

YEAR-TO-YEAR VARIATIONS OF THE HORIZONTAL OZONE DISTRIBUTIONS IN THE NORTHERN HEMISPHERE WINTER

Kohji KAWAHIRA and Masahiro WAKASHIMA

Toyama National College of Technology, 13, Hongo-machi, Toyama 939

Abstract: In order to research a link of the recent rapid ozone depletion to the circulation in the stratosphere and troposphere in the Northern Hemisphere (NH) winter, the horizontal total ozone distributions, given from the observations by Nimbus 7/TOMS (ver. 6), are analyzed by Fourier decomposition along latitude circles in middle latitudes from 1978 to 1991. The results show that the increase (decrease) in the monthly and zonal mean ozone amount in December at 45, 50 and 55°N has accompanied the decrease (increase) in the amplitudes of zonal wavenumber 1 and the increase (decrease) of wavenumbers 2 and 3. Further, the comparison of the year-to-year variation between the ozone amount amplitudes and the geopotential height amplitudes clearly indicate positively correlated changes for wavenumbers 1~5. The link of geopotential height wave between the stratosphere and troposphere has also been clearly shown: Year-to-year variations of the amplitudes at 100, 500 and 850 hPa levels are similar to each other for wavenumbers 1~5. The results suggest the intimate relation of recent ozone depletion in the NH winter to a circulation change in the stratosphere and troposphere.

1. Introduction

It is well known that the recent ozone amount in middle latitudes in the NH winter has shown a rapid year-to-year depletion (*e.g.*, JAPAN METEOROLOGICAL AGENCY, 1994). However, ozone depletion in the NH has been considered not as likely to develop as the ozone hole in Antarctica, because of the stronger large scale wave activity in the NH: The waves bring about warmer a lower stratosphere, which results in relatively less active heterogeneous reactions on the surfaces of ice particles of the Polar Stratospheric Clouds (PSC's) (SOLOMON, 1990). Therefore, the process of ozone depletion in the NH may accompany circulation changes in the winter stratosphere, especially in the large scale disturbances known as planetary waves.

The present paper, on the basis of data analysis, aims to detect how the recent ozone depletion might be connected to the circulation changes in the NH winter. KAWAHIRA *et al.* (1994) elucidated the horizontal structure changes of the ozone amount distribution in the Antarctic ozone hole: The wavenumber 1 pattern became suddenly dominant at 70 and 80°S in September after 1990, being unrelated to the Pinatubo eruption which occurred in June 1991. This suggests that the changes could be related to the continuous deepening of the ozone hole from 1989 to 1994. The dominance of the wavenumber 1 pattern could promote the heterogeneous reactions which cause ozone decrease due to less dominant meridional transport of heat compared to wavenumbers 2 and 3. Therefore, the rapid depletion of the NH winter ozone amount could accompany the

circulation changes as seen in the SH (the Southern Hemisphere), which could help maintain low temperature in the winter lower stratosphere.

The data used for analysis are the daily total ozone observed by Nimbus 7/TOMS (ver. 6), and the NMC (National Meteorological Center, USA) analyzed daily geopotential height data (GPH). The analysis is based on the long term changes of the monthly mean amplitudes of the ozone amount obtained by Fourier decomposition. Through comparison of the ozone amount amplitudes to GPH amplitudes, the dynamical link of the ozone changes to large scale disturbances is studied.

2. Year-to-year Changes of the Horizontal Ozone Distribution

First an analysis is carried out to detect the year-to-year variation of the horizontal ozone distribution in the NH winter. The TOMS observed daily total ozone are analyzed by Fourier decomposition along NH middle latitudes of 40, 45 and 55°N in December. The month of December is selected because of less frequent occurrence of sudden stratospheric warmings compared to January and February, making it easier to detect the long-term trend. The monthly mean amplitudes of total ozone along latitude circles are determined as follows: We calculate at first daily amplitudes of sine and cosine components, second we calculate the monthly averages of the two components, and third we made square root of $\text{sine}^2 + \text{cosine}^2$ of the monthly mean two components. Thus, the phases of the monthly mean waves are also calculated. The missing data along latitude circles, though not many, are calculated from averages of adjacent daily

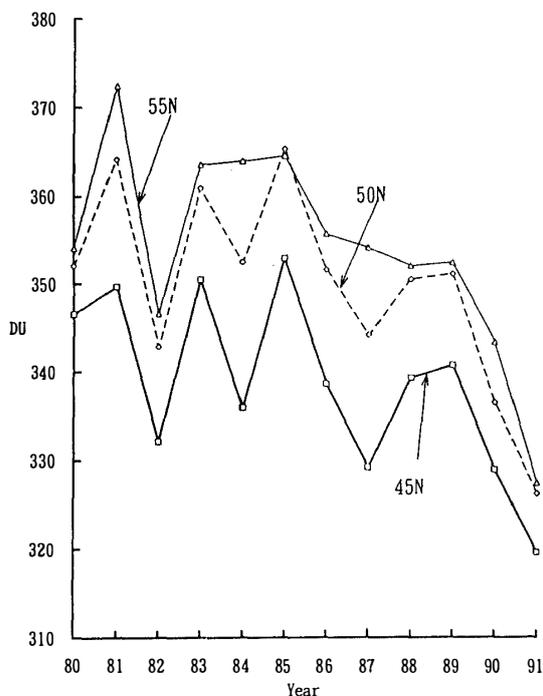


Fig. 1. Trend of zonal mean total ozone in December observed by Nimbus 7/TOMS (ver. 6) at latitudes 45, 50 and 55°N.

