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INTERANNUAL VARIATIONS OF ZONAL MEAN TEMPERATURE IN THE SOUTHERN HEMISPHERE STRATOSPHERE: WITH REFERENCE TO THE ANTARCTIC OZONE DEPLETION

Kohji KAWAHIRA* and Toshihiko HIROOKA**

Geophysical Institute, Faculty of Science, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto 606

Abstract: Interannual variations of the zonal mean temperature in the Antarctic lower stratosphere are analyzed for the past six years from 1980 to 1985 by using NMC data. It is found that the Antarctic polar stratosphere tends to cool not only in spring but also in all seasons, remarkably in the polar region. The analysis of the meridional gradient of the zonal mean temperature shows such an interesting feature that the period of temperature decrease toward the pole in winter has become longer and longer in recent years in accord with the Antarctic ozone depletion. From these evidences, the interrelation between the temperature decline and the ozone depletion is considered as follows: Slight cooling induced by the effect of increasing CO_2 can form the polar stratospheric clouds, and more clouds are formed by its radiative cooling effect. Hence, enhanced cooling in the polar region can induce the ozone depletion due to less poleward transport of ozone by planetary waves, which become less active in the polar region due to trapping by long-persistent strong westerlies.

1. Introduction

In the recent special issue of Geophysical Research Letter, **13** (12) for the Antarctic ozone depletion, ANGELL (1986) presented that from 1978 up to date the temperature in spring of the Antarctic stratosphere remarkably declined. The temperature decline is intimately related to the total ozone depletion in the Antarctic polar region as shown by FARMAN *et al.* (1985). Similar tendency has been shown in the data at Syowa Station by CHUBACHI and KAJIWARA (1986) and IWASAKA *et al.* (1986), and in the data at the South Pole by KOMHYR *et al.* (1986).

Thus, it is certain that the total ozone depletion in the Antarctic spring has accompanied the stratospheric cooling. Therefore, investigation of the process of the recent temperature decline may lead to finding of the cause of the "ozone hole".

In the present study, interannual changes in zonal mean temperature of the lower stratosphere of the Southern Hemisphere (SH) are investigated in detail using the data analyzed by the National Meteorological Center (NMC). First we show the zonal mean temperatures in middle and high latitudes on daily basis.

Furthermore, the meridional gradient of the zonal mean temperature, which is

Present address:

* Toyama National College of Technology, 13, Hongo-cho, Toyama 939.

** Numerical Prediction Division, Japan Meteorological Agency, 3–4, Otemachi 1-chome, Chiyoda-ku, Tokyo 100.

proportional to the vertical shear of the geostrophic zonal wind, is shown in order to seek any changes in wind pattern related to the total ozone depletion. On the basis of obtained evidences, the mechanism of the "ozone hole" is discussed.

2. Results

First, the zonal mean temperature is calculated from the geopotential thickness between 100 and 200 mb levels. The analysis is made on the daily pattern of the zonal mean temperature in middle and high latitudes of the SH stratosphere during the period of six years from 1 January 1980 through 31 December 1985. The daily value is 20-day running meant to identify the year-to-year changes more clearly.

2.1. Interannual variations of zonal mean temperature

Figure 1 shows the interannual change of the zonal mean temperature in the layer between 100 and 200 mb levels at about 12 km height, from 1980 to 1985. It is seen that the annual minimum temperature appeared in late winter to early spring in the polar region, whereas the maximum temperature appeared in the summer season.

This figure presents the following interesting feature of temperature changes: The region with temperature over 230 K was seen in high latitudes in January, February, and even December in the year 1980, but in the year 1985 such region disappeared. Furthermore, when we concentrate on the isoline of 215 K seen at about 50°S in the winter of 1980, the line gradually moved equatorward as the year progressed; temperature in the midlatitude of the 1985 winter became lower than 215 K.

These remarkable interannual variations are more clearly presented in terms of a period analysis; how long the characteristic temperature distribution persists each year. Figure 2 shows the result of the period analysis.

