENCES OF ARCTIC OZONE HOLE ON THE STRATOSPHERIC GENERAL CIRCULATION

Toshihiko HIROOKA, Toshihiko NISHIYOSHI, Shingo WATANABE
and Saburo MIYAHARA

Department of Earth and Planetary Sciences, Kyushu University, Fukuoka 812-8581

Abstract: Numerical experiments are performed for four years to estimate radiative and dynamical influences of the "Arctic ozone hole" on the stratospheric general circulation by using a general circulation model developed at Kyushu University. The model includes simplified ozone photochemistry interactively coupled with radiation and dynamics. The resultant temperature structure consists of cooling of about 6 K in the polar lower stratosphere and warming of about 8 K in the polar upper stratosphere, which intensifies the polar night jet by about 9 ms^{-1}. The cooling is caused by reduction of downward motion as well as decrease of solar UV heating due to ozone depletion, while the warming is caused by dynamical heating due to enhancement of downward motion. The results imply that the feedback mechanism may strengthen the ozone hole itself.

1. Introduction

The ozone hole appeared at the end of the 1970s in the Antarctic lower stratosphere and has developed early each austral spring. In addition, large ozone depletion has been observed during early spring over the Arctic in the 1990s. In particular, the ozone depletion during spring 1997 exhibited many similarities to the Antarctic ozone hole from the viewpoint of the ozone distribution as well as the stratospheric general circulation (*e.g.*, NEWMAN *et al.*, 1997; COY *et al.*, 1997). The development of a stable wintertime polar vortex is essential for the Arctic ozone depletion as well as the Antarctic ozone hole; the strong polar vortex keeps the polar stratosphere very cold and isolated from mid- and low latitudes, which reinforces the formation of polar stratospheric clouds (PSCs) in the polar lower stratosphere. Concomitantly, in such circumstances, the transport of ozone-abundant air into polar regions is fairly suppressed. Hence, we call such Arctic ozone depletion the "Arctic ozone hole" hereafter.

On the other hand, ozone depletion leads to decreased solar ultraviolet (UV) heating and lower temperatures, resulting in a colder and stronger polar vortex. This feedback mechanism may strengthen the ozone hole. In order to examine the feedback mechanism, the response of the general circulation to a prescribed Antarctic ozone hole has been investigated with the aid of general circulation models (GCMs) by various authors (*e.g.*, KIEHL *et al.*, 1988; MAHLMAN *et al.*, 1994). They obtained the characteristic temperature change consisting of cooling in the polar lower stratosphere and warming in the polar upper stratosphere of order 5-10 K along with corresponding intensification of the polar night jet of order $10\,ms^{-1}$, consistent with observations (RANDEL, 1988). However, in these GCMs the dynamical and radiative fields were not coupled interactively with the ozone field. Moreover, the mechanism bringing about such a temperature structure was not clarified sufficiently.

As regards the occurrence of the Arctic ozone hole, AUSTIN and BUTCHART (1992, 1994) examined the influence of stratospheric cooling due to an increase in the concentration of CO_2 by using a mechanistic model including major photochemical reactions. They showed that a doubling of CO_2 could bring about a large Arctic ozone hole in case of no significant planetary wave activities in the lower boundary. Recently, SHINDELL *et al.* (1998) have discussed the development of the Arctic ozone hole due to greenhouse-gas-induced cooling in the lower stratosphere, on the basis of GCM experiments of the Goddard Institute for Space Studies (GISS). However, their studies were focused on the possible future development of the Arctic ozone hole, not on the feedback mechanism itself.

Hence, in our earlier paper (HIROOKA *et al.*, 1999), we used a GCM including simplified ozone photochemistry which is coupled with radiation and dynamics, and investigated radiative and dynamical impacts of the Arctic and Antarctic ozone holes. In both ozone hole experiments, resultant temperature and wind changes were very similar to those of former studies. In the Arctic experiment, cooling of 5 K in the polar lower stratosphere and warming of 3 K above it, and intensification of the polar night jet of about $5\,ms^{-1}$, were obtained; these values were smaller than the Antarctic ones by a factor of 0.5. In the Arctic experiment, however, stratospheric sudden warmings occurred in winter and/or early spring, which would make the estimate difficult. Concerning the mechanism, we concluded that the cooling was caused by decrease of solar ultraviolet heating due to ozone depletion while the warming was caused by dynamical heating due to enhancement of downward motion.