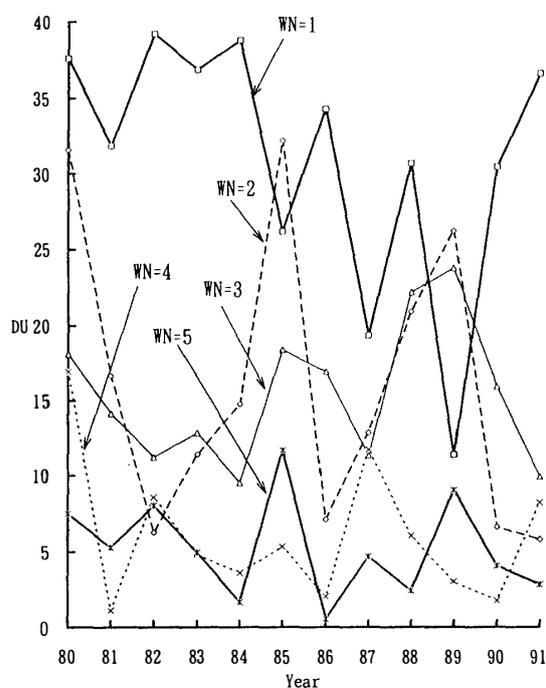


Fig. 2. Trend of the amplitudes of 'total ozone' waves along latitude 45°N for December. The amplitudes are calculated by Fourier decomposition of daily total ozone.

data. This manner can not affect the calculated results because we focus on larger scale distribution than wavenumber 5 along latitude circles.

Long-term variations of the monthly mean ozone amount for December are shown in Fig. 1, where the variations at 3 latitudes are shown from 1980 to 1991. After 1989, the rapid depletion of zonal mean ozone amount is evident for each latitude, though the data are shown until 1991. The rapid depletion began before the eruption of Pinatubo in June 1991. Therefore it is not likely that the recent ozone depletion is due only to aerosol increase in the stratosphere. In Fig. 1 the data are shown until 1991, but this depletion in winter NH middle latitudes continued until 1993 as shown by HOFMAN *et al.* (1994).

The variations of the amplitudes of ozone amount along the latitude circle 45°N is shown in Fig. 2 where the amplitudes of wavenumbers (WN) 1 to 5 are shown. The changes indicate that the dominant amplitude is different in each year, although the dominant amplitudes are limited to WN=1~3. It is noted that amplification of WN=1 accompanies decay of amplitudes of WN=2 and 3, and *vice versa*. This relation is different from that in the Southern Hemisphere (SH), where the dominant pattern of ozone amount is WN=1 as seen in KAWAHIRA *et al.* (1994).

The relation of zonal mean to wave pattern in ozone amount may simply indicate a relation between dynamics and ozone changes. The year-to-year variations of zonal mean and wave amplitudes are shown in Fig. 3, where amplitudes of WN=1~3 are compared to zonal mean ozone amount. In Fig. 3a the amplitude of WN=1 is compared to zonal mean ozone amount. The remarkable recent changes are that amplification of WN=1 accompanies a decrease of zonal mean ozone. In contrast,

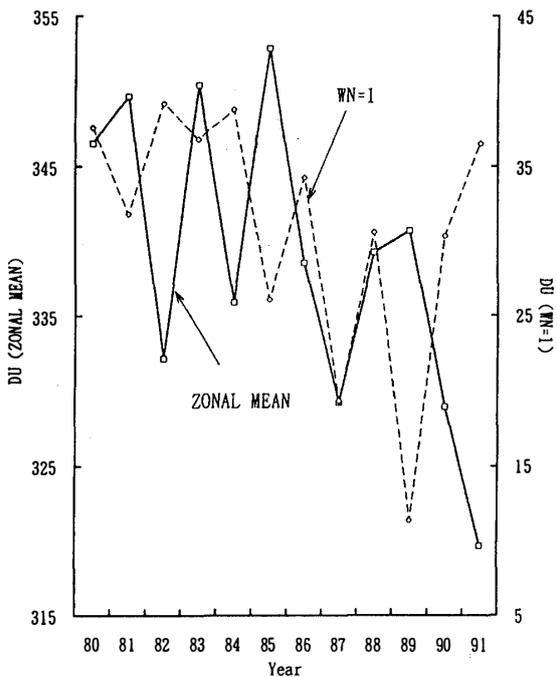


Fig. 3a. Comparison of trend of zonal mean and amplitude of WN=1 for total ozone.

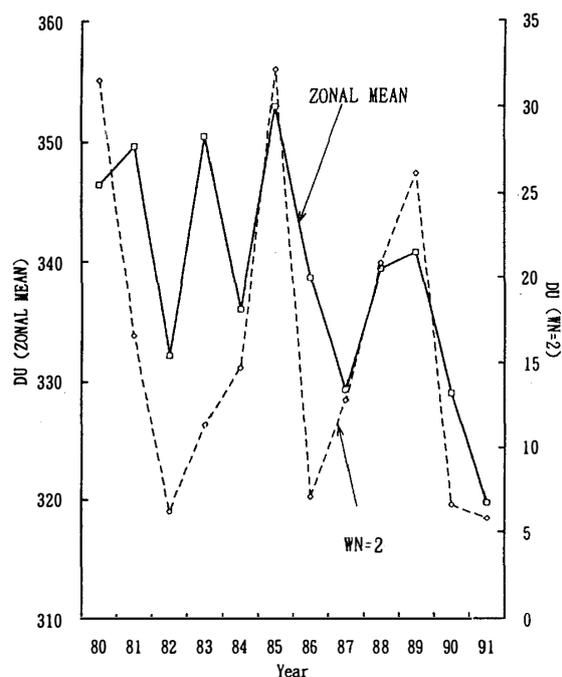


Fig. 3b. Same as (Fig. 3a) but for WN=2.

