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# Dynamical contribution to formation of an ozone mini hole in the Northern Hemisphere in mid-winter

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***Abstract:*** Ozone mini holes are localized and transient (several days) column ozone amount depletion phenomena which often appear over northern Europe. In early February 1989, the extremely low ozone value of 172 DU was observed by Total Ozone Mapping Spectrometer observation. Quantitative analyses of this event using a forward and backward trajectory method show that the total ozone depletion is by uplift of air throughout the lower stratosphere, whereas the effect of horizontal advection of ozone-poor air from lower latitudes is relatively small. Similar results are obtained for 4 other severe mini hole cases. However, these two dynamical effects cannot fully explain the total ozone depletion, which implies the existence of other possible processes responsible for ozone mini holes.

## 1. Introduction

Extremely low ozone events have sometimes been observed over northern Europe during recent mid-winter seasons. Such events occur in mid- and high-latitudes and extend over relatively narrow areas (say, $2\text{–}3\times10^3$ km) compared to the Antarctic ozone hole and are called "ozone mini holes". Moreover, these last for only a few days unlike the Antarctic ozone hole. For example, on 1 February 1989, a low total ozone of 172 DU (*e.g.*, Hood and Soukharev, 2001) was recorded over southern Scandinavia with the Total Ozone Mapping Spectrometer (TOMS) on board Nimbus 7 and lasted for a few days. As the mini hole was observed together with very low temperatures and Polar Stratosphere Clouds (PSCs), it is considered to be related to heterogeneous reactions (Wage, 1991; Bunn *et al*., 1991).

On the other hand, some studies have suggested the dominance of dynamical processes in such ozone mini holes. Petzoldt *et al.* (1994) noted the importance of vertical motions over anticyclonic disturbances in the upper troposphere connected with planetary wave activities. Hood and Soukharev (2001) investigated the linear regression between total ozone deviations from the zonal mean and corresponding 30 hPa temperature deviations for ozone minimum cases, and compared the result with an estimate based on a simplified steady transport model. Consequently they suggested a purely dynamical mechanism for these ozone minima. However, direct quantitative estimates of the dynamical contribution to the total ozone depletion have not been performed for each ozone minimum case, and the picture of the ozone mini hole has not been completed. This is partly due to the fact that the ozone depletion is plausibly connected with the heterogeneous chemistry connected with PSCs.

In this paper, we investigate severe ozone mini hole events with values under 190 DU during mid-winter of the Northern Hemisphere. We focus on dynamical processes in the ozone mini hole of early February 1989 as the possible main cause, and estimate the uplifting of air parcels throughout the lower stratosphere as well as horizontal advection of ozone poor air from lower latitudes by reconstructing the vertical profiles using a backward and forward trajectory method. We also investigate other severe events during mid-winter of the Northern Hemisphere.

## 2. Data

For the total ozone data, we used TOMS version 7 data which are available from November 1979 except for the period from November 1994 to July 1996. Assimilated data from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) (Kalnay *et al.*, 1996) and Met Office UK (Swinbank and O'Neill, 1994) were used for dynamical analyses. The former data set has 4 measurements per day from 1948, but it covers only the limited vertical region from 1000 hPa to 10 hPa. The latter data set covers the region up to 0.316 hPa, but only once daily data, and data are only available from November 1991. Quantitative analyses are performed for the ozone mini hole events by using ozone volume mixing ratio data measured by the Halogen Occultation Experiment (HALOE) instrument on board the UARS (Russell *et al.*, 1993). The data, HALOE version 19, are available from November 1991 and cover the region from approximately 10 to 65 km.

## 3. Synoptic features

As noted in the Introduction, the ozone mini hole on 1 February 1989 could be produced by both dynamical uplifting and additional ozone depletion due to heterogeneous chemistry.

