Numerical Experiment for the Impact of the Ozone Hole over Antarctica on the Global Climate①

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ABSTRACT

A numerical experiment has been carried out with IAP (Institute of Atmospheric Physics) 9-layer general circulation model to investigate the influence of the Antarctic Ozone Hole on the global climate. The results show that the changes of total amount of ozone over higher latitude and polar region of the Southern Hemisphere affect not only the climate in the Southern Hemisphere, but also that in the Northern Hemisphere significantly. In the next spring, although the total amount of ozone over Antarctica has returned to the normal value, the influences of Ozone Hole still exist.

Key words: Antarctic Ozone Hole, Climate, Numerical simulation

I. INTRODUCTION

Ozone affects strongly the stratospheric thermodynamics because of its strong absorption of solar radiation in the ultraviolet range of the spectrum. It was pointed out by Manabe and Strickler as early as 1964 when they calculated the vertical distribution of equilibrium temperature due to the absorption of solar radiation and emission of long wave radiation by water vapor, carbon dioxide and ozone. The numerical experiment with a nine-layer global general circulation model showed that the ozone heating not only affects the temperature, pressure and wind field in the stratosphere, but also affects the circulation in the troposphere by the interaction of the upper and lower atmosphere (Chen and Bi, 1992). Therefore, ozone is a factor not to be ignored when we make a study of the climate problem. Now the effects of ozone heating have been added into the GCM and climate Models, while the ozone amount input to the models is climatological mean values. The interannual changes of column ozone amount are usually ignored.

Since the 1980s, the observation indicated a major depletion of column ozone in the Antarctic region during the Southern Hemisphere spring. The so-called Ozone Hole was observed in 1985 and 1986 (Farman et al., 1985; Hofmann et al., 1987), and in October 1987, the Ozone Hole became deeper and wider (Krueger et al., 1988; Cao, 1990). The Ozone Hole limits had reduced before 1988, while it became deep and wide again in 1989, 1990 and 1991. On 8 October 1993, the minimum value of total ozone over Antarctica was observed as 85 D.U. by Meteor 3 / TOMS (Herman et al., 1995). The recent report said that the Antarctic Ozone Hole from 1994 to 1996 was more widely extended.

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Actually, the changes of ozone amount in the Southern Hemisphere can be observed not only over Antarctica but also over the middle-high latitudes of the Southern Hemisphere. The changes of ozone amount in the Southern Hemisphere will inevitably lead to the change of radiative budget and the impact on the thermal structure of the atmosphere and earth surface of the Southern Hemisphere. Kiehl et al. (1988) modelled the response of the high-latitude thermal structure to a prescribed Ozone Hole by using the NCAR GCM. They found cooling of about 5K in October in the Antarctic lower stratosphere compared with their control run. The model of Cariolle et al. (1990) shows similar results. The GFDL "SKYHI" model was also used by Mahlman (1994) to simulate the radiative and dynamical effects of the Antarctic Ozone Hole. They discussed mainly the impact of the Ozone Hole on the stratosphere and the Southern Hemisphere. Actually by the interaction of the upper and lower atmosphere, its impact will also be spread to the troposphere and the Northern Hemisphere. In order to investigate the extent and distribution of this effect, a numerical experiment has been done by using the IAP nine-layer GCM with the ozone data over Antarctica from August to December 1987. Since we have another paper to discuss the impact of the Ozone Hole on the radiative heating rate and the south polar vortex, in this paper we will mainly explore the influence of the Ozone Hole on the global climate.

II. MODEL AND CONDITIONS FOR THE EXPERIMENT

The model used in our experiment is the IAP nine-layer general circulation model (Zhang, 1990; Bi, 1993; Liang, 1996), and the most calculations of our simulation are carried out in the LASG (State Key of Numerical Modeling Laboratory for Atmospheric Science and Geophysical Fluid Dynamics).

The Antarctic Ozone Hole in 1987 is well studied and its data are more abundantly collected. It began to form in August and gradually deepened and extended until October, when the monthly minimum total ozone over the South Polar region was less than 150 D.U. The ozone amount went up again from November and returned to the normal value after December. With all these things considered, our experiment started from August 1987.

The initial data used in our experiment are meteorological data on July 31, 1987, which are obtained from the earlier calculation of IAP 9-layer GCM with monthly mean SST, sea ice and climatological mean ozone data.