The period under any specified temperature values becoming longer means that the Antarctic lower stratosphere cools. In Fig. 2a, the period analysis at 80°S is shown with October monthly mean total ozone averaged over the region poleward of 40°S cited from NEWMAN and SCHOEBERL (1986). This figure shows that the period under 195 K monotonously becomes longer from 1980 to 1985. The same tendency of the cooling in the lower stratosphere is remarked in the cases of 200 and 205 K with some exceptions. The difference of the period under 195 K between 1985 and 1980 is about 45 days, *i.e.*, one and a half month. This elongation is due to the recent delay of the occurrence of final warming in the spring season, and due also to earlier beginning of the winter lower temperature as seen in Fig. 1.

Figures 2b and 2c show the result at 70 and 60°S, respectively. The elongation of the period lower than 210 K at 70°S is apparently seen, which changes from about 140 days in 1980 to 170 days in 1985. The period lower than 200 and 205 K shows similar change as that in the case of 210 K. The change at 60°S is seen in the period lower than 215 K, which is from 120 days in 1980 to 170 days in 1985.

When we compare the total ozone data with the temperature data in Fig. 2a, the similar tendency is found. This fact supports the conclusion obtained by ANGELL (1986); the total ozone depletion in the Antarctic polar region has accompanied the cooling in the lower stratosphere in spring. However, since the present analysis con-