In the lower stratosphere, time variations of isentropic surfaces correspond to the vertical displacement of air parcels, because potential temperature is approximately conserved for a few days following the advection of air parcels. Figure 1 shows the total ozone distribution around 1200 UTC for 4 successive days, from 30 January 1989 to 2 February 1989, in the Northern Hemisphere, together with height deviations on the 500 K isentropic surface from zonal mean values on the basis of the NCEP/NCAR data. We see good agreement between low total ozone regions and high isentropic surface regions throughout these 4 days. The ozone minimum region is stationary around Southern Scandinavia together with the height maximum region on the 500 K isentropic surface; on 1 February 1989, the ozone minimum reduces further, to 172 DU, with further rise of the isentropic surface.

Figure 2 illustrates time variations of isentropic surface heights (based on the NCEP/NCAR data) for a point in southern Scandinavia (20.0° E, 60.0° N), where the total ozone minimum was recorded on 1 February 1989, as a function of day and height. The climatological heights and widths of twice the standard deviations for each

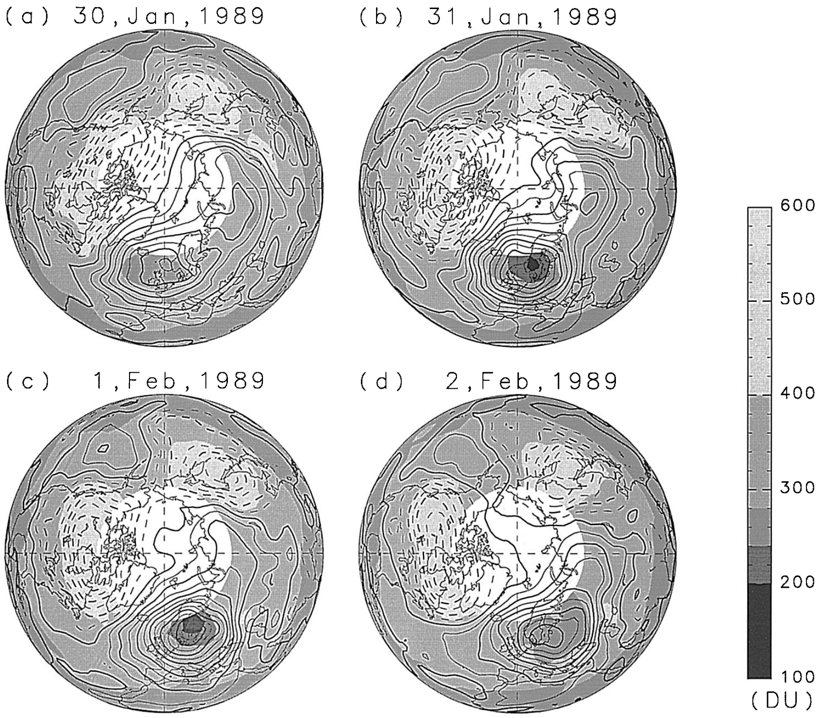

*Fig. 1. Distributions of the total ozone (shaded; see the tone bar) in Dobson Units (DU) and height deviations on the 500 K isentropic surface from zonal mean values (contoured) with 250 m contour intervals, for 4 days from 30 January 1989 to 2 February 1989. Solid contour lines mean positive anomalies (higher than zonal mean values).*

isentropic surface calculated for January and February of years from 1980 to 2000 are shown as well. We can see that isentropic surfaces are uplifted through a broader vertical range from 12 km to 25 km on 1 February 1989. For example, the 500 K isentropic surface on this day is higher than the climatological height by about 2.0 km. As a result, thicknesses of ozone-rich isentropic layers above that level are reduced while ozone-poor layers below that level become thick. Hence, extremely low total ozone can be caused by such a dynamical uplift of isentropic surfaces throughout the lower stratosphere; this effect is quantitatively investigated in Section 4.2.