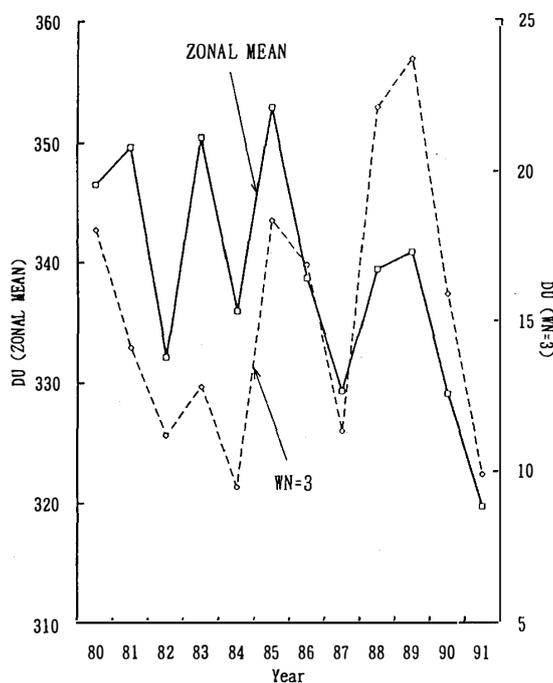


Fig. 3c. Same as (Fig. 3a) but for $WN=3$.

amplification of $WN=2$ and 3 accompanies a decrease of zonal mean ozone amount. These interesting relations are quite evident in the recent period of rapid ozone depletion after 1989.

What can be derived from these amplitudes and zonal mean ozone changes? Although the total ozone is the vertically integrated ozone amount, dynamical transport can be detected through variation of total ozone because ozone number density is maximum in the lower stratosphere where the residence time of ozone reactions is long enough to be influenced by transport (e.g., BRASSEUR and SOLOMON, 1984). The wave pattern of ozone also could indicate dynamical effects in the winter stratosphere. The relation shown in Fig. 3 can be explained by noting that dominance of $WN=2$ and 3 can cause effective meridional exchange giving rise to increase of zonal mean ozone, but dominance of $WN=1$ induces relatively weak meridional transport, giving rise to decrease of zonal mean ozone. Furthermore, dominance of the $WN=1$ pattern in middle latitudes means an equatorward shift circumpolar vortex from the north pole. The amplification can accompany a decrease of zonal mean ozone when the ozone amount inside the vortex is less than that outside.

3. Comparison of Wave Amplitudes between Ozone Amount and Geopotential Height

The ozone 'wave' and zonal mean changes are the results of dynamical effects of planetary scale waves seen in the winter stratosphere. The 'ozone wave' and planetary waves are also compared in terms of their monthly mean values. The data of geopotential heights (GPH) were analyzed by NMC at the levels of 200, 500 and 850 hPa. The first comparison was made for GPH waves at 200 hPa (about 11 km height in the lower

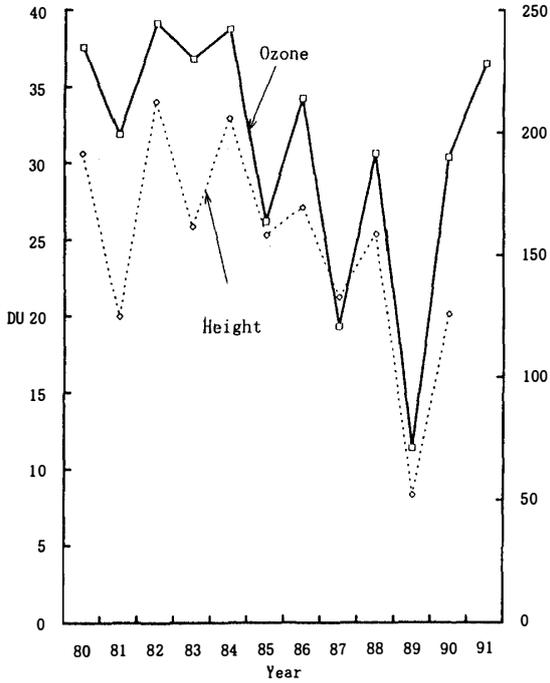


Fig. 4a. Comparison of trend of the amplitude of $WN=1$, for total ozone and geopotential height at 200 hPa.

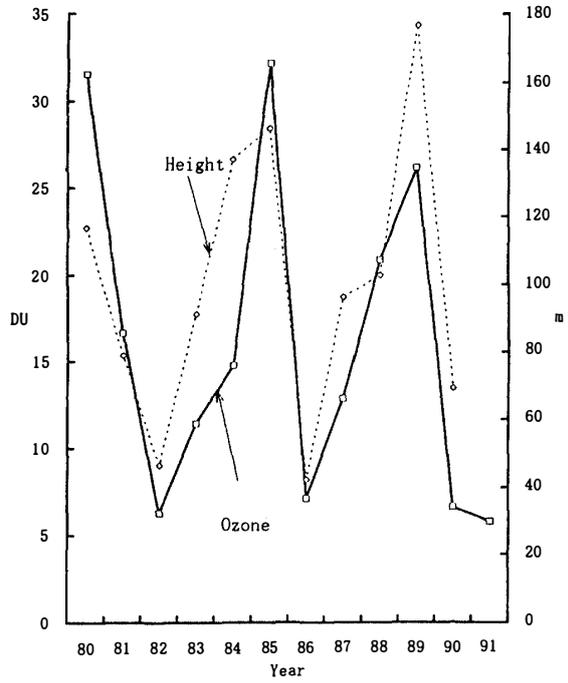


Fig. 4b. Same as Fig. 4a but for $WN=2$.