The main purpose of the present study is to perform further experiments, especially for the Arctic ozone hole, in order to exclude the influence of stratospheric sudden warmings and to obtain more reliable estimates.

2. Model and Experimental Method

The GCM used in this study is the same as that used in HIROOKA *et al.* (1999), *i.e.*, a global spectral model developed at our laboratory, with triangular truncation at wavenumber 21 in the horizontal direction and 37 vertical layers extending from the surface to about 83 km. The GCM includes realistic topography and has a full set of physical processes, such as the boundary layer, hydrology, dry and moist convection, and radiative processes. Concerning the radiative process, the scheme of CHOU *et al.* (1991) is used for long wave radiation, along with that of LACIS and HANSEN (1974) for short wave radiation. Rayleigh friction and gravity wave drag parameterization (MCFARLANE, 1987) are introduced for the zonal momentum equation to represent the drag force due to unresolved motions.

In order to make the ozone field interactively couple with the radiative and dynamical fields, the ozone mixing ratio is calculated for the region up to about 55 km on the basis of a parameterized Chapman cycle proposed by HARTMANN (1978), in which the catalytic destruction of ozone due to HO_x and NO_x is parameterized through the tuning of reaction coefficients, whereas the ratio above that level is prescribed by climatological values. The ozone destruction near the surface is expressed by introducing a suitable deposition velocity around the altitude of 1 km. For details, see MIYAHARA *et al.* (1995).

The ozone hole is produced in the present GCM by a parameterized loss term $-\chi/\tau$ added in the continuity equation for the ozone mixing ratio, where χ is the ozone mixing ratio and τ is the *e*-folding time fixed at 30 days. The choice of 30 days is somewhat arbitrary but a slight change of the value would not affect the results. The loss term $-\chi/\tau$ is switched on for the region between 120 and 16 hPa, when three conditions are met, *i.e.*, a noontime zenith angle less than 85°, a temperature lower than 200 K, and a latitude higher than 64°. These conditions are similar to those of MAHLMAN *et al.* (1994). An ozone hole experiment is started from 1 August in a certain year and performed over successive 4 years; during the first experimental year, *i.e.*, the period from 1 August to 31 July of the next year, only the Antarctic ozone hole is intended to be formed, while after that ozone holes are to be formed in the Arctic and Antarctic regions. Then, the results are compared to those of a "control" experiment which is calculated without the extra loss term from the same initial value as that on 1 August of each experimental year of the ozone hole experiment.

3. Results

Both in the Arctic and Antarctic regions, we obtained ozone holes. Figure 1 shows latitude-time sections of the zonal mean total ozone during experimental year 2 through year 4, along with average total ozone distribution for the three years in the lowest panel. Ozone holes occur in each early spring for both poles. The Arctic ozone hole is very similar to observations, whereas the Antarctic ozone hole is unrealistic: Ozone depletion begins in April and continues until January. After that the ozone recovery in the polar region is insufficient. This seems to be mainly caused by the somewhat warmer temperature threshold of 200 K to initiate the ozone loss term for the Antarctic experiment. As a result, the ozone depletion is considered to occur during too long a period. Note that the systematic ozone excess in higher latitudes of about 50 DU compared to the observational value is due mainly to the excess of tropospheric ozone, which is attributed to the insufficient destruction of ozone near the ground surface in the GCM. Nevertheless, the Arctic ozone hole is realistic with moderate interannual changes.

Figure 2 shows a latitude-time section of the depletion amount of the zonal mean total ozone averaged over the three experimental years compared with the control experiment. In the Antarctic region, we can see that the ozone depletion unrealistically occurs during autumn in addition to spring. On the other hand, the appearance period of the Arctic ozone hole is very similar to observations. The depletion amount exceeds 160 DU over the Arctic region in the mature stage during April. As for the geographical distribution, a zonal wavenumber 3 pattern was seen with the ozone hole slightly north of Greenland (HIROOKA *et al.*, 1999). These characteristics are also very similar to the TOMS observation of the Arctic ozone hole during March 1997 (see NEWMAN *et*

