TEMPORAL DEVELOPMENT OF THE CORRELATION BETWEEN OZONE AND POTENTIAL VORTICITY IN THE ARCTIC IN THE WINTERS OF 1988/89, 1989/90 AND 1990/91

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ABSTRACT

Ozone sonde data of the winters 1988/89, 1989/90 and 1990/91 from a group of Arctic stations are used in this study. The ozone mixing ratio on several isentropic surfaces is correlated to the potential vorticity (P). The P is based on the initialized analysis data from the European Centre for Medium-Range Weather Forecasts. Similar investigations were made by Lait et al. (Geophys. Res. Lett., 17, 521–524, March Supplement 1990) for the AASE campaign (January and February 1989), showing how the ozone mixing ratio varies with the distance to the edge of the vortex. Their findings are confirmed and extended to the following two winters. Furthermore we have studied the temporal development of the P-ozone correlations during these winters in order to recognize any chemical ozone depletion.

1. INTRODUCTION

The study of the temporal development of ozone within the winterly Arctic vortex is more difficult than within the Antarctic vortex of winter and spring for two reasons. First the seasonal effect of ozone depletion in the Antarctic is much more pronounced and second the vortex is much more stable. Up to now the ozone content in the Arctic vortex is much more influenced by dynamical than by chemical processes in contrast to the southern counterpart.

To separate dynamical from chemical processes several groups reported case studies of limited measurements often performed only at one location (e.g. Hofmann and Deshler [1991], Koike et al. [1991]). In this paper we present ozone mixing ratios (X) derived from 610 ozone soundings at 15 locations during the time periods November - March of the winters 1988/89, 1989/90 and 1990/91. A statistic of the launches is given in Table 1. For our purpose we turn from the three dimensional spherical coordinate space to a two dimensional space whose coordinates are given by the potential temperature θ and potential vorticity P (see next section for definitions). In this sense θ substitutes height, P geographic latitude, while for the missing third coordinate, substituting geographic longitude, means are taken. P could be understood as a measure of the distance to the vortex border as it is in general increasing from low latitudes to the center of the vortex. Furthermore the temporal development of X is studied. It should be clearly pointed out that θ and P are only conservative quantities in respect to adiabatic and frictionless processes. Conclusions should therefore keep in mind that in a real atmosphere heating (cooling) processes and friction always occur.

2. METHOD

We use Ertels potential vorticity (P) given by:

$$P = -g\,\eta\,\frac{\partial\theta}{\partial p} \qquad (1)$$

where g is the gravity acceleration, η is the absolute isentropic vorticity, p is pressure and θ is the potential temperature.

The data used in the calculation are the 6 hourly T106 initialized analyses data from the European Centre for Medium-Range Weather Forecasts. They are available in 19 levels up to 10 hPa. Five isentropic levels are used here: 350, 425, 475, 550 and 700 K. The pressure on the θ-surfaces is determined under the assumption that the temperature varies linearly with $\log(p)$. The spatial derivatives are calculated using a centered difference scheme. This is not possible, however, for the vertical derivatives between the two top levels (10 hPa and 30 hPa) making P more inaccurate at 700 K and sometimes at 550 K. It should be noted that the fact that there are only few model levels available in the stratosphere generally makes the vertical derivatives and thus P somewhat approximate. P values are finally interpolated linearly to the mean time between launch and burst times of the respective sounding.

The edge of the polar vortex is defined as the place where the isentropic gradient of P is biggest. For simplicity approximate P values at the edge of the vortex on the different isentropic levels are available in Table 2. Because of the large gradient of P at the edge of the vortex a whole range of P values around the given number should be used for picking out the edge of the vortex.

TABLE 1. Stations with latitudes, longitudes and quantities of ozone soundings in different winters.