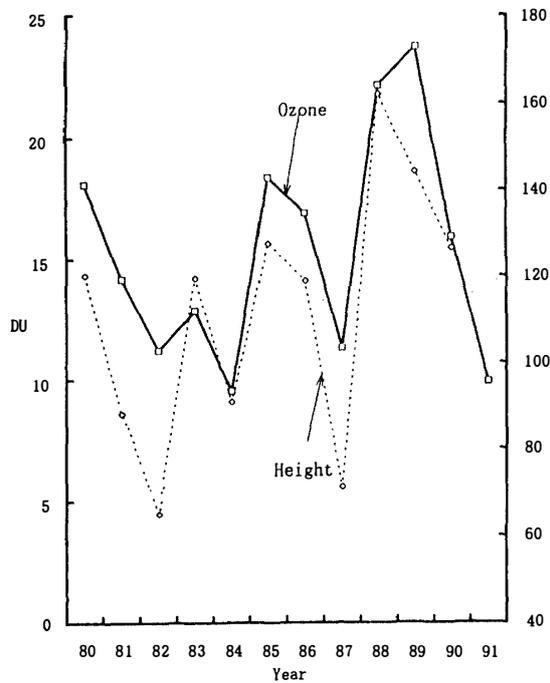


Fig. 4c. Same as Fig. 4a but for $WN=3$.

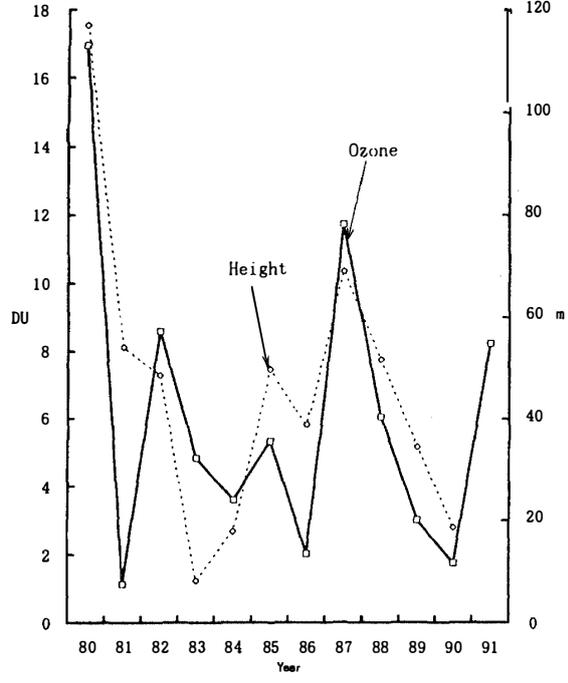


Fig. 4d. Same as Fig. 4a but for $WN=4$.

stratosphere) and ozone amount. The activity of large scale waves could be roughly detected by the GPH at 200 hPa because of its large vertical wavelength (MATSUNO, 1970). The year-to-year comparison was made for each wavenumber as seen in Fig. 4.

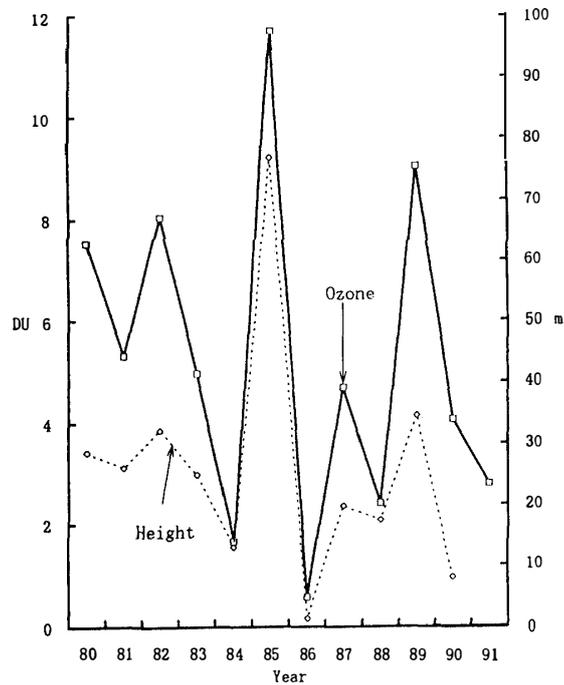


Fig. 4e. Same as Fig. 4a but for $WN=5$.

The two correlate positively for wavenumbers 1 to 5. It is interesting that a clear positive correlation is seen even for wavenumber 5, suggesting that baroclinic scale waves affect the ozone variation in the lower stratosphere.

The results suggest, as seen in the ozone 'wave' and mean changes, that the recent ozone depletion after 1989 was accompanied by amplification of the GPH wavenumber 1, but decay of wavenumbers 2 and 3 at the 200 hPa level. Its cause is beyond the scope of the present study. However, planetary waves in the stratosphere have their energy source in the troposphere (MATSUNO, 1970). In the following the wave analysis of the GPH is extended to the troposphere where the selected levels are the 500 (about 5.5 km height) and 850 hPa (about 1.5 km height) levels, middle and lower troposphere respectively.

