Proc. NIPR Symp. Polar Meteorol. Glaciol., 8, 1–13, 1994

A QUALITATIVE ASSESSMENT OF HEIGHT DEPENDENT INTERANNUAL VARIABILITY OF POLAR STRATOSPHERIC OZONE PART I: LONG-TERM VARIABILITY AND STRATOSPHERIC OZONE DEPLETION

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Abstract: Until now continuous balloon-borne observations of vertical ozone distributions in the Antarctic stratosphere for all seasons of a year do not well cover one solar cycle. Thus, long-term ozone variations in vertical and interannual patterns caused by dynamic and chemical processes of different scales cannot be analyzed by consistent data sets. Most regular Antarctic observations have been made for the months September and October since the beginning of ozone soundings at Syowa Station in 1966. An attempt is presented to assess long-term ozone variations by using monthly mean ozone data obtained at Syowa Station and additional data from Georg Forster Station and Neumayer Station. These ozone data together with monthly means of potential temperature and their standard deviations as observed at Syowa Station, as well as the monthly means of the QBO phase as observed at 10 hPa altitude in tropical latitudes, are used to discuss the long-term control of polar stratospheric ozone by atmospheric dynamics. Signals of the tropical QBO-phase can be found in polar stratospheric ozone variations at altitudes above the 20 hPa isobaric surface. It is suggested that inside the polar vortex chemically caused ozone reductions at 70 hPa are also controlled by dynamic processes. Significant impacts of volcanic aerosols on stratospheric ozone dominate at 150 hPa pressure level, showing additional severe ozone depletion.

1. Introduction

Measurements and model studies have indicated that ozone depletion in the southern polar stratosphere is mainly caused by chemical reactions between ozone and chlorine after the return of sunlight in spring (STOLARSKI *et al.*, 1992; CRUTZEN and ARNOLD, 1986; CRUTZEN *et al.*, 1992). This regular repeated ozone loss in the southern lower stratosphere in spring has developed during the last solar cycle since the late 1970s, and is still growing. In 1982, balloon-borne observations first indicated this significant change in stratospheric ozone (CHUBACHI, 1984). The strengthening as well as the detailed vertical extent of this feature can be shown by about 60 ozone soundings at Georg Forster Station for the period September through October in 1985 (GERNANDT, 1987). Since lower stratospheric ozone depletion has been evident (FARMAN *et al.*, 1985), the year to year variations of this spring ozone loss also indicate possible important dynamic control of the chemical reactions which deplete ozone in the southern polar stratosphere during spring.

Long-term, regular observations are necessary with sufficient temporal and spatial resolution in order to understand the impact of global stratospheric circulation and planetary wave activity on temperature and ozone in the polar stratosphere. Furthermore, the importance of very long-term atmospheric variations due to internal, nonlinear interactions has not been considered in this context so far. Sufficient regular observations of the vertical ozone distribution in southern polar latitudes for all seasons of a year have been made since the mid-1980s. That is less than one solar cycle. Thus, signals of very long-term variations of the global atmospheric circulation cannot be seen in present by available data sets. But, such data are needed for reliable trend analyses. Recently, preliminary assessments addressed to long-term interactions between global circulation patterns and the changing vertical ozone distributions in the Antarctic stratosphere can only be made by means of data from a small number of stations.

2. Data

Ozone, temperature and quasi biennial oscillations (QBO) data obtained by balloon-borne observations are used in the present study. The balloon-borne ozone observations were carried out using electrochemical ozone sensors, *i.e.* RSII-KC 79 ozonesonde at Syowa Station (SY), OSE ozonesonde at Georg Forster Station (GF) and ECC ozonesonde at Neumayer Station (NM). The corresponding temperature data are obtained from regular radiosonde launches.

Ozone sounding data used are those at Syowa (69°S, 39°E) from 1966 to 1992, those at Georg Forster (71°S, 12°E) from 1985 to 1991, and those at Neumayer (70°S, 08°W) for 1992. October monthly means of ozone mass mixing ratios (MO3) have been calculated for SY at isobaric levels of 150 hPa, 70 hPa and 20 hPa for the period from 1966 to 1992 except for a few years without observations. All available September and October monthly means of MO3 from all stations, also including the 10 hPa isobaric level, are used to discuss the period from 1982 to 1992 in more detail. Monthly means of potential temperature (PT) and their standard deviations (SD) were calculated for October from 1966 through 1992 from daily radiosonde observations at SY (Kaneto, private communication, 1993). These analyses are made at isobaric levels of 20 hPa, 70 hPa and 125 hPa. The variations of standard deviation (SD) of monthly mean PT are understood as signals for horizontal and vertical transport of air masses at the corresponding isobaric levels. Monthly means of the phase of QBO at 10 hPa in the tropical stratosphere (Naujokat, 1993) for September and October are used to assess signals of dynamic interactions between the polar stratosphere and global circulation.