Station	°N	°E	88/89	89/90	90/91
Alert	82.3	−62.2	40	36	9
Heiss Island	80.6	58.1	10	-	-
Ny-Ålesund	78.9	11.9	33	29	55
Resolute	74.4	−94.6	29	21	6
Bear Island	74.3	19.0	28	15	9
Scoresbysund	70.5	−22.0	20	-	-
Egedesminde	68.7	−52.9	-	-	7
Kiruna	67.9	21.1	-	17	-
Sodankylä	67.4	26.6	14	27	23
Ammassalik	65.6	−37.6	22	-	-
Gardermoen	60.1	11.0	-	-	9
Lerwick	60.1	−1.2	32	-	-
Churchill	58.5	−94.0	18	18	4
Edmonton	53.3	−114.1	16	9	6
Goose	53.2	−60.2	22	18	8
Sum			284	190	136

For each isentropic level the calculated condensation temperature and pressure for PSC type I particles are shown in Table 2. For the saturation pressure of nitric acid over NAT (nitric acid trihydrate) the expression of Hanson & Mauersberger [1988] is used together with LIMS January mean values at 76°N for the nitric acid mixing ratio.

P was calculated for each ozone sounding and θ level. In Figures 1 and 2 dots denote the P values of single measurements of X or T (selected levels) in the specified θ level at the times of the ozone soundings. Fields of X or T in the P-time planes were calculated from the measurements and presented as isoline plots. Each measurement contributes to every place in the plane weighted by the exponential of the negative distance from the dot to that place. The unit distance in each direction is indicated by the radius of the circle in the upper right corner of the figures. In the time direction this unit distance amounts to 5 days, in the P directions it varies from 0.46 P-units (1 PU = 10^{-6} K m^2/kg/s) at θ = 350 K to 17 PU at θ = 700 K. The figures do not change significantly if other suitable weights are used.

3. INTERPRETATION

The stations of the ozone soundings usually did not cover the vortex well. But looking at time scales of one circulation period of the vortex (approx. 1 - 2 weeks) the X fields could be considered representative for that P part of the vortex if the measurement density (given by the dot density) is sufficiently high. This could not be noted for the temperature fields since T is not a conservative quantity at all. The temperatures in the figures represent some kind of coarse zonal mean temperature and should be used with care. Nevertheless the temporal change in the observed P values provides some information on the development of the vortex: In the winters 1988/89 and 1989/90 the mid winter vortex was strong and cold. In the former winter the final warming occurred already in mid February, while in the latter the vortex lasted into April [Naujokat et al., 1989 and 1990]. The winter 1990/91 had a very disturbed circulation. The vortex was weak and temperatures were high [Naujokat et al., 1991].

The Brewer-Dobson circulation necessary to maintain the dislocation of ozone from its primary source region in the middle tropical stratosphere is driven by diabatic heating. This circulation consists of rising motion in the equatorial regions, downward motion at the winter pole and a quasi horizontal motion between them. The primary source region for ozone is situated at about 10 hPa according to LIMS data. At this pressure the ozone mixing ratio has its maximum in the tropics and decreases towards the poles. The 700 K isentropic level is placed at about this height and the ozone mixing ratio is thus in general decreasing towards the poles. Therefore X is generally decreasing with P on this isentropic level as seen in the figures.

The downward motion in the Arctic stratosphere due to diabatic cooling enhances X on isentropes below the maximum of X. For this reason there is a general increase of X towards the pole on isentropes well below the region where X has its maximum. Outside the vortex the air is well mixed, so the meridional gradient of X along an isentrope is small. Inside the vortex X can just go on building up. That explains why X is generally increasing with P at 475 K and below as seen in the figures. This tendency is supported by Lait et al. [1990] for the winter 1988/89. The level of 550 K is a sort of transition region. Above 550 K (at 700 K) X is in general decreasing with P, while X is increasing with P below. At 550 K X seems to have a maximum at the edge of the vortex.