## 4. Quantitative analyses

### *4.1. Analysis strategy*

As shown in the previous section, uplift of isentropic surfaces may have been an important mechanism for formation of the ozone mini hole on 1 February 1989. Hence, we examine the contribution of the uplifting effect to the total ozone depletion. In order to estimate the uplifting effect as simply as possible, we make the following assumptions:

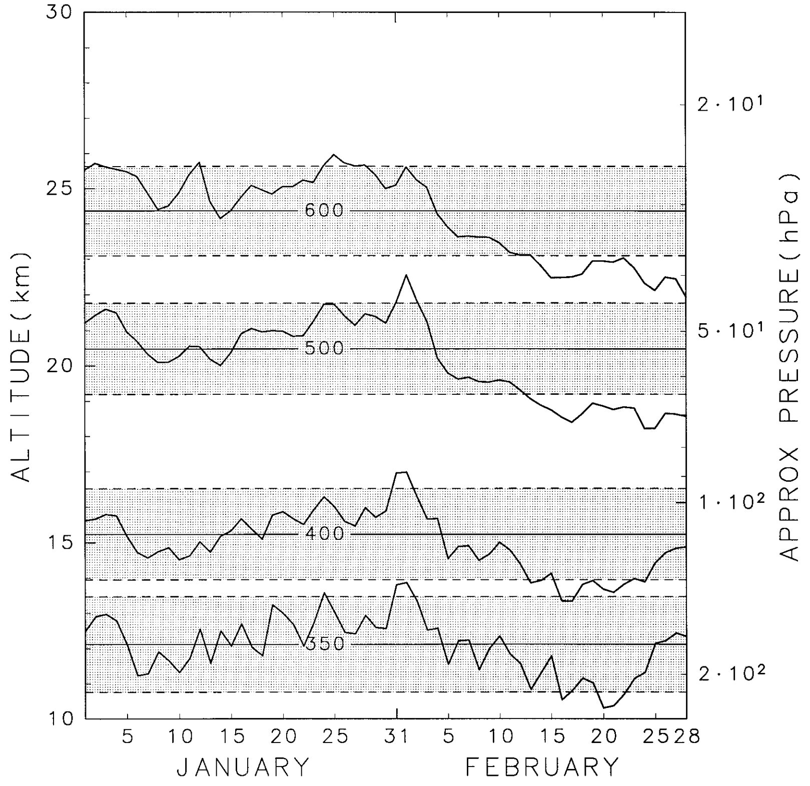

*Fig. 2. Time variations of isentropic surface heights from 350 K to 600 K potential temperature at a point of southern Scandinavia (20.0°E, 60.0°N). The climatological heights (horizontal straight lines) and range of twice the standard deviation (shaded) for each isentropic surface calculated for December and January of the years 1980 to 2000, are attached.*

(1) The climatologically estimated vertical profile of ozone mixing ratio $\chi$ as a function of potential temperature $\theta$ is kept constant in the lower stratosphere ($350 \leq \theta \leq 700$ K) throughout the advection.

(2) Air parcels are advected on each isentropic surface to be redistributed to different altitudes from the initial state owing to the vertical displacement of isentropic surfaces in the same vertical range. As a result, the vertical profile of $\chi(p)$ is changed from the initial state.

(3) In the middle and upper stratosphere ($p \leq 6.8$ hPa), where ozone is in photochemical equilibrium, the climatological vertical profile of $\chi(p)$ is maintained in spite of the vertical displacement of isentropic surfaces, and ozone mixing ratio values from the 700 K potential temperature level to the 6.8 hPa pressure level are calculated by linear interpolation.

(4) In the troposphere ($p \geq 464$ hPa), $\chi(p)$ is calculated on the supposition that the ozone density profile $n(p)$ has a constant value from the ground to the 464 hPa level where the mixing ratio $\chi$(464 hPa) is fixed to the climatological value. For the region from the 464 hPa level to the 350 K level, $\chi(p)$ is calculated by linear

interpolation.

Next, the total ozone value is estimated by vertical integration of the ozone mixing ratio $\chi(p)$.