For comparison, our experiment includes two sets: (1) using the SST and sea ice data from August 1,1987 to May 31, 1988 and climatological mean ozone data (this set is called control run below); (2) using the same data as (1) except that the ozone data from August to December 1987 are replaced by the observed data which are zonally averaged. (It will be called Ozone Hole run below). Both sets of experiment are made from August 1, 1987 to May 31, 1988. The results are compared with each other to investigate the influence of Ozone Hole on the global climate.

Since the changes of total ozone amounts appeared not only over Antarctica, but also over the higher-latitudes of the Southern Hemisphere during the period of the Ozone Hole, the climatological mean ozone amounts are used from 40°S to the Northern Hemisphere for both experiments, while the total ozone amounts from 40°S to the South Pole used in Ozone Hole run are given in Table 1, which are taken from "Monthly Ozone Data for the World" for August-December, 1987 and interpolated to the latitudes corresponding to the IAP model.

Table 1. The Total Ozone Amounts from 40°S to the South Pole, August — December, 1987(in D.U.)

Lat. Month	42.2	46.6	51.0	55.5	59.9	64.4	68.8	73.3	77.7	82.2	86.6
87.8	333	328	326	315	285	260	261	260	259	258	257
87.9	345	365	358	335	285	233	225	219	215	210	205
87.10	361	369	374	350	285	221	205	191	177	163	150
87.11	341	337	347	336	300	272	257	241	226	210	195
87.12	302	310	323	324	310	296	322	319	318	316	314

The distribution of ozone amounts shown in Table 1 is consistent mainly with that from satellite. The total amounts of ozone over the Southern Hemisphere in October 1987 from Nimbus-7 show that the ozone amounts over whole Antarctica are less than 200 D.U. and there was a high value belt of ozone amounts between 40°S and 58°S with the value higher than 350 D.U.. The similar distribution can be seen in Table 1, except that it is zonally averaged.

In the IAP model, the parameterization methods for the radiation process from NCAR CCM1 are used for reference, and the absorption and emission of ozone in ultraviolet and visible bands are calculated in detail. Although there are only two layers in the stratosphere in the IAP model, the atmosphere from 100 hPa to 0.5 hPa is divided into 16 small layers for calculating the ozone amount and optical path length of ozone. Therefore, the calculation of the ozone heating rate is fairly accurate. The calculation method and circumstances of Ozone Hole in our simulation are described in detail in our another paper (The Numerical Study for the Impact of Antarctic Ozone Hole on the Global Atmospheric Radiation Heating Field).

III. RESULTS

As mentioned above, our experiment includes two sets, the same boundary conditions in the bottom were used in both sets, while the values of total ozone in the stratosphere were different. Comparing and analyzing the results of both experiments, we see that the reduction of total ozone amount in the stratosphere over the higher-latitudes and polar region of the Southern Hemisphere leads to the change of the solar radiation heating rate of that area. In October and November when the Ozone Hole was the deepest, the simulated total radiation heating rate (solar heating plus long wave heating) over the South Polar region reduced about 0.43°C / day and 0.6°C / day respectively, compared with that simulated without the Ozone Hole. The changes of radiative heating rate made the temperature in the lower stratosphere over Antarctica in the Ozone Hole period significantly lower than the normal value. From October to November, the 25 hPa temperature over Antarctica simulated from the Ozone Hole run was 4-5°C lower than that obtained in the control run, which agreed well with the results simulated by Kiehl (1988) and Cariolle (1990). In their papers, they discussed mainly the impact of Ozone Hole on the stratosphere and the Southern Hemisphere. From our experiment we found that the changes of the heating rate and temperature in the stratosphere over the higher-latitudes and polar region of the Southern Hemisphere result in the changes of the pressure and wind fields, which occurred not only in the stratosphere of the Southern Hemisphere, but also in the troposphere and the Northern Hemisphere. The purpose of this paper is to describe the impact of the Ozone Hole on the temperature, pressure and wind fields in the lower troposphere and on the precipitation. The influences of the Ozone Hole on the radiative heating rate and the stratospheric temperature, pressure and wind fields have been discussed in our other papers (to be published).