TABLE 2. Potential vorticity at the edge of the vortex (P) in P-units (1 PU = 10^{-6} K m^2/kg/s), condensation pressure for NAT (p_c), condensation temperature for NAT (T_c) and HNO_3 mixing ratio at the potential temperatures (θ) shown.

θ (K)	P at edge (PU)	p_c (hPa)	T_c (C)	HNO_3 (ppbv)
700	160	10	−87.3	5.0
550	70	25	−81.4	10.5
475	36	44	−78.5	9.5
425	21	67	−76.5	7.5
350	no edge	140	−73.4	3.5

It is worthwhile to mention that any correlation between X and P on θ levels does not automatically denote the same correlation between the ozone concentration and P on the same levels. The neutral air density (ρ) is proportional to $T^{2.5}$ in adiabatic processes. Since T is in general lower in the vortex than outside the vortex a positive X, P correlation could easily direct a negative ρX, P correlation. This is the reason why the ozone column density inside the vortex is usually less than outside the vortex even as the positive X, P correlation holds over the maximum concentration region of the ozone layer.

In the Arctic winter stratosphere ozone is well conserved in the absence of catalytic destruction - probably better than P. From the figures it is evident that X in general is increasing with time for constant P and θ. There are some remarkable cases where on the contrary there is a fast decrease of X for constant P and θ. They occur inside the vortex after periods with temperatures low enough for PSC's to form. The critical temperatures for PSC condensation on the different isentropic levels are available in Table 2. At the 700 K and 350 K levels temperatures were not low enough for PSC's to form (not evident from data presented here). In 1988/89 at 475 K and 60 PU there is a decline in X from 3.4 to 3.0 ppmv within about 13 days in the first half of February. Usually P is considered approximately conserved for 1 to 2 weeks in the lower stratosphere. In this case ozone reduction amounts to 1.0 % per day not inconsistent with chemical depletion rates reported by McKenna et al. [1990]. In the winter 1989/90 the most rapid ozone reduction at 475 K and 425 K occurs as late as in the beginning of March where the vortex was still intact and there are large amounts of sunshine to drive the ClO dimer cycle. It is questionable though, if the ClO presumably produced much earlier when temperatures where low, has not been converted to its reservoir substances, $ClONO_2$ and HCl. In the winter 1990/91 temperatures were so high that very few PSC's were possible, and X continued its increase with time throughout the winter for constant P and θ.

4. CONCLUSION

For all three winters investigated it is evident that X (the ozone mixing ratio) changes substantially with P (the potential vorticity) on an isentropic level. At 475 K and below X and P are positively correlated while there is a negative correlation at 700 K. This is easily explained qualitatively by the Brewer-Dobson circulation and LIMS data. The substantial change of X with P means that observations from a particular station have to take movements of the polar vortex into account before addressing the question of a possible ozone depletion. Hofmann and Deshler [1991] claim that ozone depletion is evident in ozone mixing ratios in the 22 km region obtained with ozone soundings made in Kiruna in January and February 1990. Our results show that such a conclusion is not justified without taking the movements of the vortex into account.

However, there are some periods where X decreases rapidly for constant P and θ. These periods occur inside the vortex after periods where the temperatures were low enough for PSC's to form. They might be caused by chemical destruction of ozone, but our results do not make this conclusion certain due to the non conservation of P.

A P-θ mapping of ozone has often been used to extend observed mixing ratios to regions where no observations are available. The figures presented in this paper give an indication of the validity of such an approach.