For the period 1966 through 1992 the long-term interannual variabilities of MO3, PT and SD for October are discussed using SY data only. On the one hand the interannual variations in October are interesting with regard to the spring ozone depletion and its interannual variability but, on the other hand, data from SY for almost all these years are only available for this month.

The long-term mean profiles of ozone partial pressure calculated for SY with data from 1987 through 1992 and for GF with data from 1985 through 1991 are compared in Fig. 1. The data to calculate these mean profiles are corrected in accordance with commonly applied procedures using independent total ozone data obtained at SY by Dobson instrument and at GF by M-124 filter spectrometer. In September and October significant differences of the ozone partial pressure between SY and GF appear in the tropospheric boundary layer. In stratospheric altitudes the more pronounced differences of ozone partial pressure between both stations are related to the spring ozone depletion which develops in the lower stratosphere. Above the 70 hPa isobaric level, lower ozone values are observed at GF for both months. That might be an indication that GF is located more inside the long-term mean vortex pattern than SY during September and October. However, the differences between the profiles are less than the standard deviations of GF data themselves. Thus, we suggest that the vertical ozone distributions obtained at both stations are characteristic of the poleward side of the vortex margin. Greater differences between SY and GF will occur when a strong horizontal displacement of the vortex pattern occurs. Then both stations are no longer located similarly with regard to the vortex margin, and stronger horizontal gradients of MO3 must appear between the stations. The large differences of MO3 in the years 1988, 1990 and 1991 (Table 1) might be explained by this rough approximation. Smaller differences of MO3 appear in years with a more symmetric mean circumpolar vortex pattern. Of course, there still remain deviations, differences of MO3 increasing with altitude, between the observed ozone profiles, caused by the different ozone sensors used. That must

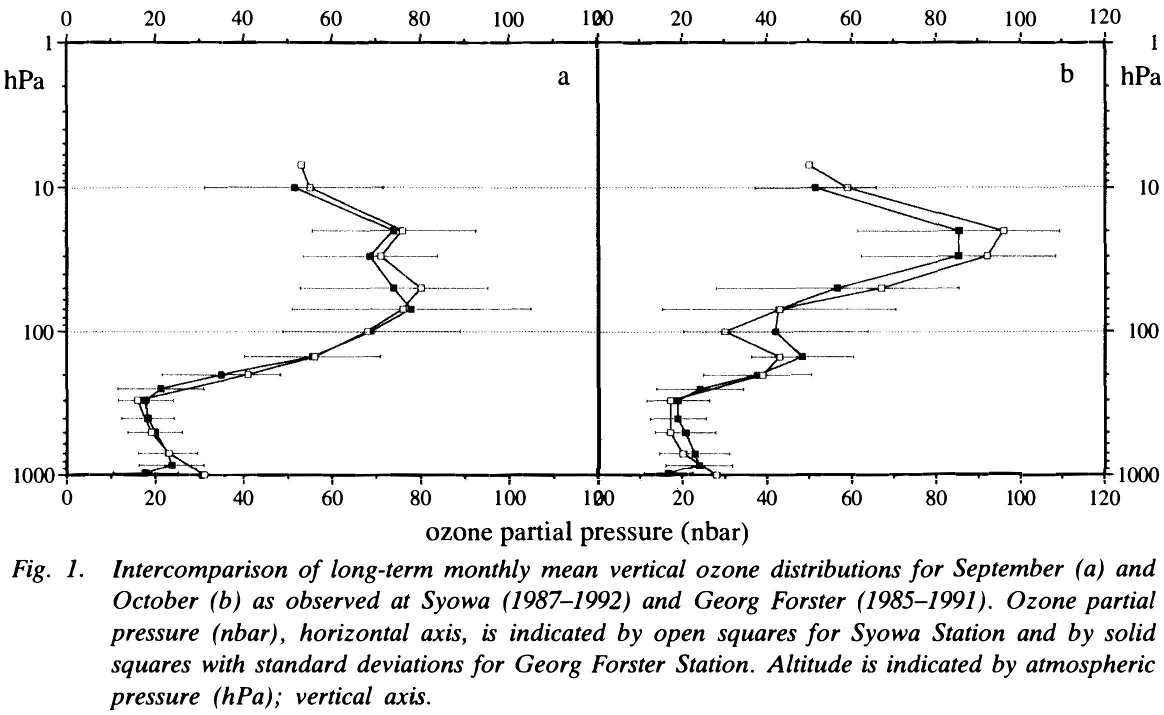

Fig. 1. Intercomparison of long-term monthly mean vertical ozone distributions for September (a) and October (b) as observed at Syowa (1987–1992) and Georg Forster (1985–1991). Ozone partial pressure (nbar), horizontal axis, is indicated by open squares for Syowa Station and by solid squares with standard deviations for Georg Forster Station. Altitude is indicated by atmospheric pressure (hPa); vertical axis.

