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A very deep ozone minihole in the Northern Hemisphere stratosphere at mid-latitudes during the winter of 2000

By N. SEMANE, H. TEITELBAUM* and C. BASDEVANT, *Laboratoire de Météorologie Dynamique, École Normale Supérieure, 24 rue Lhomond, 75231 Paris cedex 05, France*

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ABSTRACT

Ozone miniholes appear on total ozone maps as localized ozone minima with horizontal extents of a few hundreds of kilometres. They are characterized by a rapid and small-scale appearance of a columnar ozone decrease with an equally rapid recovery after a few days. They are frequently observed at Northern Hemisphere mid-latitudes in winter. Evolving too rapidly to be the result of an ozone chemical destruction, miniholes should be the result of meteorological processes. According to some authors, miniholes should be due to the northeast motions of air patches with low total ozone content. However, several studies attribute the formation of ozone miniholes to the uplift of air masses, which decreases the ozone columnar content by simply decreasing the pressure thickness of the ozone layer, without changing the mixing ratio. According to these studies, the latter mechanism explains the main reduction of ozone that occurs between the tropopause and the ozone maximum during an ozone minihole event. A region of extreme low ozone values passed over Europe from 27 to 30 November 2000. The total ozone values were measured with the Total Ozone Mapping Spectrometer (TOMS). A radio sounding, launched on 29 November 2000 from Payerne at the place and time of the deepening of the minihole, allows us to perform a detailed analysis of its formation mechanism. It is shown that the uplift of isentropic surfaces plays an important role in the columnar ozone decrease and explains the lower part of the depleted ozone profile. However, the deepening of the minihole is explained by another mechanism: namely, at this time the minihole air column intersects the polar vortex at high altitudes and then encounters ozone-poor air masses.

1. Introduction

Rapid and small-scale decreases in total ozone content are often observed in winter in the mid-latitudes of both hemispheres (James, 1998). The typical duration of these events is of the order of 1–5 d. They have been named ‘miniholes’ because of their relatively small horizontal scale (1000–3000 km) with respect to the wider polar ozone hole (Newman et al., 1988). Given the negative correlation between total column ozone and harmful solar UV-radiation levels reaching the surface, ozone miniholes are important phenomena to understand.

The rapidity of changes in ozone concentrations during minihole events excludes chemical processes as causes of the formation of miniholes (Petzoldt, 1993). Having ruled out chemical reactions we must concentrate on purely dynamical contributions for minihole formation. Early last century, Dobson et al. (1929) stated that total column ozone levels undergo substantial local short-term fluctuations that closely correlate with the passing of synoptic weather systems. Later, Reed (1950) showed that these fluctuations were part of synoptic-scale regions of depleted ozone being advected under the influence of tropospheric

* Corresponding author.
e-mail: teitel@lmd.ens.fr

dynamics. Peters et al. (1995) suggested that miniholes could be due to northeastward motions of air patches with low ozone content coming from subtropical latitudes. Unlike these authors, McKenna et al. (1989) showed that the low ozone air within the minihole is not a material entity, but the consequence of a local distortion of the flow. To forecast the level of harmful UVB radiation, Spänkuch and Schulz (1995) searched for reliable relations between total column ozone and suitable meteorological parameters. They used with some success temperature gradient and geopotential height. Hoinka et al. (1996) found that 50% of the total columnar ozone variation can be explained by variations in the tropopause pressure, and Steinbrecht et al. (1998) found a general ozone column decrease of 16 Dobson Units (DU) per kilometre increase of tropopause height. The decrease of total ozone column due to upwelling of air masses was first presented by Salby and Callaghan (1993).