1. *The Influence of the Ozone Hole on the Surface Air Temperature*

The simulated surface air temperature in both the Southern and Northern Hemisphere is evidently different between the two cases with the Ozone Hole and without the Ozone Hole. Fig. 1 shows the distributions of simulated differences (Ozone Hole run minus control run, similarly hereafter) of the zonally averaged surface temperature with latitude for the three seasons in the Ozone Hole period and after the period. We can see clearly from Fig. 1 that the surface air temperature at high latitudes of the Southern Hemisphere for September–November 1987 simulated in the Ozone Hole run was generally higher, because more solar radiation reached the earth surface under this case. From December to February, when the Ozone Hole disappeared, the simulated surface air temperature in the Ozone Hole run was lower in the region south of 60°S. And this impact is still clear in the next spring (from March to May). Fig. 1 shows that the surface air temperature in the lower latitudes changed very little due to the Ozone Hole in the three seasons, while it changed more significantly in the middle and higher latitudes of the Northern Hemisphere. In the period from September to November with the deepest Ozone Hole, the simulated surface air temperature sharply dropped down in the region north of 40°N. From December to February, the simulated surface air temperature from 45°N to the North Pole in the Ozone Hole run was still lower, while it was warmer in the region of 15°N —45°N. The changes of surface air temperature from March to May caused by the Ozone Hole are smaller, but still noticeable. The phenomenon that the influence of the Ozone Hole on the surface air temperature in the Northern Hemisphere is more significant than that in the Southern Hemisphere can also be seen in the GFDL simulated results by Mahlman(1994, Fig. 5 of that paper). Obviously, the change of surface air temperature in the Northern Hemisphere is not directly caused by the Antarctic ozone depletion and the variation of radiative heating. It results from the dynamical heating which we will discuss below.

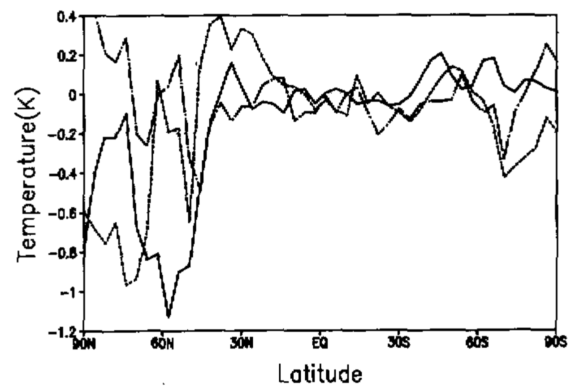

Fig. 1. Meridional distribution of simulated difference of zonally averaged surface air temperature (Ozone Hole run minus control run). —— September to November, ----- December to February, — • — March to May.

For the global distribution, the strong impacts of the Ozone Hole on the surface air temperature appeared in the continents, specially in Eurasia and North America. Fig. 2 shows the simulated difference of surface air temperature for the autumn of 1987 (from September to November), Fig. 3 and Fig. 4 are the same as Fig. 2 except for the winter (from December 1987 to February 1988) and spring (from March to May 1988) respectively. As shown in Fig. 2, the difference of surface air temperature ranged from −2℃ to +1℃ along the coast of Antarctica. And it ranged from −4℃ to +3℃ in North America, +1℃ — +2℃ in the western Europe, East Asia and South Asia. In North Asia it could reach −4℃. Particularly the Ozone Hole made the temperature drop about 7℃ in the Siberia area in October 1987. The temperature rose in Alaska, East China and India.

In December 1987, the total ozone amount over the higher latitudes of the Southern Hemisphere and the South Polar region went up again and it returned back to normal in January and February 1988. However, the influence of the Ozone Hole was still significant in that winter. The simulated difference of surface air temperature in the Northern Hemisphere caused by the Ozone Hole was larger than that in the Southern Hemisphere, and it was larger in continents than that in oceans. It can be seen from Fig. 3 that in the Northern Hemisphere winter, the positive value appeared in Alaska, it reached +4℃. It was also warmer in the case with the Ozone Hole in the most part of Asia. We can also see that the surface air temperature dropped down in Canada and Europe with the maximum value about −4℃ — −5℃.