Table 1. Differences between monthly means (September and October) of ozone mixing ratio (ppmm): MO3 (Syowa)–MO3(Forster) for the years 1986–1991 and MO3 (Syowa)–MO3 (Neumayer) for the year 1992; and mean differences (M) and their standard deviations (SD) at four pressure levels for the period 1986–1992.

	September				October			
Year	150 hPa	70 hPa	20 hPa	10 hPa	150 hPa	70 hPa	20 hPa	10 hPa
1986	—	—	—	—	+0.095	−0.057	−1.487	−1.143
1987	+0.011	−0.258	−0.882	—	+0.095	+0.331	+0.030	—
1988	+0.210	+1.027	+3.855	+3.364	−0.075	−0.122	+0.754	+6.018
1989	+0.050	+0.186	−0.014	−0.076	+0.014	−0.239	+0.152	−0.033
1990	+0.197	+0.139	−0.298	+0.120	+0.153	+0.572	+2.531	+2.190
1991	−0.103	+0.121	+0.545		−0.070	+0.351	+4.810	+3.022
1992	+0.071	+0.582	+0.016	−1.491	−0.148	−0.263	+0.356	+0.116
M	+0.073	+0.315	+0.537	+0.479	+0.009	+0.082	+1.021	+1.695
SD	0.118	0.439	1.691	2.053	0.111	0.331	2.049	2.616

Table 2. Mean ozone loss from September to October, locations of observation, and monthly mean phase of QBO

Year	September mean (ppmm)	Loss from September through October (ppmm)	(%)	%/day	Location	QBO
1982	2.296	−0.307	−13.37	−0.45	SY	W
1983	2.841	−0.142	−05.00	−0.17	SY	E
1984	2.036	−0.255	−12.52	−0.41	SY	W
1985	2.341	−1.534	−65.39	−2.18	GF	E
1986	1.891	−0.607	−32.10	−1.07	GF	E
1987	1.715	−1.264	−73.70	−2.46	SY+GF	W
1988	2.470	−0.491	−19.88	−0.66	SY+GF	E
1989	1.777	−0.639	−35.96	−1.20	SY+GF	W
1990	1.351	−0.217	−16.06	−0.54	SY+GF	E
1991	1.362	−0.448	−32.89	−1.09	SY+GF	E
1992	1.366	−1.187	−86.90	−2.90	SY+NM	W

be considered for data above the 20 hPa isobaric level in particular (Fig. 1).

Assuming similar mean positions of both stations with regard to the mean vortex pattern, the ozone observations of GF and SY might be taken together as a "sector zonal mean" to discuss the interannual behavior on the poleward side of the vortex margin. We have decided to use September and October mean values of MO3 obtained by data from SY or GF as well as from both, GF and SY or SY and NM, as representative values for the region along 71°S between 10°W and 40°E (Table 2). Furthermore, in the discussion of interannual variations, data of one station are considered for the whole region if only data for that one station are available. These rough assumptions are necessary to overcome the lack of data in September and October from 1982 through 1992.

3. Results

The interannual variations of SD at 125 hPa, 70 hP and 20 hPa in the polar stratosphere and of the QBO phase at 10 hPa in the tropical stratosphere are shown for October from 1966 to 1992 (Fig. 2). These are late wintry conditions inside the stratospheric vortex just before its breakup in November or December. Transient features of biennial or longer period oscillations of SD appear at all isobaric levels. These variations are well correlated between 70 hPa and 125 hPa, although the periodicities are different for different intervals. There is not seen any correlation between the lower isobaric levels and the 20 hPa isobaric level in general. Furthermore, additional transient correlations occur. Between 20 hPa and 70 hPa the interannual SD variations coincide for the 6 years from 1971 till 1977. Later a well pronounced biennial oscillation appears at the levels 70 hPa and 125 hPa for about 5 years, from 1985 until 1990. This downward shift of good correlation seems to be a characteristic feature for a changing dynamic response of the polar stratosphere from 1966 through 1992.