While the dynamical processes associated with a minihole act mainly to redistribute ozone molecules within the lower stratosphere over the timescale of a few days rather than to destroy them, their influence on the total column amount is significant. When an isentropic layer is displaced upward, the ozone density decreases by adiabatic expansion (Teitelbaum et al., 1998). The lifting of isentropic surfaces above an anticyclone leads to the divergence of ozone-rich stratospheric air out of the column (and thus to a lower total ozone column amount above that location) and causes adiabatic cooling of air parcels flowing along these surfaces (McCormack and Hood, 1997). A geographical correlation between Ertel potential vorticity (EPV) trends at 330 K and ozone trends has been found by Hood et al. (1999) for the months of February and March over the period from 1979 to 1998. This result has been obtained using National Centers for Environmental Prediction (NCEP) analyses and Total Ozone Mapping Spectrometer (TOMS) data. Teitelbaum and Sadourny (1998) and Teitelbaum et al. (2001), in their studies of the polar stratospheric clouds (PSC) and their associated miniholes in both hemispheres, showed that in all cases the main cause of both phenomena was a synoptic upwelling of isentropic surfaces that dilutes the ozone and cools the air masses. These results were obtained using European Center for Medium-range Weather Forecasts (ECMWF) analyses and Tiros Operational Vertical Sounder (TOVS) data.

Our purpose in this paper is to highlight the causes of the formation of a very deep ozone minihole recorded by TOMS during 28 and 29 November 2000 over Europe. As in other studies and with the help of ECMWF analysis, we will show that this ozone minihole appeared within an upward displacement of isentropic surfaces induced by an anticyclonic isentropic potential vorticity (IPV) flow anomaly. Three-dimensional forward trajectories are used to study the displacement of the air masses starting from the column of low ozone content. The trajectory results will confirm that the horizontal transport plays no role in the minihole formation. The fact that above 540 K the air column belongs to the edge and even the interior of the vortex explains the very low value of the ozone content.

Moreover, we use simultaneous data of ozone, temperature, pressure and altitude obtained by in-situ soundings in order to investigate the invoked mechanism. In fact, with an original approach, we will show a significant contribution of adiabatic rising to the reduction observed in the ozone profile during the minihole event of 29 November 2000.

In Section 2, we show the contribution of the adiabatic uplift mechanism in the formation of the studied minihole by using ECMWF analyses, trajectory calculations and ozonosonde data. However, as this mechanism does not explain the entire decrease of the stratospheric ozone, we show in Section 3 that the decrease in the upper part of the ozone profile can be explained by the fact that at these altitudes the air column travels through the edge of the polar vortex.

Finally, some comments and conclusions are given in Section 4.

2. The adiabatic uplift mechanism

The evolution of the ozone minihole we studied is displayed in Fig. 1, where columnar ozone maps given by TOMS are shown. The minihole is clearly seen on 27 November 2000 over Spain (Fig. 1a); the minimum of ozone depletion is then about 215 DU. The minihole intensifies when crossing France during 28 and 29 November (Figs. 1b and c); at that time, the ozone minimum is then lower