### 4.2. 1 February 1989 event

Here, we apply the above method to the event on 1 February 1989. In Fig. 3, dashed lines indicate climatological vertical profiles of the volume mixing ratio $\chi(p)$ and the molecular number density $n(p)$. The climatological profile of $\chi(p)$ was calculated on the basis of the UARS/HALOE data averaged over the Northern Hemisphere for the periods from January to February of available years (1991–2000). We converted it to a number density profile $n(p)$ by the use of climatological temperature and geopotential height profiles (based on the Met Office data) at the southern Scandinavia point (20.0°E, 60.0°N), where the total ozone was extremely depleted on 1 February 1989. The

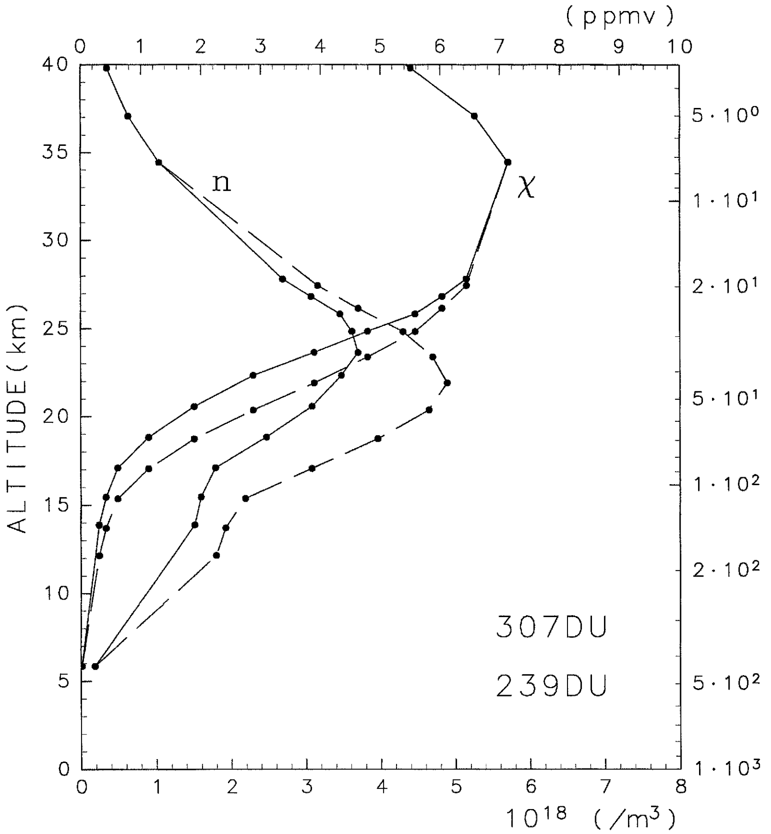

*Fig. 3. The calculated ozone profiles of volume mixing ratio $\chi$ and molecular number density $n$ at a southern Scandinavia point (20.0°E, 60.0°N). Climatological profiles are shown by dashed lines; the estimated total ozone is 307 DU. Uplifted profiles calculated from the dynamical profiles on 1 February 1989 are shown as solid lines; the estimated total ozone is 239 DU.*

resultant total ozone value amounted to 307 DU.

On the other hand, solid lines in Fig. 3 give vertical profiles of $\chi(p)$ and $n(p)$ calculated from the same climatological mixing ratio profile but using the dynamical field on 1 February 1989 (based on the NCEP/NCAR data), which shows the uplift of isentropic surfaces. Both the climatological ozone profiles (dashed lines) and the uplifted profiles (solid lines) are plotted to show the effect of vertical displacements of isentropic surfaces.

Comparing the uplifted profiles with the climatological profiles, we can see that the adiabatic uplift of the air in the vertical range from 350 K to 700 K causes the ozone mixing ratio to decrease greatly since it increases with height in this vertical range. Moreover, we can clearly see the severe decrease of the ozone number density around the maximum density region. The total ozone value for the uplifted profile is 239 DU, which means that the effect of the vertical uplift can account for 68 DU depletion of the total ozone. The ozone molecules which disappear from the vertical column are transported and redistributed in other places.