Figure 5 is the result of the trend of wave amplitudes at the 3 levels 200, 500 and 850 hPa for $WN=1\sim 5$. A gross feature seen in the figures is that the year-to-year changes at the 3 levels have positive correlation with respect to all wavenumbers, even to $WN=5$. The $WN=1$ amplitude changes show nearly positively correlated changes at 3 levels, but in 1984 the changes at 200 hPa show negative correlation for the 500 and 850 hPa levels. Further, at 850 hPa in 1990 the changes are different from those at 500 and 200 hPa. Other wavenumbers have shown well correlated changes between the 3 levels, indicating the strong link of large scale waves between the lower stratosphere and troposphere as has already been confirmed theoretically and observationally (e.g., ANDREWS *et al.*, 1987).

A remarkable characteristic shown in the figures is the recent amplitude changes of $WN=1\sim 3$ related to recent ozone depletion after 1989. Before 1985, the amplitude of $WN=1$ was larger than $WN=2$ and 3; from 1985 to 1989 the amplitude quickly

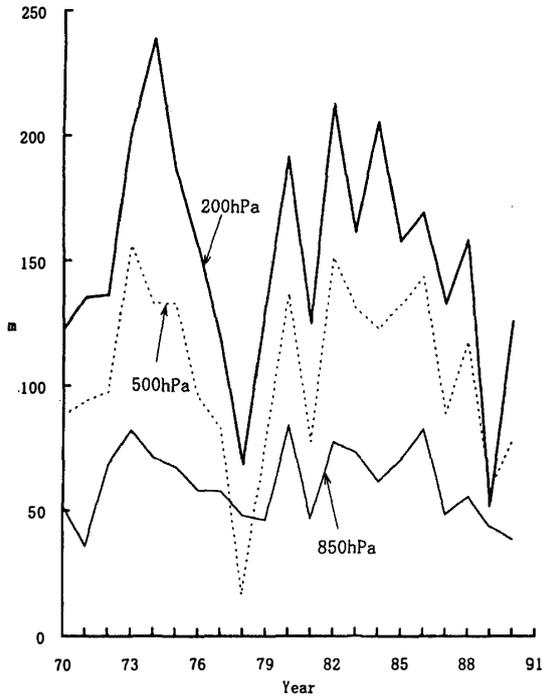


Fig. 5a. Comparison of trend of geopotential height amplitudes of $WN=1$ at 200, 500 and 850 hPa.

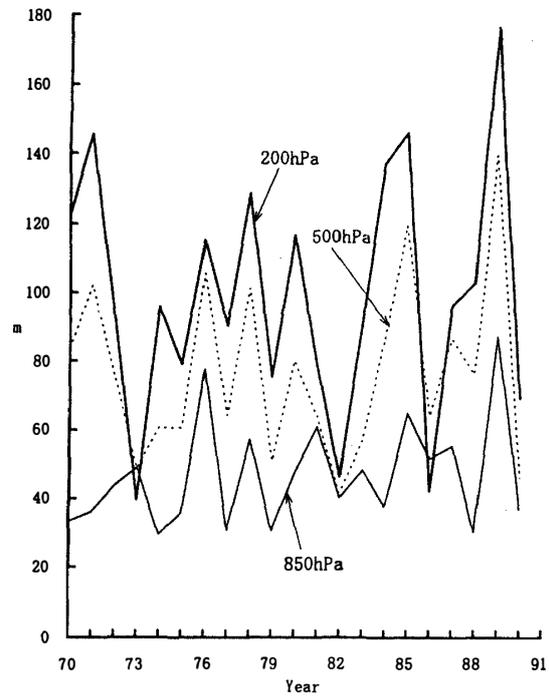


Fig. 5b. Same as Fig. 5a but for $WN=2$.

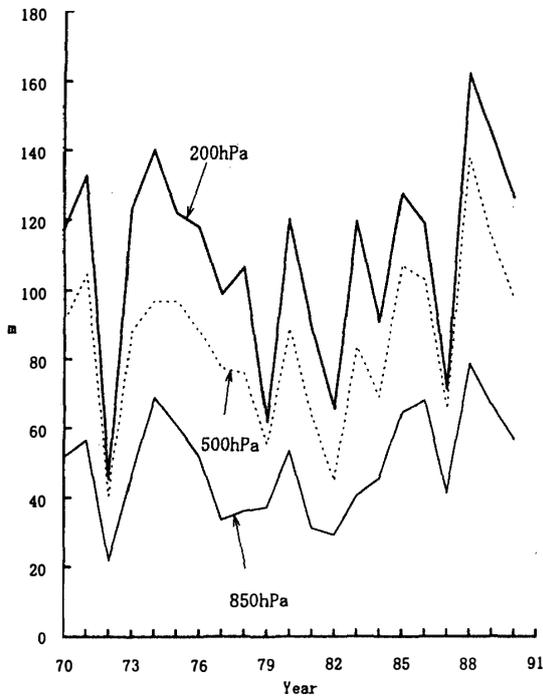


Fig. 5c. Same as Fig. 5a but for $WN=3$.