In the next spring (from March to May 1988), the Ozone Hole had disappeared for three months, while its influence still exist. However Fig. 4 shows that the simulated difference of surface air temperature for this period was almost contrary to that for the winter. We can see from Fig. 4 that the difference of the temperature caused by the Ozone Hole in the north of North America and Asia—Europe continent ranged from −4℃ to +5℃. The positive values appeared in most part of U.S.A., the eastern Canada, and North Asia, while the negative values appeared in the western Canada, Europe and China. The simulated surface air temperature over the ocean shows little change, because of the great heat capacity of sea water and its good regulation to temperature.

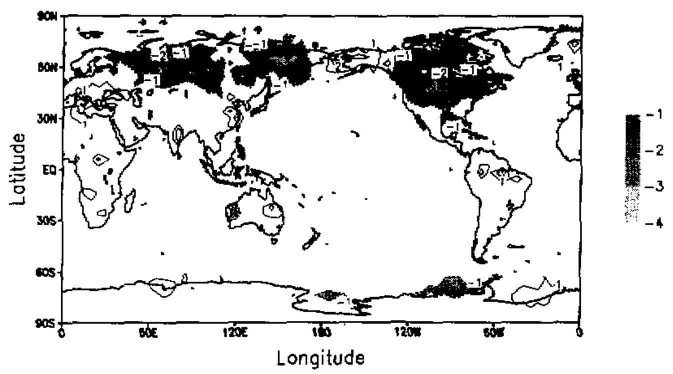

Fig. 2. Simulated difference of surface air temperature (Ozone Hole run minus control run) for the autumn.

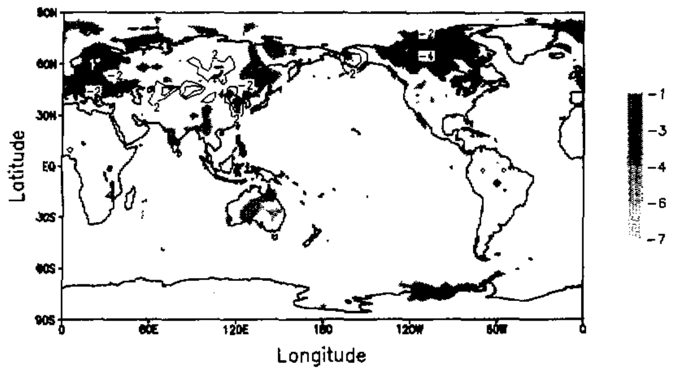

Fig. 3. Simulated difference of surface air temperature (Ozone Hole run minus control run) for the winter.

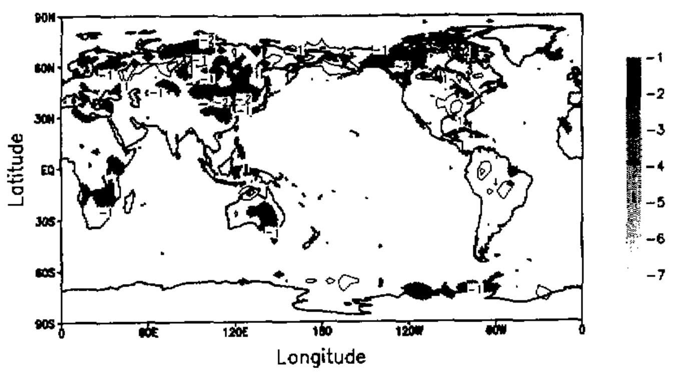

Fig. 4. Simulated difference of surface air temperature (Ozone Hole run minus control run) for the spring.

2. *The Influence of the Ozone Hole on the Sea Level Pressure*

The main distributions and seasonal characteristics of the tropical low pressure zone and subtropical high pressure are well simulated in the control run. Fig. 5 shows the meridional distribution of the simulated difference of the zonally−averaged sea level pressure between two experiments for the autumn, winter and spring. It can be seen from Fig. 5 that there are some similarities as well as differences in the seasonal changes. The similarities are: The sea level pressure (SLP) was slightly affected by the Ozone Hole from 30°S to 30°N, but that to the south of 30°S and north of 30°N changed obviously. In the autumn and winter, the zonally−averaged SLP in the area between 30°S and 45°S (near and south of the subtropical high pressure zone of the Southern Hemisphere) rose about 1.5 hPa due to the Ozone Hole. In the regions south of 45°S, SLP sharply dropped down and it decreased by 4 hPa and 5 hPa respectively to the south of 75°S. The difference is that though the autumn (September to November) was the period of the strongest Ozone Hole, the SLP to the north of 30°N was