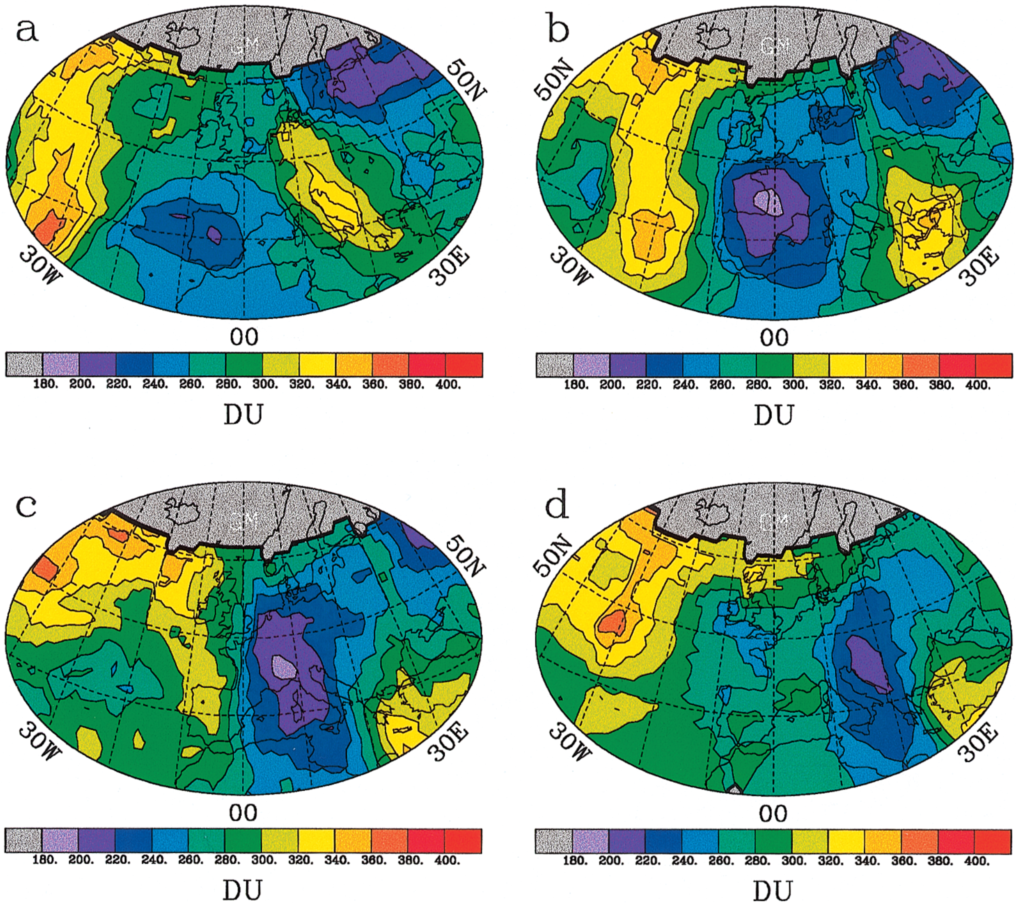

Fig. 1. TOMS total ozone maps for (a) 27 November 2000, (b) 28 November 2000, (c) 29 November 2000 and (d) 30 November 2000 (Dobson Units).

and reaches 195 DU. On 30 November (Fig. 1d) the ozone minimum returns to a value close to the 27 November value, the minihole at this time being over eastern Europe.

We will first stress the importance of the uplift mechanism in the formation of the minihole that appears as a localized total ozone decrease. To this end Fig. 2 displays the geopotential height maps on the 475 K isentropic surface obtained from ECMWF analyses, for 28 and 29 November 2000. The crosses on the maps indicate the position of the minihole. The comparison of ozone maps and geopotential height in Figs. 1 and 2 for corresponding days clearly show the strong correlation between the uplift of the isentropic surface and the appearance of the minihole. The fact that the uplift of air masses causes an ozone flow out of the observed column has already been noted by other authors (McKenna et al., 1987; Salby and Callaghan, 1993; Teitelbaum and Sadourny, 1988; Teitelbaum et al., 2001). We can add that the anticyclonic IPV flow anomalies (not shown) are localized near the tropopause in the same geographical places (Teitelbaum et al, 2001). These anomalies are consequences of the deformation of IPV isolines by synoptic scale waves (Hoskins et al., 1985).

As in the case studied in Teitelbaum et al. (2001) we are observing a minihole that moves in time toward east. If the minihole were a consequence of the advection of an air mass coming from regions of low ozone content, its trajectory should