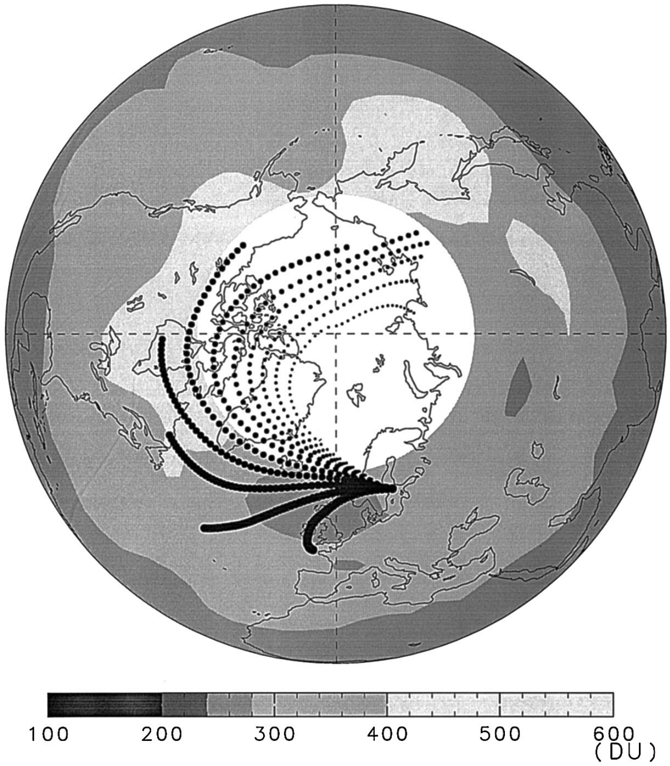

*Fig. 4. 2-day isentropic backward trajectories from 350 K to 700 K potential temperature originated from the ozone mini hole on 1 February 1989. Larger circles mean points on lower isentropic surfaces. Distribution of the total ozone on 30 January 1989 is depicted by the shading (see the tone bar).*

Moreover, we also investigated the horizontal advection of ozone. Ozone is transported on an isentropic surface not only vertically but also horizontally in the lower stratosphere. Figure 4 shows 2-day isentropic backward trajectories from 350 K to 700 K potential temperature surfaces from the point of the ozone minimum on 1 February 1989, which are calculated on the basis of the dynamical fields in the NCEP/NCAR data, together with the total ozone distribution on 30 January 1989. The trajectories at lower altitudes indicate the transport from lower latitudes where the ozone mixing ratio is small. It is considered that advection from lower latitudes can reduce the total ozone value further.

Hence, we examined the effect of horizontal advection on the total ozone depletion as well. At first we determined ozone mixing ratio values at each starting point on 30 January 1989 (shown in Fig. 4). Because there are no available vertical profile data at the starting points on this day, we estimated a global distribution of climatological ozone mixing ratio $\chi(x, y, z)$ on the basis of the UARS/HALOE data for December through March, and converted it into the one for 30 January 1989 $\chi(x, y, z, t_0)$ by linear adjusting of the climatological total ozone values to those at the starting points on that