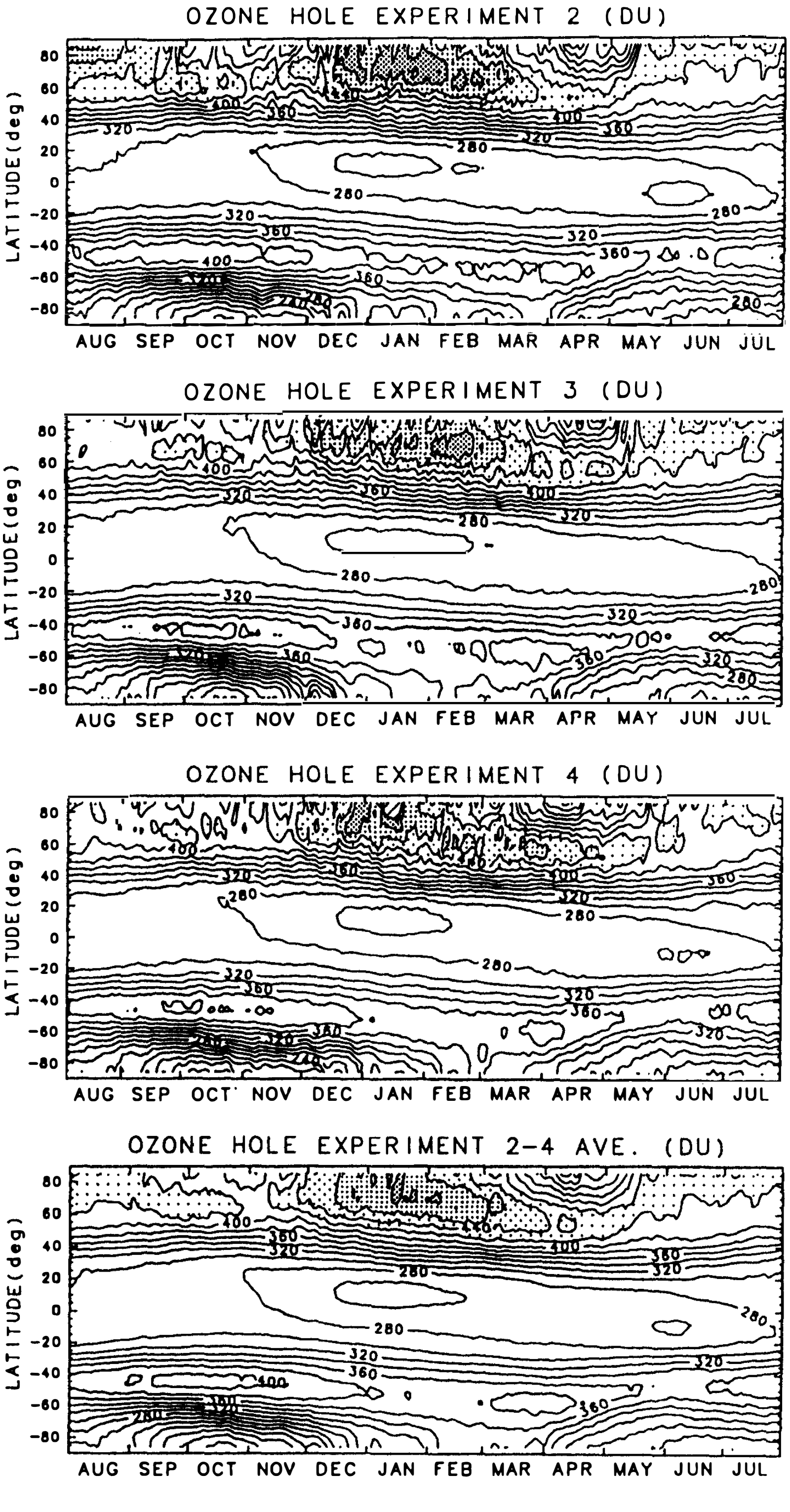

Fig. 1. Latitude-time sections of the zonal mean total ozone during experimental year 2 through year 4, along with the average total ozone distribution for the three years in the lowest panel. Units are DU (Dubson Unit) and the contour interval is 20 DU. The dark shading denotes ozone-abundant regions.