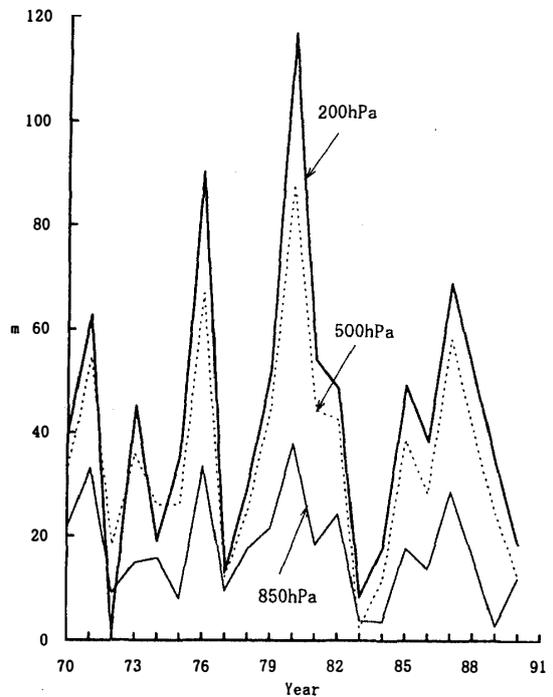


Fig. 5d. Same as Fig. 5a but for $WN=4$.

decayed. However, since 1989 the amplitude of $WN=1$ has rapidly grown, being larger than $WN=2$ and 3. On the contrary, the amplitudes of $WN=2$ and 3 have grown from

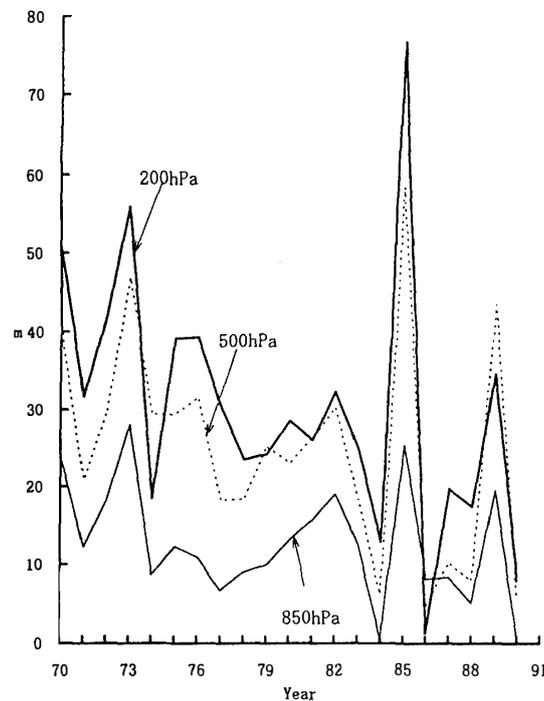


Fig. 5e. Same as Fig. 5a but for $WN=5$.

1985 to 1989, being larger than $WN=1$, and since 1989 both amplitudes have rapidly become smaller than $WN=1$. These mutual changes of the amplitudes are seen in the changes of ozone 'waves'. These rapid variations of wave amplitude related to ozone depletion may suggest that around 1989, a circulation change occurred, and the change could have caused the ozone depletion in the NH troposphere and stratosphere. This issue will be studied in the future through more detailed analysis.

4. Discussion and Summary

The analysis of the variations of ozone and GPH has confirmed their links between the stratosphere and troposphere. Furthermore, the recent ozone depletion since 1989 in temperate latitudes has a link to circulation changes in the troposphere. It is an important question why the rapid ozone depletion began in 1990, and how are the dynamical conditions different from those in the years before 1989? To investigate the reasons is valuable to predict the future ozone variations in the NH. The present results have shown that the rapid ozone depletion began before the eruption of Pinatubo, and thus the ozone depletion cannot be due only to aerosol increase following the Pinatubo eruption but due also to circulation changes. From this point of view, the relation between ozone depletion and circulation changes is discussed.

It is speculated that a remarkable circulation change in recent NH middle latitude winters could be linked to ozone change. A well known recent climate change is the warmer winters in Northern temperate latitudes since 1987. The analysis of radiosonde data by ANGELL (1994) has pointed out the trend toward warmer winter temperature in NH middle latitudes, as seen in Fig. 6a, which is the surface temperature anomaly from