At all considered isobaric levels, relative minima of SD appear in 1973, 1976, 1980, 1987, 1992, respectively. Smallest SD values coincide with the easterly phase of QBO at 10 hPa in the years 1973, 1976, 1980 and with the westerly phase of QBO in the years 1987 and 1992. There is also seen a height dependent change in the correlation between transient biennial oscillations of SD and the QBO at 10 hPa in the tropics. From 1970 through 1980 the SD maxima at 20 hPa coincide with the westerly phase of QBO. But, from 1985 to 1990, the

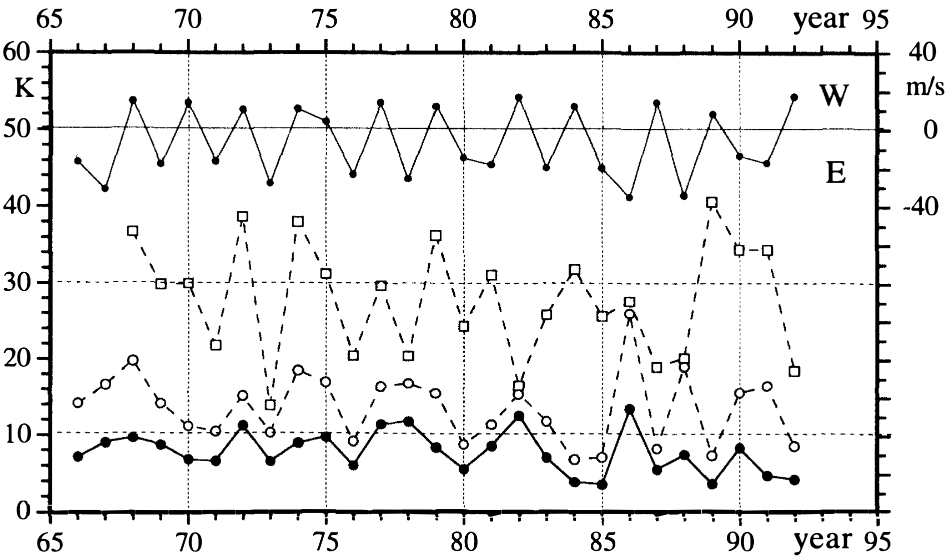

Fig. 2. Interannual variations in October from 1966 to 1992: phase of QBO (wind from East by − m/s, wind from West by +m/s) at 10 hPa in the tropics (upper panel) and standard deviations (SD) of monthly mean potential temperatures (K) at 20 hPa (open squares), 70 hPa (open circles), 125 hPa (solid circles) as observed by radiosondes at Syowa Station (lower panel).

SD maxima at 70 hPa coincide with the easterly phase of QBO.

The standard deviations (SD) of monthly mean potential temperatures calculated from daily radiosonde measurements show signals correlated to the phase of QBO. Such signals might be understood as an indication of the coupling between the polar lower stratosphere and stratospheric dynamic processes at lower latitudes. This coupling seems to have been height dependent from 1966 until 1992. The correlation between isobaric levels generally changed from 1982 through 1985 in altitude and periodicity. Therefore, it will be convenient to discuss the whole period from 1966 through 1992 and, separately, the changed conditions after 1982 through 1992.

3.1. *Ozone variations from 1966 through 1992*

The October monthly means of ozone mass mixing ratios (MO3) and of potential temperature (PT) obtained from Syowa Station are shown for three isobaric levels in Fig. 3a–3c. Monthly means of MO3 before 1986 are only based on few data, *i.e.* 1 to 3 observations per month. This small number of ozone observations compared to the daily radiosonde measurements makes comparison difficult because not all possible ozone variations are covered. Since 1986 the number of ozone soundings has been increased up to 7 observations per month.

Ozone mixing ratios (MO3) at 20 hPa, in general, do not follow the interannual variations of PT (Fig. 3a). No significant trend is found in MO3 means. But, the potential temperature grew from 1966 through 1992. Greatest interannual variability of MO3 is revealed for October months before 1975 and

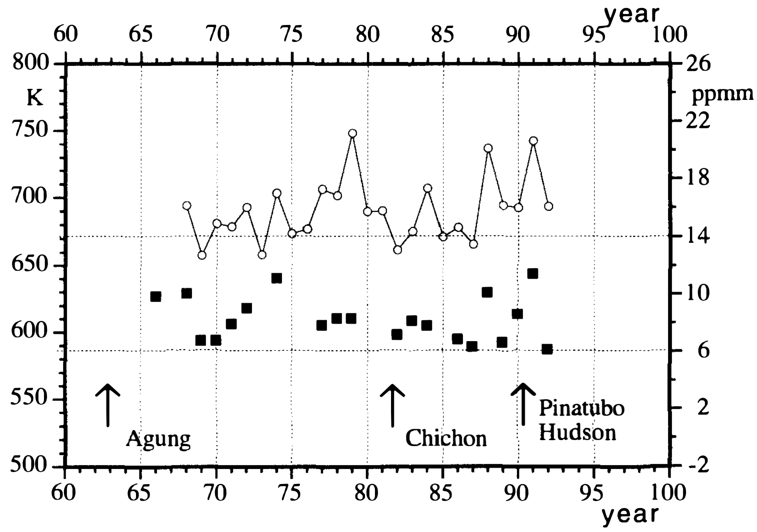

Fig. 3a. Interannual variations of monthly October mean potential temperature (PT) (circles), left scale in K, and monthly mean ozone mixing ratios (MO3) (solid squares), right scale in ppmm, at 20 hPa for the period from 1966 till 1992 as observed at Syowa Station. Volcanic eruptions with stratospheric aerosol loading are indicated by arrows. Agung means Mt. Agung, Chichon means El Chichon, Pinatubo means Mt. Pinatubo and Hudson means Cerro Hudson.