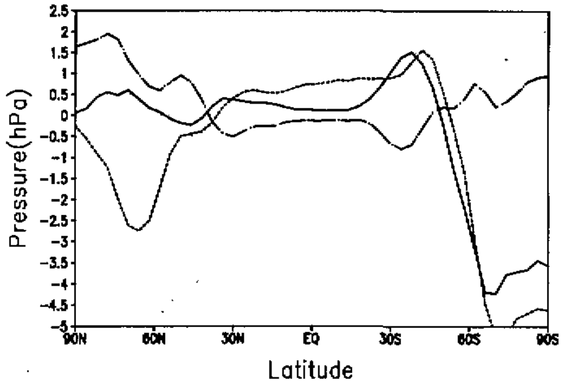

Fig. 5. Meridional distribution of simulated difference of zonally averaged sea level pressure (Ozone Hole run minus control run). —— September to November, ----- December to February, — · — March to May.

affected by the Ozone Hole not too much and it changed from −0.5 hPa to 0.5 hPa. While in the following winter, the SLP to the north of 40°N was obviously lower and decreased over 2.5 hPa from 60°N to 70°N. From March to May of the next year, the Ozone Hole disappeared. At that time the SLP of the Southern Hemisphere didn't change much, while it changed clearly to the north of 45°N due to the Ozone Hole and its variation range reached 2 hPa in the North Polar region.

3. *The Influence of the Ozone Hole on the Asian Winter Monsoon*

Our simulated results show that the reduction of ozone amount over the higher latitudes and polar region of the Southern Hemisphere affected both on pressure and wind fields. In this section, we mainly discuss the simulated Asian monsoon. From the 850 hPa geopotential height in December simulated in the control run we can see the main pattern of winter monsoon: a high pressure in Siberia and Mongolia and a large pressure−trough in East Asia. Corresponding to this pattern, the simulated 850 hPa winds are mainly northwesterly in Northwest China, North China, East China and along the coast of Southeast China and the wind speed ranged from 5 m / s to 10 m / s. In Northeast China the wind from north reached 5 m / s. Fig. 6 shows the difference of the 850 hPa geopotential height between the two experiments. From Fig. 6 we can see the large pressure−trough in East Asia weakened clearly. The 850 hPa isobaric surface in East China, North China and Northeast China rose by 20 geopotential meters, and it ascended over 40 geopotential meters in the Korean peninsula. There were pressure−fall centers in Lake Balkhash, Lake Baykal and Mongolia. In Siberia the 850 hPa isobaric surface dropped down by 20−40 geopotential meters. The variations of 500 hPa isobaric surface were similar to those of 850 hPa. The isobaric surface of 500 hPa rose by 40−60 geopotential meters in the East Asian trough area. Corresponding to this variation, the wind fields changed obviously. Fig. 7 shows the distribution of the 850 hPa wind difference between the two experiments. It can be seen that after several months of the ozone amount reduction over the Southern Hemisphere, the northwesterly wind in East Asia weakened clearly and the speed decreased by 3−4 m / s. The wind speed in East Asia was lower than 10 m / s, and the isotach of 5 m / s was limited north of 30°N. It also can be seen from this figure that the southeasterly wind strengthened in the coastal region of Southeast China and the lower reaches of the Yangtze–Huaihe River. Thus it was favorable for the warm and humid air over sea to reach these areas and resulted in the warming in most areas of East Asia. For instance, in East China and Hebei province temperature went up about 2–6℃, and the warm center was located in Hebei province and Shandong province. The simulated variation of temperature, pressure and wind fields for January was similar to that for December. In sum, during the Northern Hemisphere winter following the Antarctic Ozone Hole, the simulated East Asian monsoon weakened and most part of China became warmer.