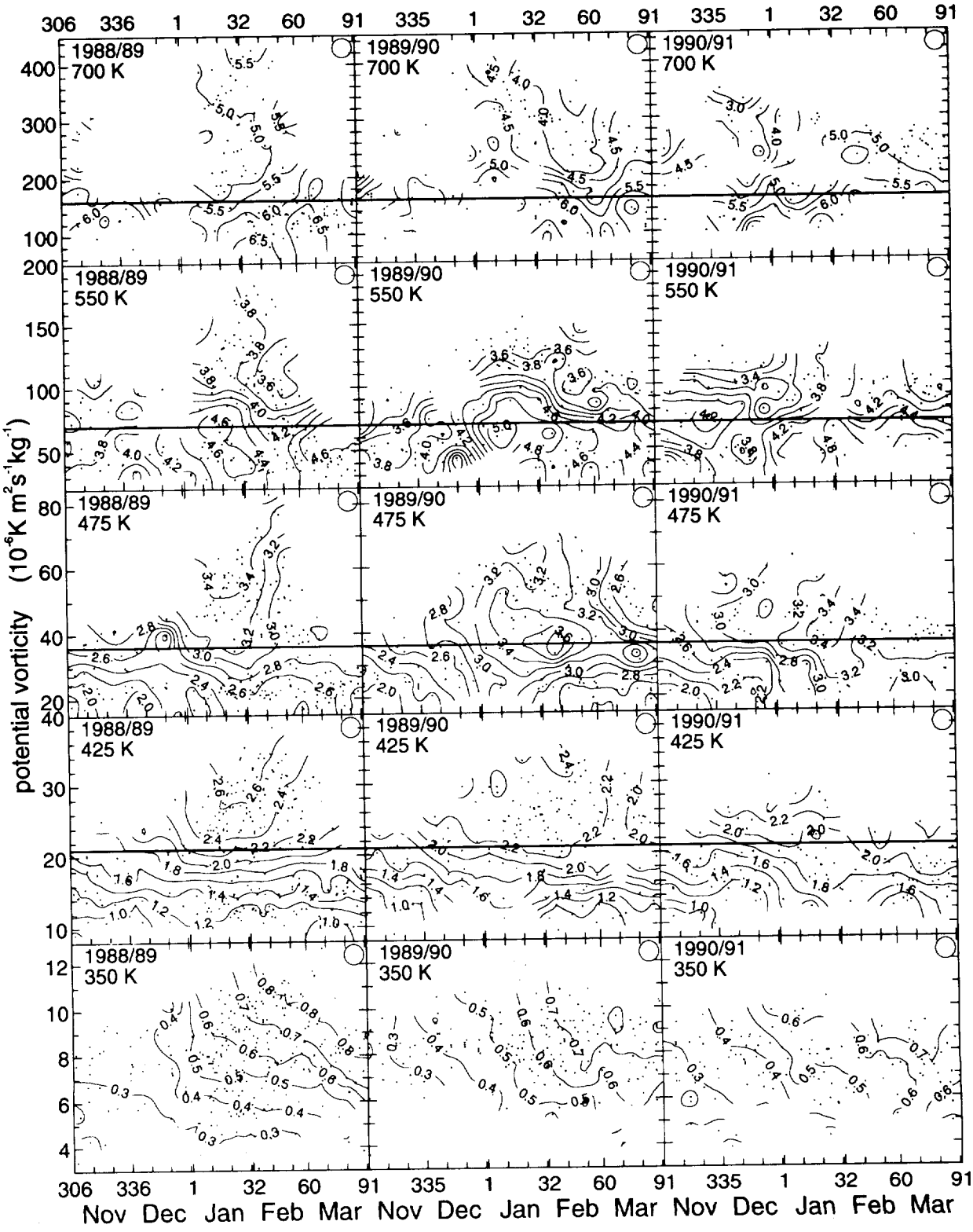

Fig. 1 Ozone mixing ratios in ppmv at different potential temperatures levels. Day 1 denotes 00:00 of 1. January. The horizontal thick lines indicate approximate P values at the vortex edge. For more information see text.