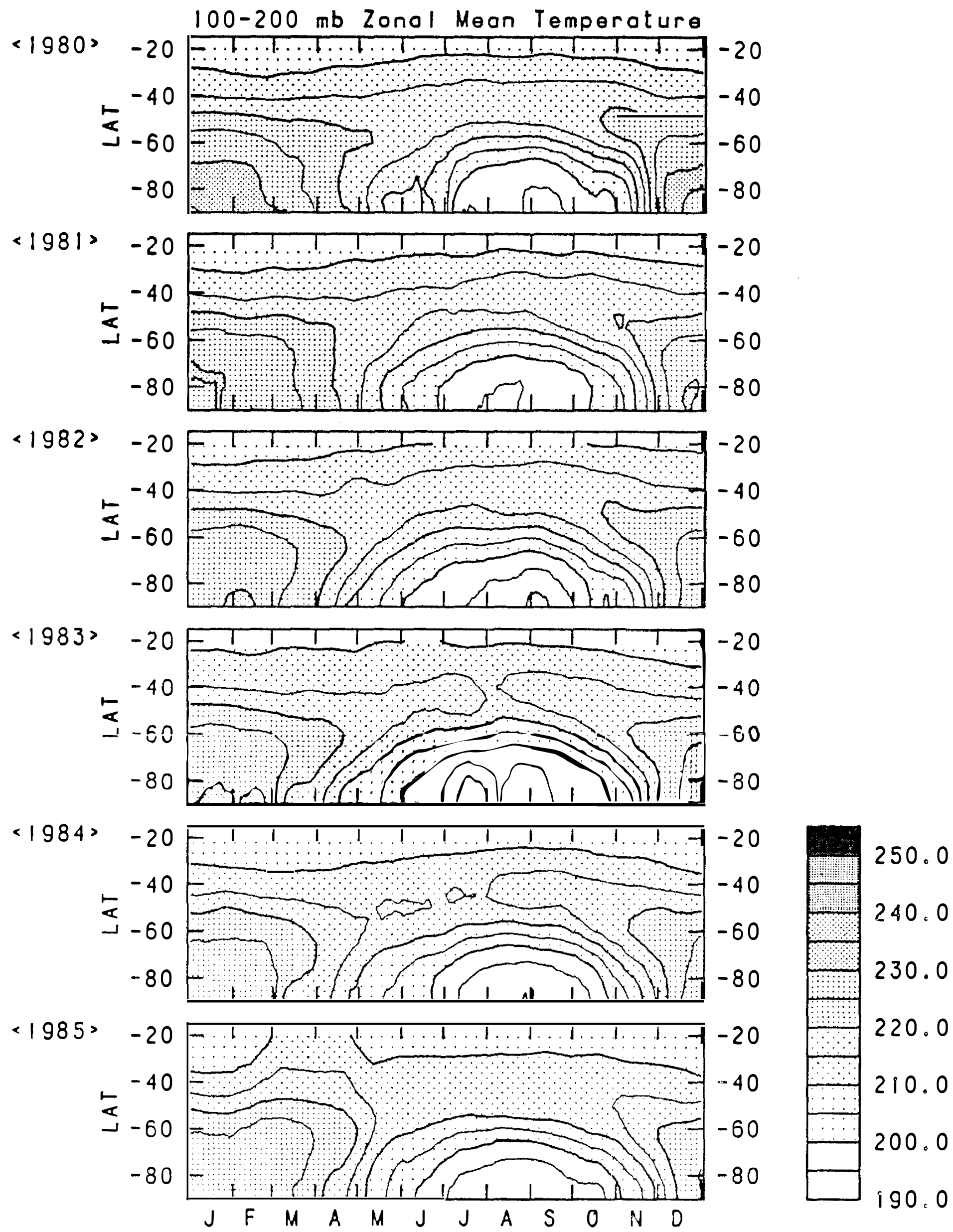

Fig. 1. Interannual changes of the zonal mean temperature at 100–200 mb levels in the Southern Hemisphere for 1980–1985. The contour interval is 5 K. The zonal mean temperature is calculated from the NMC geopotential thickness between 100–200 mb levels and 20-day running mean is done.

cerns not only the spring season but also all seasons, a tendency of the recent remarkable cooling in high latitudes in the Antarctic lower stratsophere is more firmly detected.

2.2. Meridional gradient of temperature

In order to seek a change in wind pattern related to the ozone depletion, the meridional gradient of the zonal mean temperature is analyzed. The gradient is proportional to the vertical shear of the zonal mean geostrophic winds. The gradient

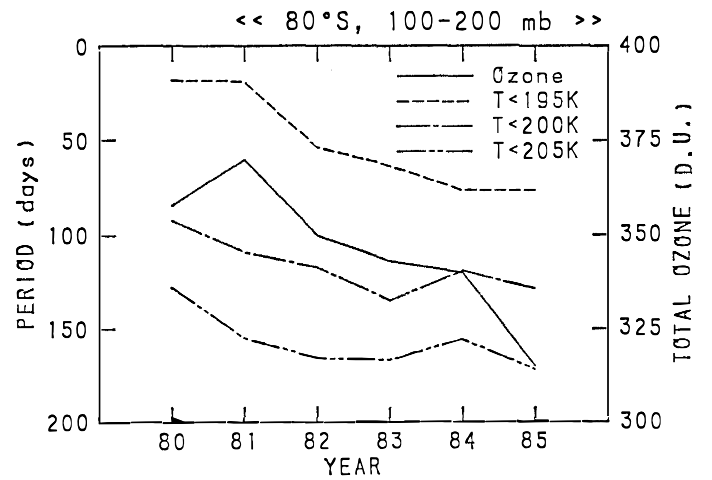

Fig. 2a. *Year-to-year variations of the period during which the temperature is under 195, 200 and 205 K, respectively at 80°S. The averaged October monthly mean total ozone south of 40°S (after* NEWMAN *and* SCHOEBERL, *1986) is also shown.*

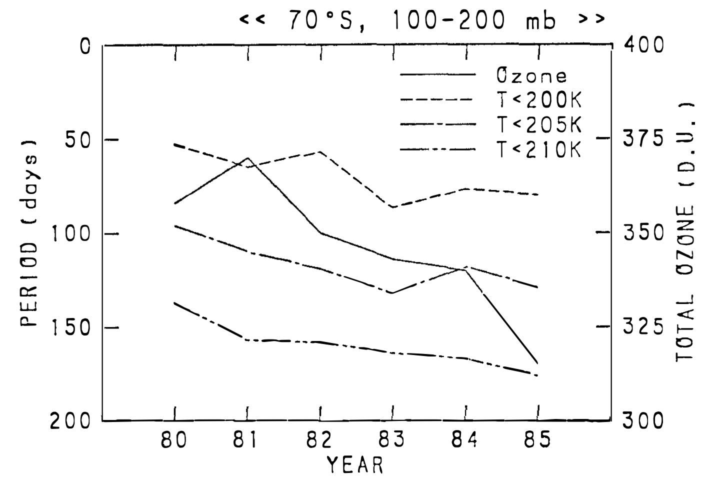

Fig. 2b. Same as Fig. 2a but at 70°S.