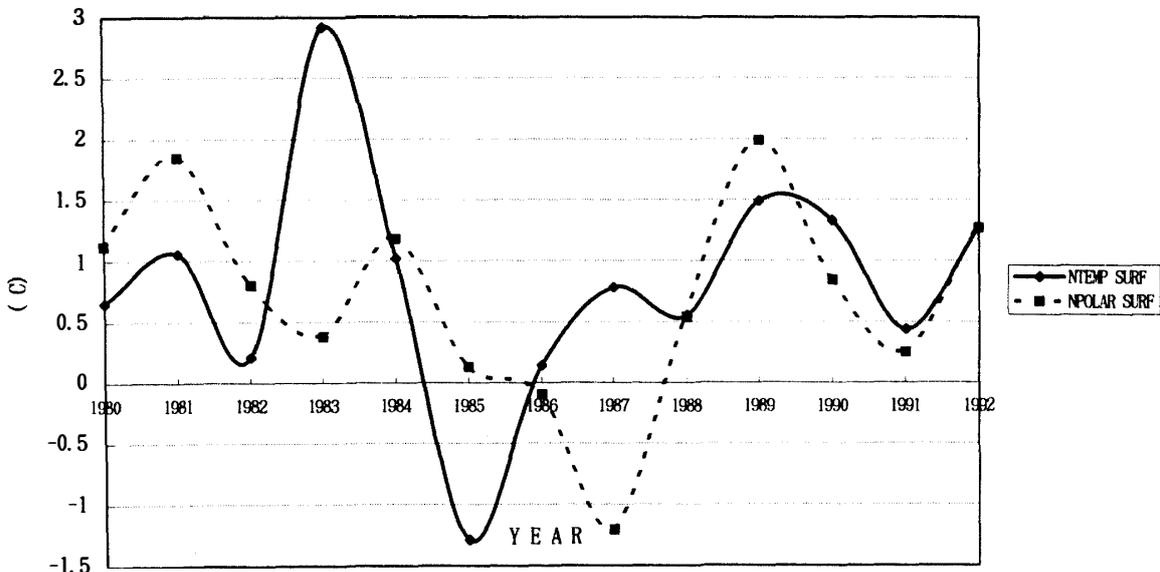


Fig. 6a. Temperature anomaly trend at surfaces averaged in temperate latitudes (30°N – 60°N) (line) and polar latitudes (60 – 90°N) (dotted line), and averaged for the winter season (December–February) obtained on the basis of radiosonde data. The anomaly is the deviation from the mean during 1958–1977 (adapted from ANGELL, 1994).

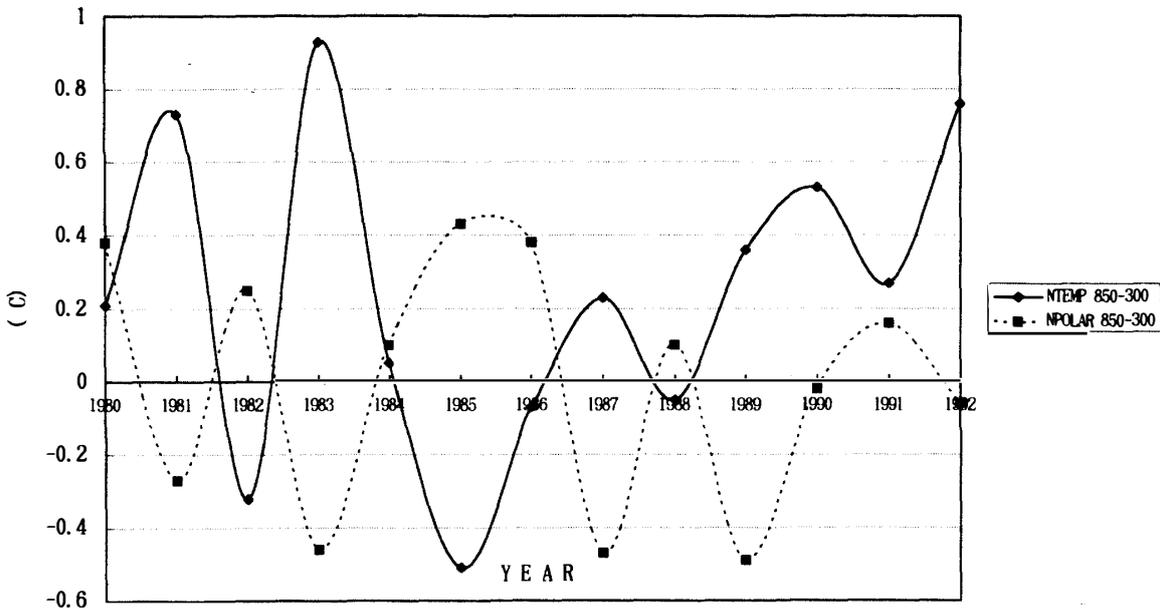


Fig. 6b. Same as Fig. 6a, but for averaged temperatures in the layer 850–300 hPa.

the mean temperature for the period 1958–1977. The temperatures are averaged between 30 and 60°N and over time for the 3 months from December to February. Since 1987, the anomaly has been more than $+1^{\circ}\text{C}$, indicating successive warmer recent winters in NH middle latitudes at the surfaces. The anomaly in North Polar Latitudes (60 – 90°N) at the surfaces also shows warmer winters since 1988. The further trends of the temperature averaged over the 850–300 hPa layer, determined as in the surface temperature, are shown in Fig. 6b, which indicates the trend of the temperature anomaly in the

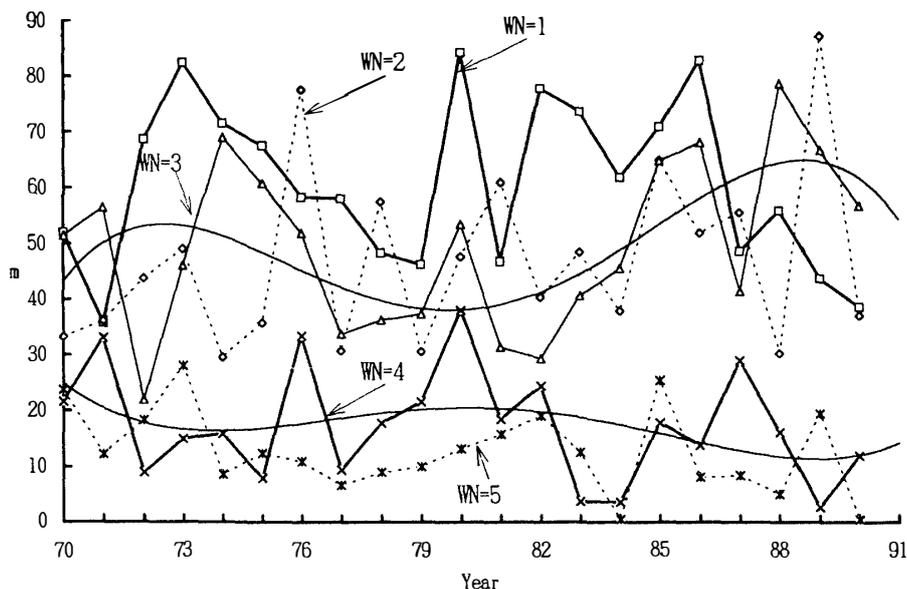


Fig. 7. Year-to-year variations of GPH amplitudes at 850 hPa at 45°N. The lines indicate trend of amplitude of WN=3 (upper line) and the amplitude of WN=4 (lower line).

troposphere. There is a negative correlation between the temperate and polar latitudes, and the recent warmer winter in middle latitudes is accompanied by nearly no changes in the polar latitudes. It is stressed from Fig. 6b that since 1989 the temperature difference between middle and polar latitudes has roughly been large and helped strengthening of the westerly jet through the thermal wind relation.