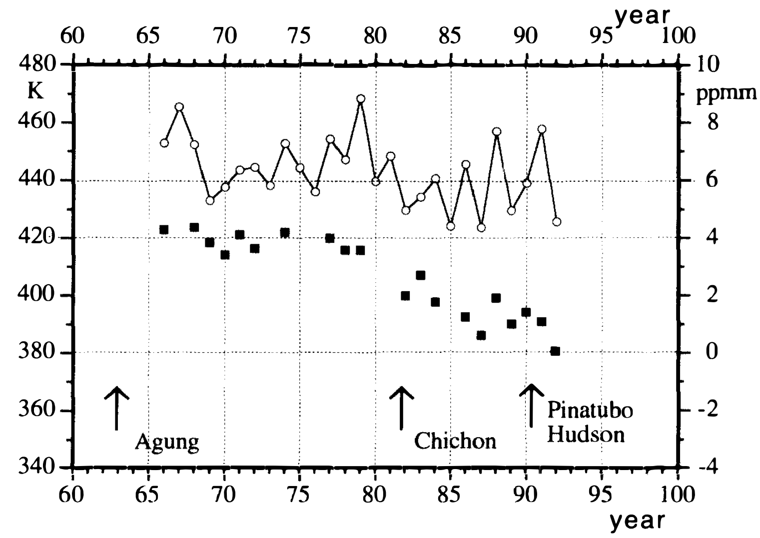

Fig. 3b. Same as Fig. 3a but for the 70 hPa level.

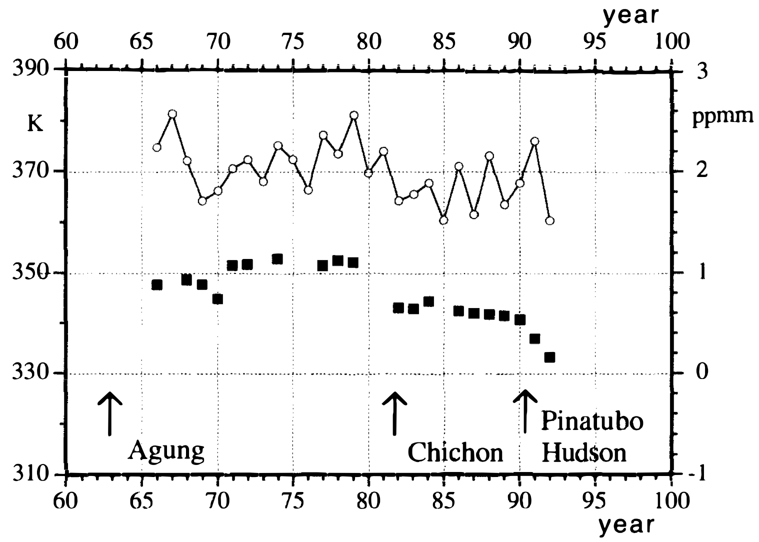

Fig. 3c. Same as Fig. 3a but for PT at 125 hPa and MO3 at 150 hPa level.

after 1987. The correlation between MO3 and PT became better after 1986. That might be mainly explained by the increased number of ozone observations.

At the 70 hPa level the October means of MO3 clearly show increasing ozone depletion in spring after 1979 (Fig. 3b). PT values show biennial oscillations with lowest PT in 1985, 1987 1992, but very little correlation to MO3 values. Comparing the MO3 variations (Fig. 3b, 4b) and the SD variations (Fig. 2) relatively high October means of MO3 appeared during the easterly phase of the QBO, and relative minima of MO3 coincided with the westerly phase of the QBO and the lowest PT values.

At 150 hPa the MO3 does not follow the oscillations of PT (Fig. 3c). Nearly constant high MO3 values were observed from 1971 until 1979. A significant decrease occurred from 1979 until 1982 following the El Chicon eruption before October 1982. Additional significant ozone losses occurred after the eruptions of Pinatubo and Cerro Hudson in 1991. This "new ozone loss" continued in 1992. Compared to the previous "undisturbed" MO3 level in the 1970's, ozone was reduced to about 15% in 1992 at this isobaric level over Syowa Station.