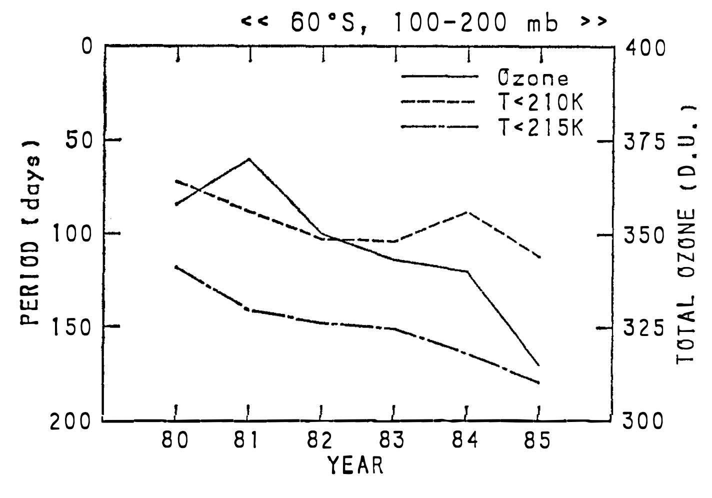

Fig. 2c. Same as Fig. 2a but at 60°S.

has been defined as a difference of the zonal mean temperature between 10 degree latitudes.

The results are shown in Fig. 3, where the positive (negative) corresponds to the temperature decrease (increase) toward the south pole (the equator). From now on, we define the onset of the winter (summer) circulation is the beginning of the positive (negative) gradient. For example, in 1980 occurred the change at 80°S in late November or early December, but late December in 1985. The profiles, thus clearly demonstrate a recent delay of the beginning of final warming.

The most remarkable change seen in Fig. 3 is that at 80°S the positive region began