4. *The Influence of the Ozone Hole on the Precipitation*

The effects of ozone depletion over Antarctica on the precipitation are noticeable in the tropical and subtropical region. For October 1987 with the strongest Ozone Hole, the simulated differences of the total precipitation between two cases ranged from −6 to +9 mm / day

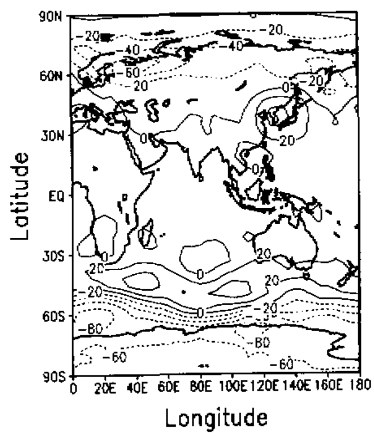

Fig. 6. Simulated difference of 850 hPa geopotential height for December.

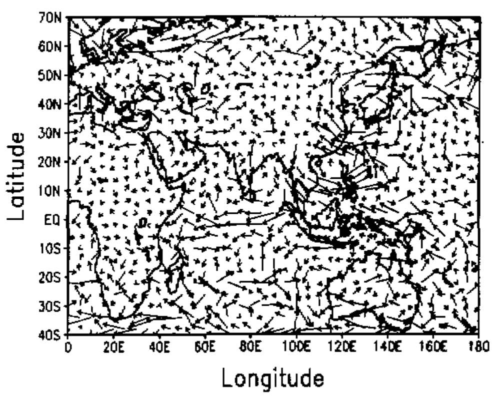

Fig. 7. Simulated difference of 850 hPa wind fields for December (Ozone Hole run minus control run).

in South Asia, Fig. 8 gives the simulated differences of the average precipitation from September to November. We can see many centers with positive value or negative value located in the tropical, subtropical ocean and the monsoon region. The characteristics of the precipitation change due to the Ozone Hole are that the scale of the positive and negative centers is much smaller than that of the temperature change. The Ozone Hole made the rainfall decrease in Southwest China, but increase in Northeast China and south–east coast of China, and middle America in this season. The change of rainfall caused by the Ozone Hole ranged from −8 to +8 mm / day.

In the Northern Hemisphere winter, from December 1987 to February 1988, the simulated difference of precipitation in the Bay of Bengal and the Indonesian region reached −2—−8 mm / day, and it ranged from −5 mm—+5 mm / day or more in the central America, Brazil, the south–east part of Africa and the middle Pacific.

Fig. 9 shows the variation of the simulated difference of zonally averaged precipitation month by month. It can be seen that from September to December 1987, the simulated

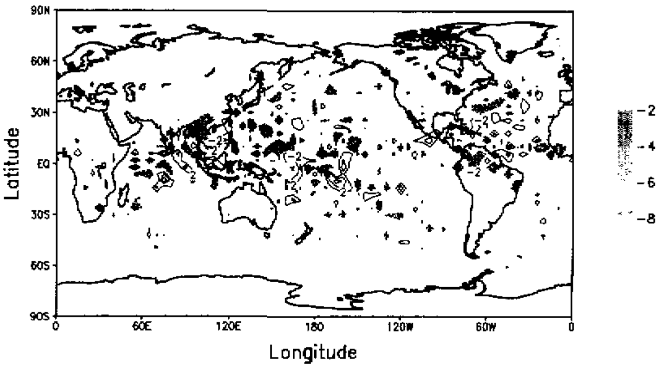

Fig. 8. Simulated difference of total precipitation for the autumn.

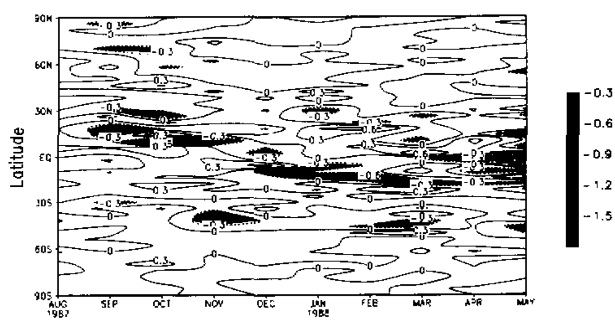

Fig. 9. Simulated difference of zonally averaged total precipitation from August 1987 to May 1988 (Ozone Hole run minus control run).

precipitation decreased in the Northern Hemisphere in the case with the Ozone Hole, while it increased in the Southern Hemisphere. After January 1988, the total amount of precipitation increased in the Northern Hemisphere, while decreased in the Southern Hemisphere. Up to May 1988, although the Ozone Hole had disappeared about half a year ago, its influences on the precipitation are still significant.