3.2. Ozone variations from 1982 through 1992

Using ozone sounding data from SY, GF and NM, monthly means of MO3 for September and October can be calculated for each year from 1982 until 1992. Assuming in a first approximation that all considered stations represent vertical ozone distributions inside the stratospheric vortex in spring, the "regional zonal mean" MO3 values give some idea of the interannual ozone variations at isobaric levels 150 hPa and 70 hPa (Fig. 4b) and, with some exceptions, also at 10 hPa and 20 hPa (Fig. 4a).

During this period, relative MO3 maxima were observed at 20 hPa and 10 hPa during years with pronounced easterly phases of QBO (Fig. 4a). With some exceptions this correlation to QBO signals can be seen in both the September and October MO3 data. It is pronounced in the "regional zonal means" of MO3, which has been calculated from data from two stations since 1986 (Table 2). It is less pronounced in the MO3 values obtained from only one station before 1986 (GF for 1985 and SY for 1982 until 1984). That behavior might be an indication

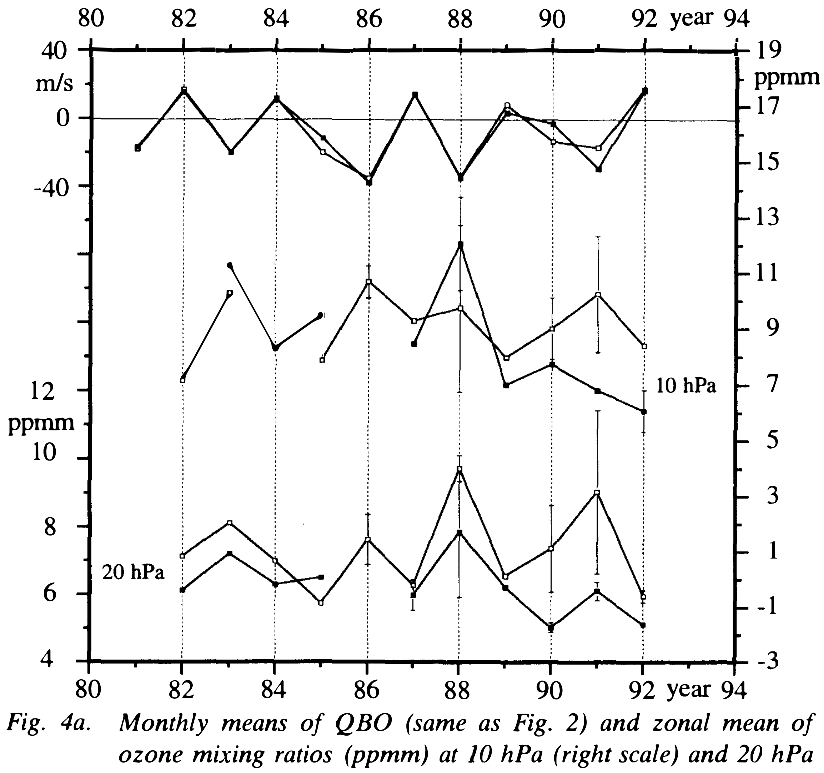

Fig. 4a. Monthly means of QBO (same as Fig. 2) and zonal mean of ozone mixing ratios (ppmm) at 10 hPa (right scale) and 20 hPa (left scale), calculated by data taken at SY, GF, and NM stations for September (solid squares) and October (open squares) according to Table 2 for the period from 1982 until 1992.