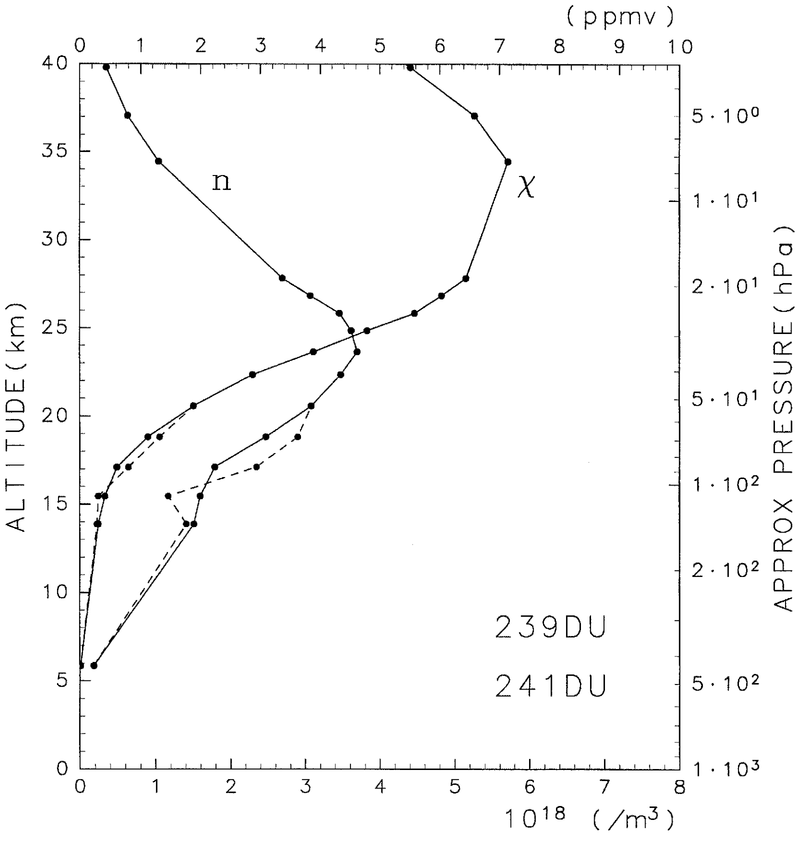

*Fig. 5. Size distribution, crystalline nature and morphology of ice pellets observed at Kiruna on December 20, 25–26, and 31, 1997 and January 3 and 4, 1998. The marks are identical with Fig. 2.*

day. These air parcels at each starting point are assumed to be transported forward along the trajectories (shown in Fig. 4) with the ozone mixing ratio kept constant in constructing the ozone profile on 1 February 1989. The values at starting points at high latitudes could not be determined because neither the UARS/HALOE data nor the TOMS data covered the high latitude region in winter. Hence, ozone mixing ratio values of the air parcel transported from such regions were assumed to be those of the uplifted profile (solid lines in Figs. 3 and 5). The resultant profiles are shown by dotted lines in Fig. 5.

As a result, we could estimate the effect of horizontal advection only from lower latitudes but not from higher latitudes, which corresponds to the advection at lower altitudes (below 20 km). The total ozone value is 241 DU; this is 2 DU larger than the value calculated with the uplifting effect only. In this case, the horizontal advection of ozone-poor air from lower latitudes seems to be compensated for by transport of ozone-rich air from northern Canada.

### *4.3. Other ozone mini hole events*

We investigated the TOMS data over the available period (1979–2000) and found other low total ozone events in the Northern Hemisphere during mid-winter. We picked up 4 severe depletion events which had depleted the total ozone value to under

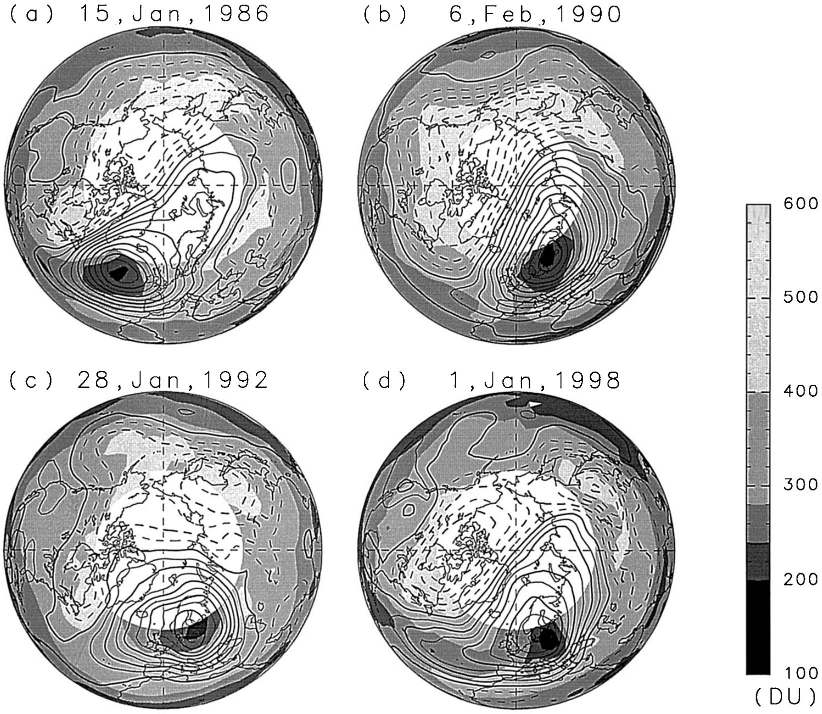

*Fig. 6. The same as in Fig. 1 for low ozone events with the values less than 190 DU but for (a) 15 January 1986, (b) 6 February 1990, (c) 28 January 1992, (d) 1 January 1998.*

190 DU during January and February, *i.e.*, (a) 15 Jan 1986, the minimum value 190 DU; (b) 6 Feb 1990, 184 DU; (c) 28 Jan 1992, 183 DU; (d) 1 Jan 1998, 181 DU.