The analysis of the 500 hPa surface height anomaly relating to warmer winters by JMA (Japan Meteorological Agency) has found that a winter mean flow pattern around the North Pole has become relatively symmetric compared to the 30-year averaged pattern (JAPAN METEOROLOGICAL AGENCY, 1994). This recent flow pattern suggests that planetary scale waves of WN=1~3 could be relatively dominant compared to baroclinic waves of WN=4~6. The long-term changes of GPH amplitudes at 850 hPa for the December mean at 45°N are shown in Fig. 7, where the two lines indicate the trend of the amplitude of WN=3 (upper line) and that of WN=4 (lower line) determined from regression analysis by a cubic equation. It can be seen in Fig. 7 that before 1980 the ratio of the magnitudes of amplitudes in WN=4~5 to those in WN=1~3 was smaller than the ratio after 1985. For example, the amplitude of WN=4 had a tendency to decay from 1980 to 1990 shown by the lower line. In contrast, the amplitudes of WN=3 have a growing tendency from 1982 to 1990 as shown by the upper line. This trend is very qualitative and needs further detailed study, but the winter flow pattern changes relating to recent warm winters may be confirmed also in Fig. 7.

In summary, the recent ozone depletion in the NH winter middle latitudes is intimately related to a circulation change, beginning around 1989, in which the planetary scale waves of WN=1~3 have become more active compared to baroclinic waves of WN=4~5, and the heat fluxes by baroclinic waves have become less active, resulting in warm winter at the middle latitude surfaces in the Northern Hemisphere troposphere.

The baroclinic waves in the troposphere play a principal role in meridional heat flux in the troposphere; thus, the decay of the waves in winter middle latitudes helps prevent equatorward flow of cold air in polar latitudes. However, the cause of the decay of baroclinic waves is still vague. As for the winter stratosphere, a speculative process is that the warm winter troposphere in middle latitudes can enhance the jet stream through the thermal wind relation due to larger temperature gradient between middle and polar latitudes in the troposphere, as seen in Fig. 6b, and the westerly jet enhancement can inhibit vertical propagation of planetary waves, more effectively for $WN=2$ and 3 than for $WN=1$. However, to confirm the speculative process is also the object of a forthcoming study involving detailed analysis.

In the analysis of ozone and GPH, the wave pattern variation clearly indicated that dynamical effects are important in the recent ozone depletion in NH winter middle latitudes. The mechanism of dynamical effects on the ozone change will be investigated as a further step.

Acknowledgments

The authors thank the two reviewers for their valuable comments. The Ozone Processing Team at Goddard Space Flight Center are acknowledged for the use of the TOMS data. This study is supported by a Grant-in-Aid for Scientific Research from the Ministry of Education of Japan and also the project 'The Synthetic Study on the Observations and Analysis of the Variations in the Ozone Layer' organized by the National Institute for Environmental Studies.

References

- ANDREWS, D. G., HOLTON, J. R. and LEOVY, C. B. (1987): *Middle Atmosphere Dynamics*. Orlando, Academic Press, 489p.
- ANGELL, J. K. (1994): Global, hemispheric, and zonal temperature anomalies derived from radiosonde records. *Trends '93: Compendium of Data on Global Change*, ed. by T.A. BODEN *et al.* Oak Ridge, Oak Ridge National Laboratory, 636–672 (ORNL/CDIAC-65).
- BRASSEUR, G. and SOLOMON, S. (1984): *Aeronomy of the Middle Atmosphere*. Netherlands, Kluwer Academic Publ., 441p.
- HOFMAN, D. J., OLTMANS, S. J., KOMHYR, W. D., LATHROP, J. A., HARRIS, J. M., LANGFORD, A.O., DESHLER, T., JOHNSON, B.J., TORRES, A. and MATTHEWS, W.A. (1994): Ozone loss in the lower stratosphere over the United States in 1992–1993: Evidence for heterogeneous chemistry on the Pinatubo aerosol. *Geophys. Res. Lett.*, **21**, 65–68.
- JAPAN METEOROLOGICAL AGENCY (1994): *Report on Abnormal Weather '94* (in Japanese). Tokyo, JMA, 444p.
- KAWAHIRA, K., HASEGAWA, T. and HIROOKA, T. (1994): Recent sudden changes of the horizontal structure of the ozone hole in Antarctica. submitted to *J. Geophys. Res.*
- MATSUNO, T. (1970): Vertical propagation of stationary planetary waves in the winter northern hemisphere. *J. Atmos. Sci.*, **27**, 871–883.
- SOLOMON, S. (1990): Progress toward a quantitative understanding of Antarctic ozone depletion. *Nature*, **347**, 347–354.

(Received November 12, 1994; Revised manuscript received January 31, 1995)