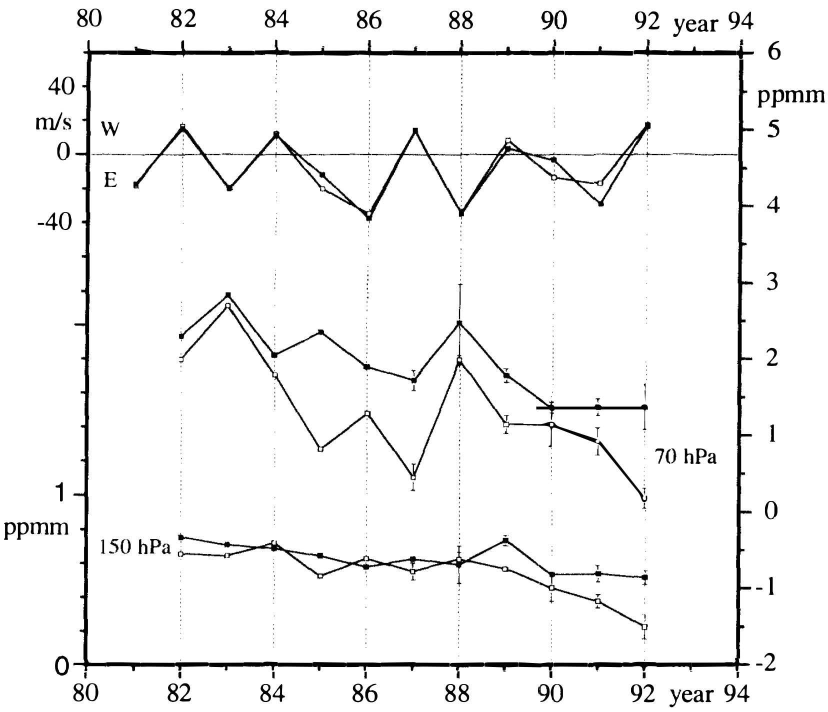

Fig. 4b. Same as Fig. 4a but for 70 hPa (right scale) and 150 hPa (left scale).

of the interannual variability of horizontal ozone transport into the vortex interior mainly at altitudes above the 20 hPa isobaric level.

Increasing and partially significant differences between the September and October MO3 means can be found at 10 hPa and at 20 hPa after 1988. September values are always smaller than corresponding October values. The decrease of ozone in September with regard to values before 1989 does not correspond to the QBO variations. Similar ozone losses in the 25–30 km altitude region have been observed over South Pole and McMurdo Stations in September and also in October 1991 (HOFMANN *et al.*, 1992). The earlier disappearance of this ozone loss over GF and SY, *i.e.* near the vortex margin, might be associated with vortex shrinkage and increasing ozone transport in October. These observations at South Pole and McMurdo as well as at SY and GF confirm that this ozone loss was extended over much and possibly all of the vortex area in 1991.

At 70 hPa the correlation to QBO phase variations are less pronounced. Both the September and October ozone mass mixing ratios show the development of PSC-related springtime ozone depletion until 1992 (Fig. 4b). At 70 hPa is a clear negative trend of decreasing MO3 in September. However, the rapid ozone loss from September to October each year shows a pronounced interannual variability. Considerable ozone losses can be seen from September through October in 1985, 1987 and 1992. They are smaller in magnitude from 1988 to 1991 and before 1985. The ozone reduction rate amounts to about −2 %/day to −3 %/day in 1985, 1987 and 1992 (Table 2).

At 150 hPa MO3 values seem to not be related to MO3 variations at greater altitudes or to QBO phases (Fig. 4b). Significant differences between September and October data appear after the eruptions of Pinatubo and Cerro Hudson in 1991, which increased the volcanic aerosol loading in the stratosphere. Furthermore, the comparison with data before 1982 (Fig. 3c) possibly suggests an impact of volcanic aerosols on stratospheric ozone, especially at these low stratospheric altitudes lasting several years.

4. Discussion

Year-to-year variability of zonal mean geostrophic winds in the southern hemisphere from 1980 to 1989 has been investigated by SHIOTANI *et al.* (1993). Global geopotential heights were derived from the Stratospheric Sounding Unit of TIROS-N/NOAA satellite observations. Although major warmings hardly occur, large variances during winter and spring can be seen in this analysis. The maximum variance appears around 60°S in spring. During late winter and spring, until the vortex breakup in November, the core of the westerly jet moves poleward. This circulation pattern is generally consistent with a possible strong impact on the polar stratosphere in spring. We have found signals of the QBO phase variations on potential temperature and on ozone inside the vortex for the same period. Both results show that a dynamic impact is controlling the ozone variations and possibly the chemical ozone loss in spring. Processes responsible for these interactions are not well specified so far. The present study of long-term interannual ozone variations is a first attempt at a qualitative assessment, which ought to be considered for more detailed investigations.

A basic interpretation of the results from a dynamic viewpoint might be as follows. Assuming that the polar vortex is fairly symmetric and planetary wave activity is relatively weak, it is appropriate to consider a zonal mean model as a first-order approximation to the vortex circulation. In this context the similarity of the mean vertical ozone distributions observed at SY and GF (Fig. 1) is assumed as the zonal mean at 71°S between 10°W and 40°E. Monthly mean ozone data from one station as well as means from two stations, *i.e.* SY and GF or SY and NM, show signatures possibly controlled by global dynamic processes. During the westerly phase of QBO the lower ozone mixing ratios at the isobaric levels of 20 hPa and above might be explained by lower planetary wave activity, *i.e.* less horizontal transport of ozone into the vortex interior at these heights during these years. SCHOEBERL *et al.* (1992) found a strong poleward gradient of the poleward horizontal velocity of residual mean meridional circulation by analysis of AAOE data (Airborne Antarctic Ozone Experiment) for August and September 1987. It is suggested by them that the latitudinal poleward gradient of meridional velocities (v^*) causes significant vertical downward motions at the poleward side of the vortex edge in view of mass conservation. Thus, it is supposed that, possibly, a dominant impact of global circulation processes to the lower levels inside the vortex might be explained in a two dimensional framework by the "downward control" principle (HAYNES *et al.*, 1991). This interpretation anticipates low eddy activity in the lower stratosphere while higher eddy activity in the upper stratosphere and the mesosphere occurs in the southern polar atmosphere in spring. Then the QBO signal in the MO3 values at 20 hPa and 10 hPa might be explained by horizontal transport into the vortex. Because of the downward principle, vertical transport possibly controls the ozone reduction rates from September through October as it is seen at 70 hPa (Fig. 4b). Following the results of our long-term analyses this global dynamic impact into the southern polar stratosphere must have a considerable interannual variability and could control in a certain part the yearly development of the spring ozone depletion.