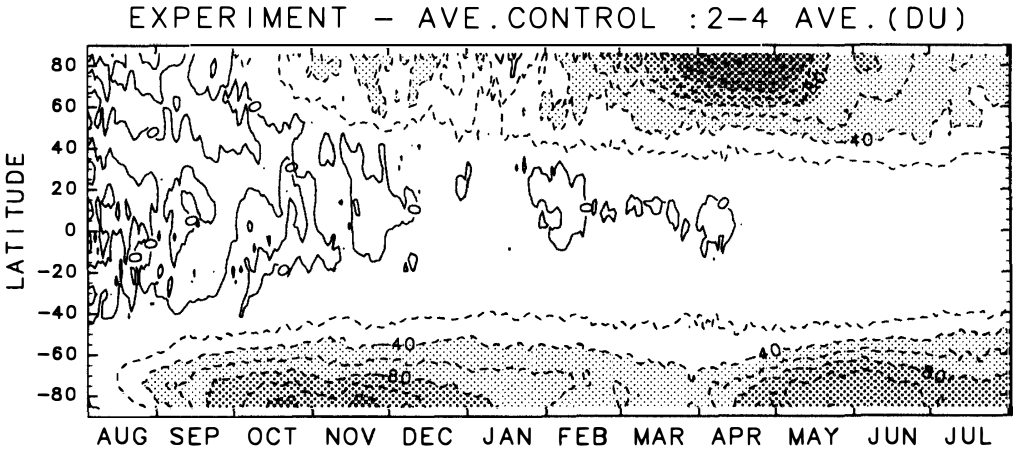

Fig. 2. *Latitude-time section of depletion amounts in zonal mean total ozone averaged over the three experimental years compared with the control experiment. Units are DU and the contour interval is 20 DU. The dark shading denotes regions of large ozone depletion.*

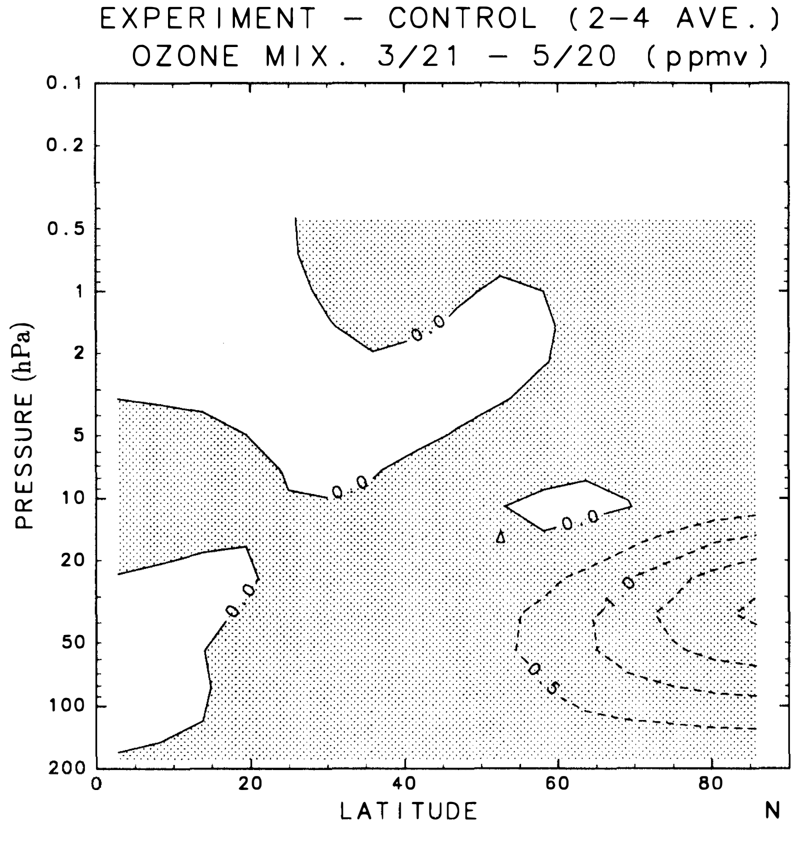

Fig. 3. *Latitude-height section of the difference of the zonal mean ozone mixing ratio between the ozone hole experiment and the control experiment for the period from 21 March to 20 May. Values are averaged over the three experimental years. Units are ppmv and the contour interval is 0.5 ppmv. The shading denotes regions of negative values.*