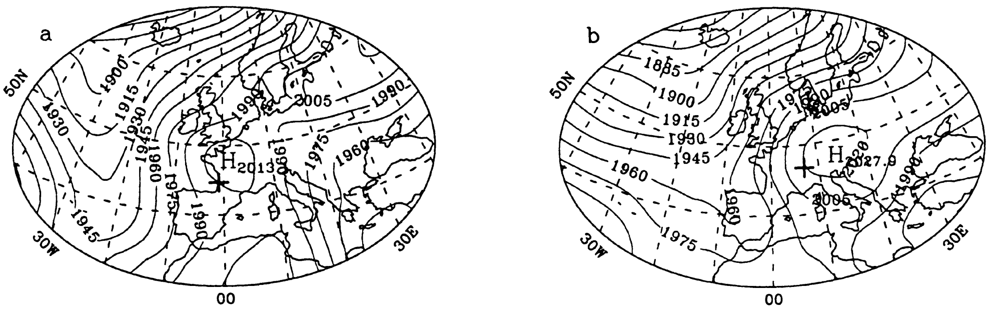

Fig. 2. Geopotential height isolines on the 475 K isentrope for (a) 28 November 2000 and (b) 29 November 2000. Contour interval is 15 dam. Crosses indicate the centres of the observed minihole at the same days. The symbols H and L indicate the places of the highest and lowest values of geopotential height.

follow this air mass. Figure 3 demonstrates that this is not the case. On this figure forward trajectories are plotted for three days starting from the minihole location on 27 November. These are three-dimensional trajectories, computed with the help of the FLEXTRA trajectory model (Stohl, 1999). They have been computed from three initial levels (18, 20 and 22 km) covering the altitude range that contributes most to the total ozone column. The trajectories clearly show that the speed and the direction of the air mass displacement are completely different from those of the minihole (represented by successive X-symbols on the drawing). We can therefore conclude that the low-ozone column within the minihole is not a material entity advected by the flow, but is essentially the signature of the anticyclonic IPV anomaly in the minihole region.

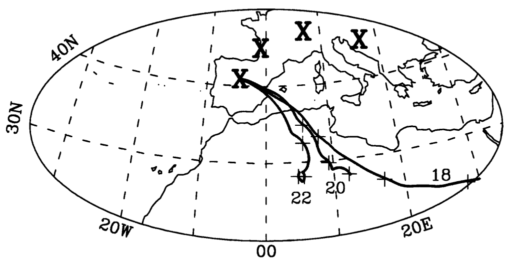

Fig. 3. Air-mass trajectories starting from the 18, 20 and 22 km levels. Trajectories start at 1200 UTC 27 November 2000 at the minihole location at that time. They end at 1200 UTC 30 November. The trajectories are labelled with their altitudes. The + symbol indicates, along the trajectories, the daily position after 27 November. The X-symbol indicates daily centres of the observed minihole (moving northeastward).

A new and strong argument for the interpretation of the minihole appearance can be obtained using ozone profiles.

On 11 UTC 29 November 2000 an ozonosonde was launched from Payerne (46.8°N; 6.9°E), a place close to the centre of the minihole on that day. This coincidence in time and place with the minihole event allows us to go deeply into the analysis of the phenomena with a very original approach. Figure 4a displays the ozone mixing-ratio profile as a function of altitude measured on 29 November (full line), compared with a profile measured at the same place on 20 November (dotted line). Among the days on which ozonosonde are available at Payerne we choose the 20 November because during that day the columnar ozone map (TOMS map) does not exhibit any special feature at this place and thus the ozone profile can be taken as representative of a standard situation. We can see, as expected, that the ozone mixing ratio is lower on 29 November than on 20 November all along the profile.

Figure 4b shows the same profiles as those in Fig. 4a, but now the ozone mixing ratios are plotted as a function of potential temperature. In this representation both profiles between 420 and 540 K are almost the same. The close similarity of the profiles, when plotted as a function of potential temperature, can be explained as follows. If an air parcel is displaced quasi-adiabatically, its potential temperature, as well as the mixing ratio of any passive minor constituent, is conserved; this is true even if the displacement is vertical. Clearly air parcels forming the column measured by the 29 November sounding are not the same as those