Below these dynamically controlled altitudes both September and October MO3 data show the development of the normal PSC-related springtime depletion since the beginning of the 1980's. The rapid ozone loss from September through October amounts to more than −2 %/day in 1985, 1987 and 1992 (Table 2). Similar reduction rates of about −2.33 %/day, however, for September have been obtained by sensitivity calculations for the chemical destruction of ozone in the southern polar stratosphere (Crutzen *et al.*, 1992). These model studies show that rapid ozone depletions can occur with increasing solar radiation. The model results are in accordance with observations in the years 1985, 1987 and 1992. During the other years the observed ozone loss is smaller. Assuming that the chemical preconditions have been similar each spring in accordance with the sensitivity calculations by Crutzen *et al.* (1992) after 1985, we suppose a stronger dynamic impact down to 70 hPa at the poleward side of the stratospheric vortex during the other years.

At 150 hPa the possible direct interaction between volcanic aerosol or its converted compounds and ozone is considered but not yet completely understood. Strong ozone losses were observed after 1990. The ozone loss until October related to September values amounts to about −30% in 1991 and about −56% in 1992 for the "regional zonal mean". Considering only SY data, this ozone loss amounts to about −30% in 1991 and about −72% in 1992. Similar ozone reductions in the 11–13 km altitude region were observed at South Pole and McMurdo Stations in 1991 (Hofmann *et al.*, 1992; Deshler *et al.*, 1992). It is proposed by them that it is also heterogeneous ozone loss associated with volcanic aerosol loading after the Cerro Hudson eruption (Deshler *et al.*, 1992). The data of GF, SY and NM confirm these observations for the 150 hPa isobaric level. The strengthening of this ozone loss at these altitudes one year later in 1992 (Fig. 3c and 4b), as predicted by Hofmann *et al.* (1992), confirms this interpretation.

5. Conclusions

Using ozone sounding data of SY, a first qualitative assessment of stratospheric ozone variations on the poleward side of the stratospheric vortex jet core was made for October from 1966 to 1992. Similar geographical locations of the stations Syowa, Georg Forster and Neumayer with regard to the stratospheric vortex enable us to complete missed data at one place by data gained at other places in order to obtain a continuous pattern, *i.e.* "regional zonal mean", of the interannual ozone variations in the lower stratosphere for the period 1982 until 1992.

Signals of long-term as well as height-dependent correlations between MO3, eddies of potential temperature (SD) and the phase of QBO give qualitative evidence of the narrow interaction between global circulation, meridional transport of ozone and its chemical loss inside the southern polar vortex in September and October.

The standard deviations (SD) of monthly mean potential temperatures calculated from daily radiosonde measurements show signals correlated to the phase of QBO. This coupling seems to be height dependent during the considered period from 1966 until 1992. The correlation between isobaric levels generally changes from 1982 through 1985 in altitude and periodicity. It should be noticed that after this change the spring ozone depletion appeared, with a growing trend.

Acknowledgments

H. GERNANDT is highly obliged to Prof. T. HIRASAWA and Prof. T. YAMANOUCHI for providing the possibility of a working stay at NIPR in 1993, which was supported by the Ministry of Education, Science and Culture of Japan.

Thanks are due to S. KANETO, Japan Meteorological Agency, for kind support in preparing radiosonde and ozonesonde data gained at Syowa Station and to B. Naujokat, Meteorologisches Institut–FU Berlin, for providing updated QBO data. Grateful thanks are also due to G. KÖNIG-LANGLO and TH. SCHUMANN for participating in quality checks of ozone data gained at Georg Forster Station. Thanks for helpful assistance in performing the ozone sounding program at Georg Forster Station from 1985 to 1992 is addressed to the German expedition staff and to the aerological staff of the Antarctic station Novolazarevskaya (Arctic and Antarctic Research Institute, St. Petersburg).

Contribution number of the Alfred-Wegener Institute: 755

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(Received January 24, 1994; Revised manuscript received April 4, 1994)