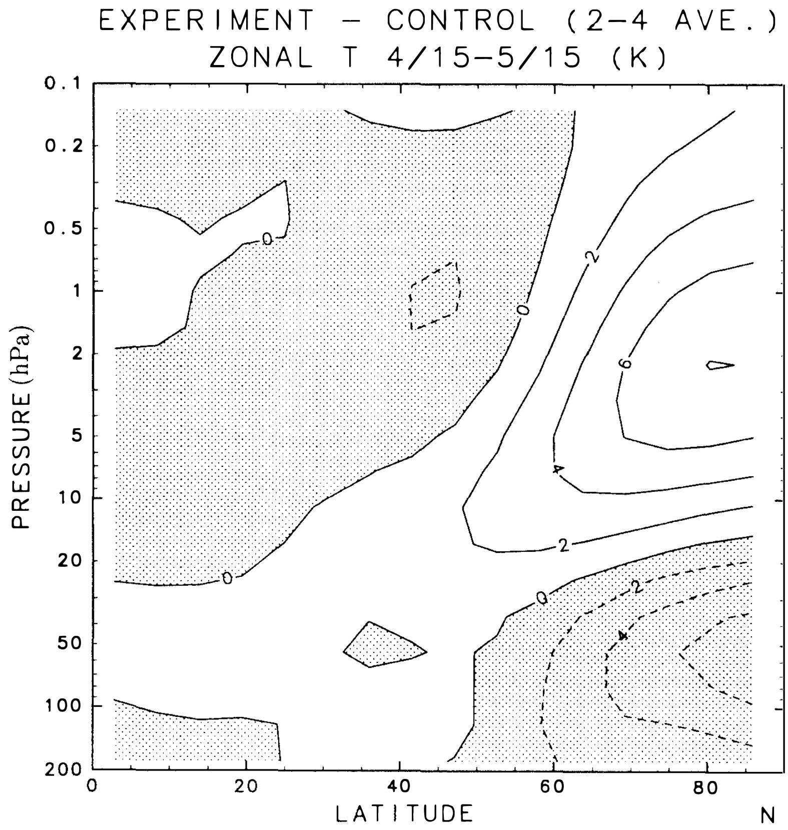

Fig. 4a. *Latitude-height section of the zonal mean temperature difference between the Arctic ozone hole experiment and the control experiment averaged over 15 April through 15 May. Values are averaged over the three experimental years. The contour interval is 2 K. Negative regions are shaded.*

al., 1997).

In the remainder of this section, we will show results concerning the Arctic ozone hole on the basis of the average over the three experimental years to exclude effects of large interannual variability due to strong planetary wave activities and sudden warmings.

Figure 3 shows a latitude-height section of the difference of the zonal mean ozone mixing ratio between the ozone hole experiment and the control experiment, for a mature ozone-hole period, *i.e.*, from 21 March to 20 May. We can see that the ozone depletion is maximized around the 30 hPa level and exceeds 2 ppmv there; this corresponds to a reduction of about 50% assuming the usual ozone mixing ratio of 4–5 ppmv in the control experiment (not shown).

Figure 4a indicates the temperature difference between the hole and control experiments averaged over 15 April through 15 May during which effects of the ozone hole are observed more clearly, while Fig. 4b shows the same figure except for the zonal mean zonal wind difference. We can see a cooling difference of about 6 K in the polar lower stratosphere corresponding to the ozone depletion region and a warming difference of