5. The Changes of General Circulation Caused by the Ozone Hole

In order to make it clear why the Ozone Hole over Antarctica affects the climate in the Northern Hemisphere significantly, the simulated wind field and circulation were analyzed.

As mentioned above, as soon as the total amount of ozone reduced over the high latitudes of the Southern Hemisphere and the South Polar region, the absorption of solar radiation by atmosphere in the stratosphere over this area reduced. The air temperature there dropped sequentially and as a result, the isobaric surface there descended, the meridional pressure gradient from the Northern Hemisphere to the Southern Hemisphere increased, so that the meridional flow as well as the meridional circulation were changed. Fig. 10 shows the meridional cross-section for the simulated difference of the flow field along 75°W in August 1987. We can see from Fig. 10 that in the case with the Ozone Hole the wind towards south strengthens significantly in the upper level. We also found that the ascending motion in the lower level changed not only in the Southern Hemisphere, but also in the Northern Hemisphere. The changes of meridional flow and vertical motion, on the one hand, led to the air temperature change dynamically, on the other hand, led to the changes of transport of water vapor as well as the cloud and precipitation in both hemispheres. And the variation of water vapor and cloud then caused more changes of radiative heating rate and latent heating rate as well as the temperature and wind field. This is the reason why the Ozone Hole affected the global climate so quickly and significantly.

IV. CONCLUSION AND DISCUSSION

Our experiment shows that there is some relationship between the global climate and the

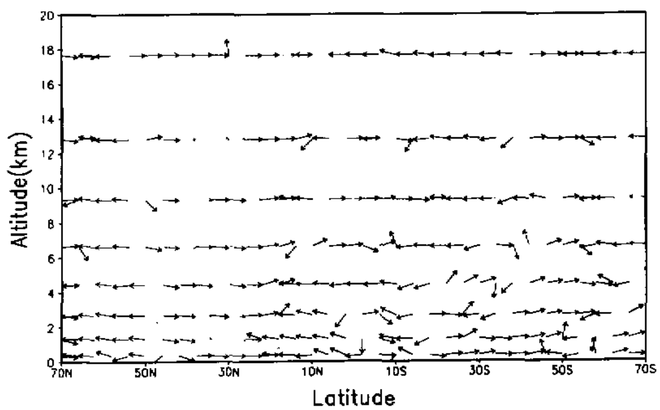

Fig. 10. Meridional cross-section for the simulated difference of the flow field along 75°W in August 1987 (Ozone Hole run minus control run).

Ozone Hole over Antarctica. The changes of radiative heating rate due to the ozone depletion in the Southern Hemisphere not only lead to the variations of meteorological field over Antarctica, but also influenced the Northern Hemisphere because of the air motion. And by the interaction of the upper and lower atmosphere, the global circulation has been affected. The surface air temperature, wind field and precipitation changed significantly. Generally speaking, the influence of the Ozone Hole on the climate in the Northern Hemisphere is more noticeable than that in the Southern Hemisphere. The effect of the Ozone Hole on the surface air temperature is much more apparent in the continents than that in the oceans, while its impact on the precipitation appeared mainly in the ocean of the tropics and subtropics and the monsoon region. And in the next spring (March to May), although the total amount of ozone over Antarctica had returned to the normal value, the influence of the Ozone Hole still existed.

We also analyzed the climatological data from September 1987 to May 1988 taken from Monthly Climatic Data for the World. It shows that there are really noticeable anomalies of surface air temperature and precipitation in that period. For example, the negative departure of surface air temperature is located at the north part of the Asian continent and North America (except Alaska) in October 1987. The center values of the departure are −6.1℃ and −5.2℃, respectively. From December 1987 to February 1988, there was still negative departure of surface air temperature in the north of Siberia, while most parts of China and the United States of America were warmer. The positive departure of air temperature in the east part of our country reached 2−4℃. Our simulated results agreed fairly well with the observations. Of course, the observed temperature departure was caused by various factors, but our results that agree with observation mean that the variation of ozone amount is also an important factor.

The simulated results given in this paper are preliminary. The mechanism of impact of ozone depletion on the global climate will be discussed in another paper. From the results, we see that the effects of the Ozone Hole on the global climate change are important. It is necessary to take the interannual change of total ozone amount into consideration when we make climate prediction.

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