Figure 6 shows total ozone distributions for these low ozone events together with the zonal height deviations on the 500 K isentropic surfaces as in Fig. 1. Substantially the same depletion mechanism as in the event on 1 February 1989 is considered to have formed these ozone depletion events because all happened in the same type of situation, *i.e.*, all were observed in mid-winter, located between the North Atlantic and northern Europe and appeared with the uplift of lower stratospheric air.

Table 1 shows the results of quantitative analyses for these 4 events and the total ozone values based on TOMS for comparison, *i.e.*, (A) TOMS minimum total ozone value; (B) Examined points nearby the occurrences of the minimum total ozone; (C) TOMS climatological total ozone at these points (B); (D) TOMS total ozone on the same day at the points (B); (E) HALOE climatological total ozone averaged over the Northern Hemisphere; (F) HALOE total ozone with uplifting effect; (G) HALOE total ozone added to the horizontal advection effect.

It is found that the uplifting effect accounts for ozone depletion of (a) 54 DU, (b) 58 DU, (c) 31 DU and (d) 43 DU, respectively. They correspond to 20–40% of the total ozone depletion. On the other hand, the horizontal advection effect is estimated to be (a) 11 DU, (b) 16 DU, (c) 4 DU and (d) 4 DU. Hence, the effect of horizontal advection is much smaller than the uplifting effect in these cases. Although we cannot compare these results directly with the actual values because we use the climatological profile $\chi(p)$ in the Northern Hemisphere, the estimated amounts of ozone depletion due to dynamical processes in the lower stratosphere cannot completely explain the ozone depletions. We discuss this problem in Section 5.

The 2-day isentropic backward trajectories from the ozone minimum points (shown in Fig. 4) for these ozone depletion events are shown in Fig. 7, together with the distributions of the total ozone on dates 2 days before each event. It is found that air parcels, which constitute the ozone profiles at the ozone minimum points, are trans-

*Table 1. Examined points and total ozone values in Dobson Units (DU). (A) TOMS minimum total ozone. (B) Examined points nearby the occurrences of the minimum total ozone. (C) TOMS climatological total ozone at the points (B). (D) TOMS total ozone of the day at the points (B). (E) HALOE climatological total ozone averaged over the Northern Hemisphere. (F) HALOE total ozone with uplifting effect. (G) HALOE total ozone added to the horizontal advection effect. The total ozone, except for (A), is the value at the examined points.*

| Date | 1 Feb. 1989 | (a)<br>15 Jan. 1986 | (b)<br>6 Feb. 1990 | (c)<br>28 Jan. 1992 | (d)<br>1 Jan. 1998 |
|---|---|---|---|---|---|
| (A) | 172 | 190 | 184 | 183 | 181 |
| (B) | 20.0° E 60.0° N | 27.5° W 52.5° N | 22.5° E 60.0° N | 22.5° E 57.5° N | 20.0° E 55.0° N |
| (C) | 348 | 330 | 335 | 349 | 325 |
| (D) | 180 | 192 | 190 | 188 | 181 |
| (E) | 307 | 298 | 307 | 307 | 293 |
| (F) | 239 | 244 | 249 | 276 | 250 |
| (G) | 241 | 234 | 233 | 272 | 246 |