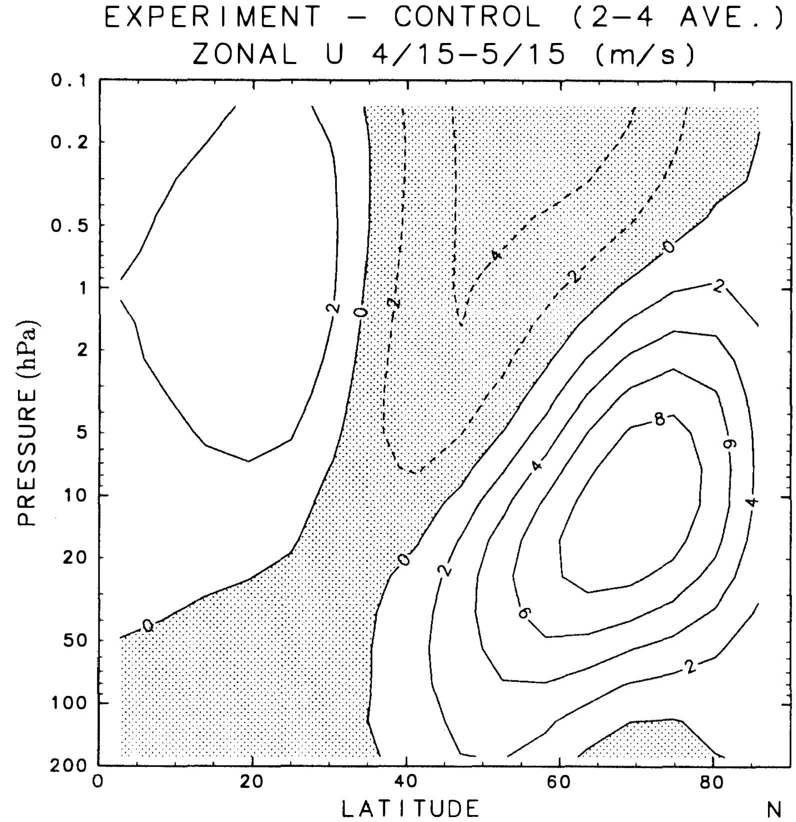

Fig. 4b. As in Fig. 4a except for the zonal mean zonal wind. The contour interval is 2 ms^{-1}.

about 8 K above it (Fig. 4a). At the same time, intensification of the polar night jet of about 9 ms^{-1} is observed in high and mid-latitudes of the stratosphere (Fig. 4b); it is caused by intensification of the horizontal temperature gradient due to the cooling in the polar lower stratosphere. These values are larger than those of our earlier study based on a single year experiment (HIROOKA *et al.*, 1999) by a factor of 2, though the depletion amount of ozone is almost the same. Therefore, our earlier estimates for the Arctic ozone hole seem to significantly suffer from the influence of strong planetary wave activities and sudden warmings.

4. Discussion

For the obtained temperature change, we consider the mechanism on the basis of the quasi-geostrophic transformed Eulerian mean (TEM) thermodynamic equation in log-pressure coordinates using standard notations (*e.g.*, ANDREWS *et al.*, 1987):

$$\frac{\partial \overline{T}}{\partial t} = -\frac{H}{R}N^2\overline{w}^* + \frac{\overline{J}}{C_p}. \qquad (1)$$

The first term and the second term on the right hand side denote the contributions of vertical motion and radiative heating, respectively. After integrating over t and

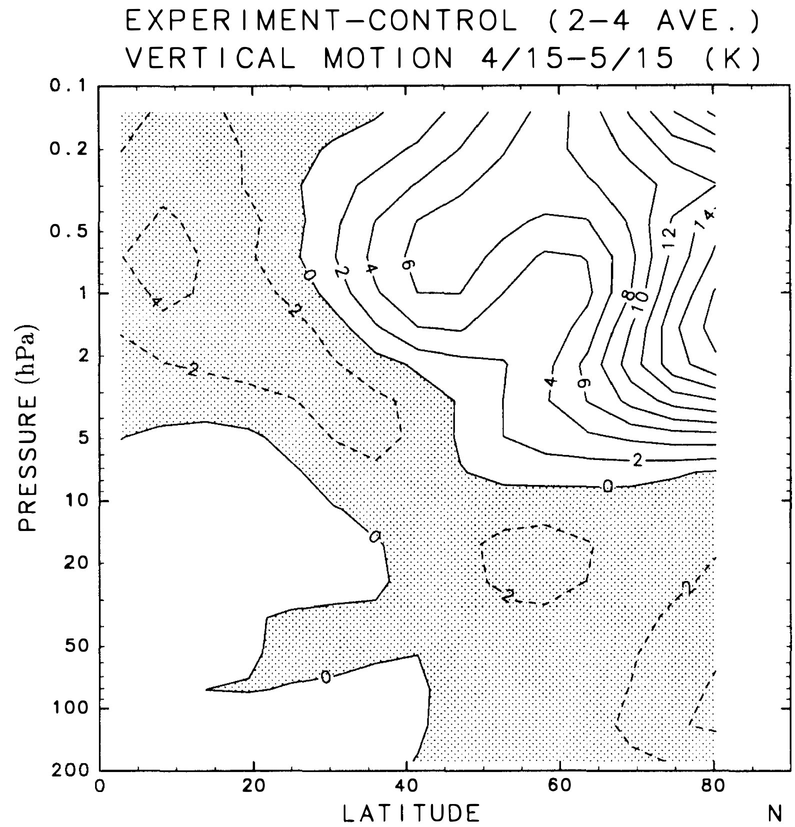

Fig. 5a. Latitude-height section of the temperature changes due to the contribution of vertical motion. Values are averaged over the three experimental years. The contour interval is 2 K. Negative regions are shaded.