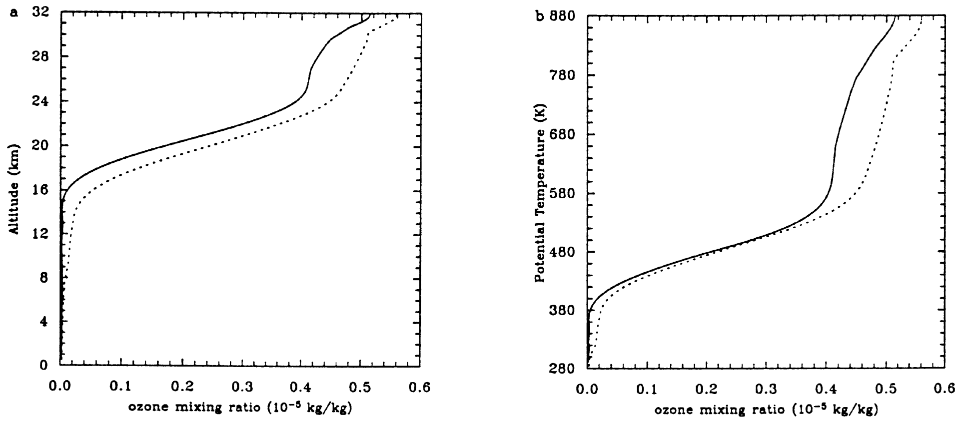

Fig. 4. Ozone mixing-ratio profiles measured by an ozonosonde launched from Payerne (48.6°N, 6.9°E) on 29 November 2000 (full line) and on 20 November 2000 (dotted line). (a) Ozone mixing-ratio profiles as a function of altitude. (b) Ozone mixing-ratio profiles as a function of potential temperature.

measured on 20 November at the same place. However, our hypothesis is that they result from the perturbation of a standard situation where the ozone mixing ratio is similar to the one of 20 November. Indeed, Fig. 4 is consistent with the fact that, flowing over a deformed isentropic surface, the uplift changes the partial pressure but not the mixing ratio.

All that has been shown above explains the decrease of ozone between 420 and 540 K levels and the minihole formation. We will show that the decrease of ozone above the 540 K level, which contributes to the minihole intensification, can be explained in another way.

3. The decrease of ozone at high altitude

It is well known that the surface area of the polar vortex, including its edge, increases with altitude. If we are concerned with an air column that is near the polar vortex, it can be simultaneously outside the vortex at its lower stratospheric layers and inside in higher layers. This is in fact what happens on 28 and 29 November, as can be seen in Fig. 5, where Ertel potential vorticity (EPV) maps have been drawn at 475 and 650 K levels for 27–29 November. EPV fields have been calculated using the relative vorticity and temperature fields provided by ECMWF analysis. On 28 and 29 November the minihole is outside the vortex at 475 and inside at 650 K. This explains why, in Fig. 4b, the higher part of the ozone soundings show an important difference in ozone mixing ratio above 540 K compared with the standard profile. (The air column above Payerne was outside the vortex at all altitudes on 20 November.) At these levels the ozone decrease is no longer a consequence of the uplift of isentropic surfaces but a consequence of its localization inside the vortex, a place where ozone depletion occurs, due to the impermeability of the vortex edge.

On the contrary, as also seen in Fig. 5, on 27 November (and also 30 November but not shown here) the minihole is outside the vortex at both levels. Unfortunately there are no ozone profiles available at the places where the minihole is found on these days (nor on 28 November). However, the positions relative to the vortex can explain why the total ozone minimum on these days is not as deep as on 28 and 29 November.

To show further the respective influence of the uplift of isentropic surfaces in the minihole formation and the vortex position in its intensification, Figure 6 displays isentropes (thin lines) and the 2.5 EPV units isoline (thick line) on a longitude/geopotential height cross-section at a fixed latitude. Figure 6a corresponds to 27 November and the latitude of the minihole that day (41°N). Similarly, Fig. 6b corresponds to 28 November and latitude 45°N. The 2.5 EPV units isoline indicates the height of the tropopause, which is, as expected for both dates, uplifted at the longitude where the minihole is found (4°W and 1°W,