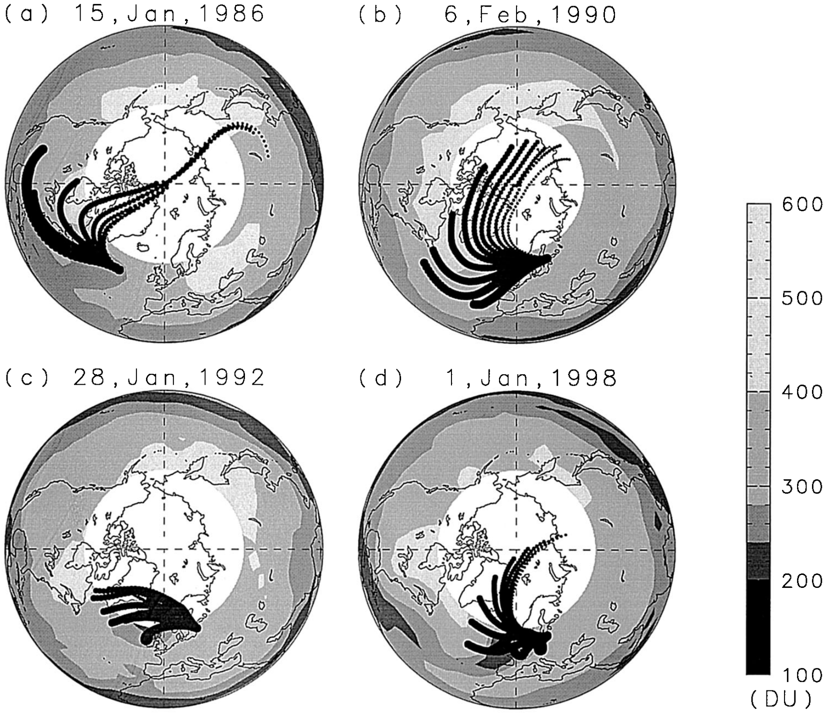

*Fig. 7. The same as in Fig. 5 but for low ozone events shown in Fig. 6. Total ozone distributions on dates 2 days before the events are also depicted by the shading.*

ported from lower latitudes in the lower stratosphere, and from the polar region in the middle stratosphere except for (c). The horizontal distribution of the ozone mixing ratio on an isentropic surface shows a larger positive northward gradient in the lower stratosphere of the Northern Hemisphere, and fluctuation of the ozone mixing ratio profile due to advection makes a larger impact on the total ozone value particularly in the lower stratosphere. Therefore, the effect of horizontal advection was stronger in events (a) and (b), in which air parcels were transported from much lower latitudes on the lowest isentropic surfaces.

## 5. Discussion and conclusions

The total ozone depletion on 1 February 1989 occurred over southern Scandinavia and lasted for a few days (Fig. 1). This event has characteristics similar to those of other extremely low total ozone events over mid- and high-northern latitudes in mid-winter (Fig. 6). In all these events, not only the 500 K isentropic surface (~20 km) but also the isentropic surfaces throughout the lower stratosphere were uplifted over the same place where the ozone depletion occurred (Fig. 2).

We estimated quantitatively the dynamical effects which could cause reduction in total ozone, using TOMS total ozone data and UARS/HALOE ozone volume mixing ratio data, by investigating vertical displacements of the isentropic surfaces and isentropic backward trajectories in the lower and middle stratosphere. According to this analysis, the effect of the uplift in the lower stratosphere (350 K–700 K) depleted the total ozone by 20–40%; the contribution of this effect appears to be somewhat unsatisfactory to explain the entire total ozone depletion. Even though the effect of horizontal advection from the lower latitudes was included, the dynamical process could explain only half of the ozone depletion at most. Especially for the event on 28 January 1992, only 23% of the total ozone depletion was explained.

There may be other dynamical effects which we did not include in this study, *e.g.*, horizontal advection from the polar region. This factor might explain some of the ozone depletion, because the ozone distribution on an isentropic surface in the middle stratosphere shows a poleward decrease, in contrast to the ozone distribution in the lower stratosphere. Moreover, it is possible that other ozone depletion processes work around the region where isentropic surfaces are uplifted. For example, heterogeneous chemistry, as was indicated by Bunn *et al.* (1991), can be included to obtain more satisfactory results. The adiabatic cooling associated with the uplift may lead to a decrease in temperature below the threshold for the formation of PSCs. This must be studied as a future problem.

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