averaging over one or several months, and then taking the difference between the ozone hole and control experiments, we obtain:

$$\Delta[\overline{T}] = \Delta[\text{Vertical Motion Contribution}] + \Delta[\text{Radiative Contribution}], \quad (2)$$

where [ ] denotes the time mean. Hence, we estimated the contribution of the two terms on the right hand side of the above equation.

Figures 5a and 5b show the differential contributions of vertical motion and diabatic heating, respectively, for the same period as in Fig. 4. The Arctic stratosphere is dominated by downward motion in this period for both experiments (not shown). The warming in the upper stratosphere is caused by enhancement of downward motion (Fig. 5a), which slightly exceeds the enhancement of radiative cooling due to the warming (Fig. 5b). On the other hand, the cooling in the lower stratosphere is caused by reduction of downward motion as well as enhancement of net radiative cooling. It was found by analyzing the radiative contribution in detail that the net radiative cooling was caused by decrease of solar UV heating due to ozone depletion. In our earlier study, the cooling was due mainly to the enhancement of net radiative cooling. The changes of the downward motion seen in Fig. 5a are considered to be brought about by changes of structure and intensity of planetary waves. As a result, the summation of

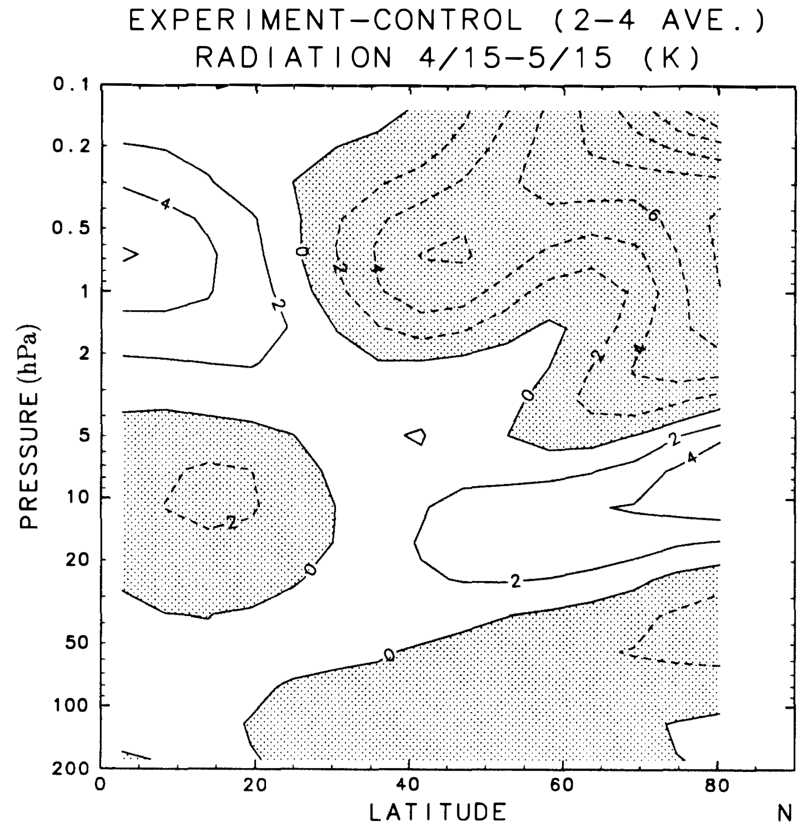

Fig. 5b. As in Fig. 5a except for the contribution of radiative heating. For details, see the text.

the two terms gives the cool and warm temperature structure shown in Fig. 4a, and the ozone hole is fed positively back to the dynamical field and intensifies the polar vortex through the thermal wind balance. The results imply that the feedback mechanism may strengthen the ozone hole itself.