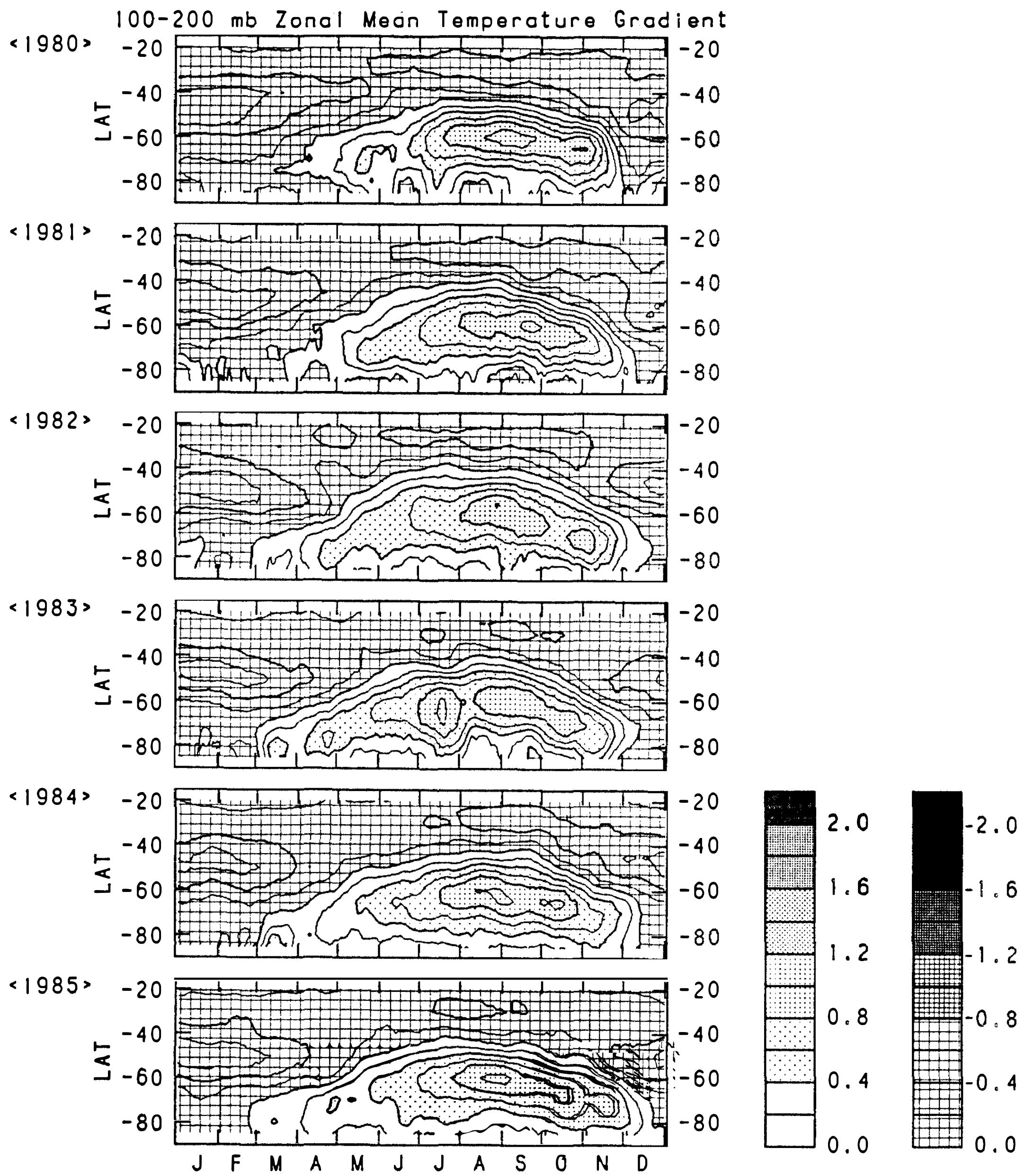

Fig. 3. Interannual changes of the meridional gradient of the zonal mean temperature at 100–200 mb levels of the Southern Hemisphere. The contour is K/latitude.

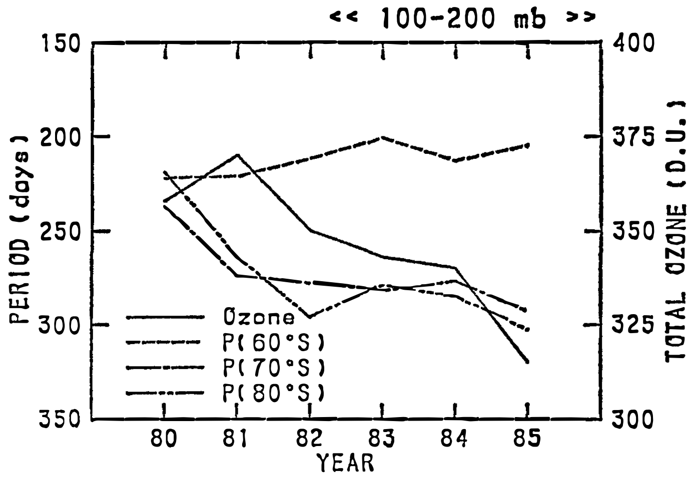

Fig. 4. The year-to-yar change of the period during which the positive gradient of the meridional gradient of the zonal mean temperature (the winter circulation) persists at 80, 70 and 60°S, respectively. Total ozone trend as in Fig. 2 is also shown.

in April in 1980, but March in 1985. The onset of the winter circulation has occurred earlier remarkably in recent years. This tendency means that the westerlies in the Antarctic polar winter stratosphere (stronger than those in the Arctic one) persist for a longer period. The persistent westerlies in the winter polar region have a very important effect on the meridional and vertical propagation of planetary-scale disturbances via inhibition of further penetration into the westerlies (*e.g.*, KAWAHIRA, 1982).

The important characteristics of the meridional gradient are more clearly presented by the period analysis, which reveals the length of period per year when the positive gradient, *i.e.*, winter circulation persists. Figure 4 shows the periods of the positive gradient at 60, 70, and 80°S with the same ozone data as in Fig. 2. It is clearly seen that the period of winter circulation at 70 and 80°S becomes longer in recent years, but at 60°S the period is nearly constant.

Thus, the recent elongation of the winter circulation is dominant only in the Antarctic polar region in accord with the total ozone depletion. This remarkable variation of the prolonged winter circulation means the long persistence of strong westerlies in the Antarctic stratosphere. The strong westerlies in the polar region can inhibit poleward propagation of planetary waves. Thus, less active waves may bring about less effective poleward transport of ozone in the stratosphere, which may be linked to the "ozone hole". Furthermore, less active waves may play an important role in the recent delay of final warmings through less effective poleward heat transport.