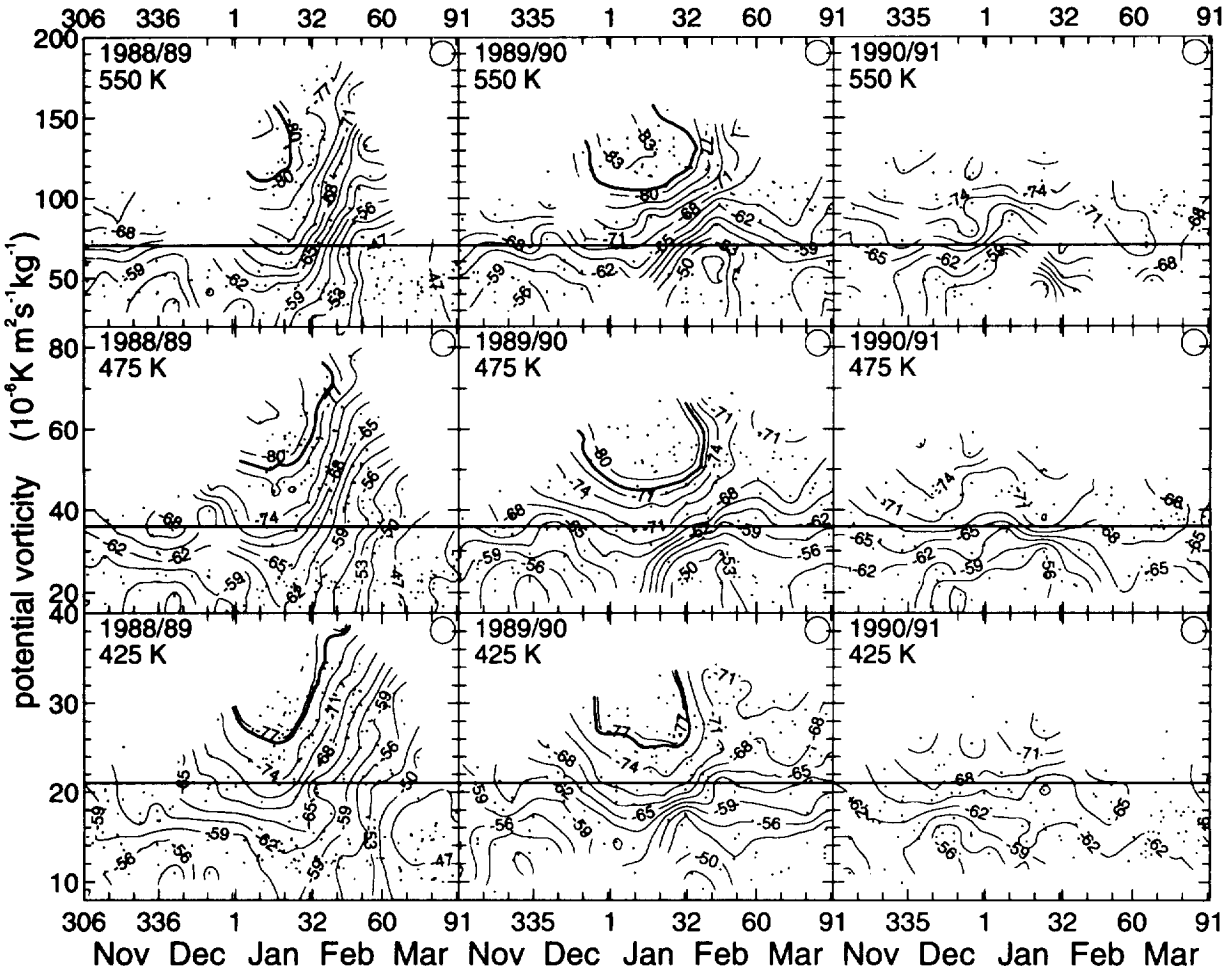

Fig. 2. Temperature distribution in °C at different potential temperatures levels. Day 1 denotes 00:00 of 1. January. The horizontal thick lines indicate approximate P values at the vortex edge. The other thick lines mark the border to temperatures below the condensation temperature of NAT as listed in Table 2. For more information see text.

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