5. Conclusions and Remarks

In the Arctic ozone hole experiment, temperature changes consistent with observations have been obtained, *i.e.*, cooling of about 6 K in the polar lower stratosphere and warming of about 8 K in the polar upper stratosphere, which bring about intensification of the polar night jet of about 9 ms^{-1}. The cooling is caused by reduction of downward motion as well as decrease of solar UV heating due to ozone depletion, while the warming is caused by dynamical heating due to enhancement of downward motion.

In the present study, the Antarctic ozone hole was unrealistic due mainly to the somewhat warmer temperature threshold of 200 K to initiate the ozone loss term in the continuity equation for the ozone mixing ratio; the results are sensitive to the temperature threshold. As for the Arctic ozone hole experiment, the integration period of the three years may be still too short to completely exclude the effects of strong planetary wave activities and sudden warmings. Therefore we must revise the temperature threshold value and perform further experiments.

Acknowledgments

We would like to thank Dr. Y. MIYOSHI and Mr. T. KAYAHARA for helpful discussions during the course of this work. Helpful comments were provided by two anonymous reviewers. This work was supported by a Grant-in-Aid for Cooperative Research with the Center for Climate System Research, University of Tokyo, and by a Grant-in-Aid for Environmental Research of the Mitsubishi Foundation. The GFD-DENNOU Library was used to draw the figures.

References

ANDREWS, D.G., HOLTON, J.R. and LEOVY, C.B. (1987): Middle Atmosphere Dynamics. San Diego, Academic Press, 489 p.

AUSTIN, J. and BUTCHART, N. (1992): A three-dimensional modeling study of the influence of planetary wave dynamics on polar ozone photochemistry. J. Geophys. Res., **97**, 10165–10186.

AUSTIN, J. and BUTCHART, N. (1994): The influence of climate change and the timing of stratospheric warmings on Arctic ozone depletion. J. Geophys. Res., **99**, 1127–1145.

CHOU, M.-D., KRATZ, D.P. and RIDGWAY, W. (1991): Infrared radiation parameterization in numerical climate models. J. Clim., **4**, 424–437.

COY, L., NASH, E.R. and NEWMAN, P.A. (1997): Meteorology of the polar vortex: Spring 1997. Geophys. Res. Lett., **24**, 2693–2696.

HARTMANN, D.L. (1978): A note concerning the effects of varying extinction on radiative-photochemical relaxation. J. Atmos. Sci., **35**, 1125–1130.

HIROOKA, T., YOSHIKAWA, M., MIYAHARA, S. and KAYAHARA, T. (1999): Radiative and dynamical impacts of Arctic and Antarctic ozone holes: General circulation model experiments. Adv. Space Res. (in press).

KIEHL, J.T., BOVILLE, B.A. and BRIEGLEB, B.P. (1988): Response of a general circulation model to a prescribed Antarctic ozone hole. Nature, **332**, 501–504.

LACIS, A.A. and HANSEN, J.E. (1974): A parameterization for the absorption of solar radiation in the earth's atmosphere. J. Atmos. Sci., **31**, 118–133.

MCFARLANE, N.A. (1987): The effect of orographically excited gravity wave drag on the general circulation of the lower stratosphere and troposphere. J. Atmos. Sci., **44**, 1775–1800.

MAHLMAN, J.D., PINTO, J.P. and UMSCHEID, L.J. (1994): Transport, radiative and dynamical effects of the Antarctic ozone Hole: A GFDL "SKYHI" model experiment. J. Atmos. Sci., **51**, 489–508.

MIYAHARA, S., MIYOSHI, Y., KAYAHARA, T., YOSHIDA, Y., OOISHI, M. and HIROOKA, T. (1995): Development of a middle atmosphere general circulation model at Kyushu University. Climate System Dynamics and Modelling, Tokyo, Center for Climate System Research, University of Tokyo, 75–103.

NEWMAN, P.A., CLEASON, J.F., MCPETERS, R.D. and STOLARSKI, R.S. (1997): Anomalously low ozone over the Arctic. Geophys. Res. Lett., **24**, 2689–2672.

RANDEL, W.J. (1988): The anomalous circulation in the Southern Hemisphere stratosphere during spring 1987. Geophys. Res. Lett., **15**, 911–914.

SHINDELL, D.T., RIND, D. and LONERGAN, P. (1998): Increased polar stratospheric ozone losses and delayed recovery owing to increasing greenhouse-gas concentrations. Nature, **392**, 589–592.

(Received January 29, 1999; Revised manuscript accepted May 28, 1999)