The remarkable change in temperature filed of the Antarctic stratosphere, especially its meridional gradient, can give a suggestion of the cause of the ozone depletion. Therefore, it is an essential problem why temperature has fallen in the recent polar stratosphere. This question is considered to be one of the most important in the Antarctic circulation.

3. Discussion and Summary

From the six year daily analysis of the zonal mean temperature and its meridional gradient, it is found that the temperature in the Antarctic polar stratosphere continuously fell in recent years, in accord with the total ozone depletion. The most apparent evidence in our analysis is the gradual cooling in the Antarctic polar region, accompanying temperature gradient deepening. In particlar, the gradient change shows the increase of the westerly shear in the polar region south of 60°S.

What could bring about the year-to-year depletion of spring total ozone? What induces the elongation of the winter circulation in the Antarctic polar stratosphere found in the present analysis? We think these two questions have a very intimate relationship.

Then the characteristic in the Antarctic polar stratosphere is lower temperature than in the Arctic one; the difference is about 20 to 30 K (BARNETT and CORNEY, 1985). Thus the recent temperature decline of the Antarctic stratosphere is low enough to produce Polar Stratospheric Clouds (PSC) as shown by IWASAKA *et al.* (1986). If PSC is formed, then its effect on radiative flux causes the cooling in the polar lower stratosphere as demonstrated by numerical analysis of POLLACK and MCKAY (1985); the PSC causes more cooling in higher latitudes, especially after the polar night period. Following the study of POLLACK and MCKAY, a threshold value between 30 and 100% formation of PSC lies between 195 and 190 K. Thus it is possible that through radiatively enhanced cooling the PSC can help form more PSC. This effect may bring about the year-to-year decline of temperature in the Antarctic polar stratosphere.

What induced the cooling in the Antarctic polar lower stratosphere enough to form the PSC? From the view of radiative role in the stratosphere, it is very natural to attribute it to the effect of increasing CO_2 as firmly indicated (*e.g.*, MANABE, 1983). When CO_2 increases and causes the cooling in the polar night stratosphere, then in the Antarctic stratosphere a slight cooling causes quite remarkable PSC formation bringing about further cooling. This cooling in the polar region may bring about long-persistent strong westerlis which can inhibit the poleward propagation of planetary waves and make the waves less active in the polar region. Hence, a poleward transport of ozone in the lower stratosphere would be less effective during the winter season which could be linked to the "ozone hole". Also, strong westerlies may be stableenough to cause the delay of final warmings as noted also in the present analysis. The delay may lead to the delay of rapid poleward transport of ozone during final warmings (YAMAZAKI, 1987): Such a condition would contribute to the ozone depletion in spring. This speculative scenario, which stresses an essential role of the CO_2 increase effect in the appearance and deepening of the ozone depletion, seems to be adequate to account for the characteristics of the "ozone hole". This scenario will be investigated more quantitatively in our succeeding study.

Lastly, the main results in the present study are summarized as follows:

(1) The temperature at lower stratosphere in the Antarctic recently falls not only during the spring season but also throughout the year.

(2) The meridional gradient of the zonal mean temperature is also analyzed; the gradient is proportional to the vertical shear of the mean zonal wind. The period

of the positive gradient, which means temperature decrease toward the pole, persists more than half a year and becomes longer in 1985 than 1980. From the observational evidences in the present study, the mechanism of the "ozone hole" is considered as follows. Main process to induce the hole is the rapid cooling in the lower stratosphere of the Antarctic polar region. The cooling may be due to an increasing effect of CO_2, and become remarkable through the formation of the Polar Stratospheric Clouds. Furthermore from thermal wind relation, the westerlies become stronger and long persistent, which can cause less effective poleward propagation of planetary waves. Therefore the poleward transport of the ozone by the waves become far less to induce the "ozone hole". There combined effects of dynamics and radiative cooling may lead to further deepening of the hole, not the recovery of the total ozone before 1979.

Acknowledgments

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