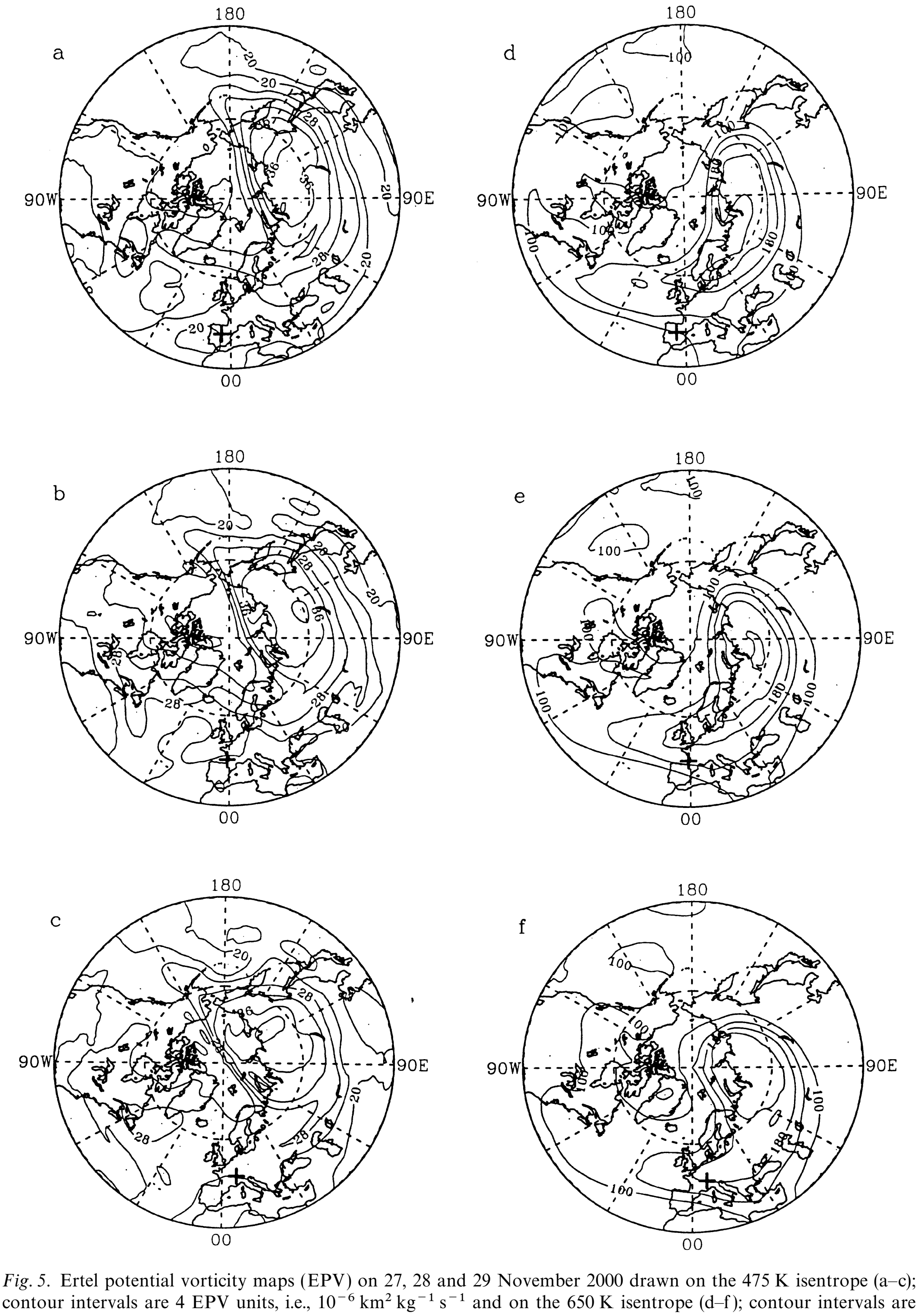

Fig. 5. Ertel potential vorticity maps (EPV) on 27, 28 and 29 November 2000 drawn on the 475 K isentrope (a–c); contour intervals are 4 EPV units, i.e., $10^{-6}\,\mathrm{km^2\,kg^{-1}\,s^{-1}}$ and on the 650 K isentrope (d–f); contour intervals are 40 EPV units. The crosses indicate the position of the centre of the observed minihole on the same days.

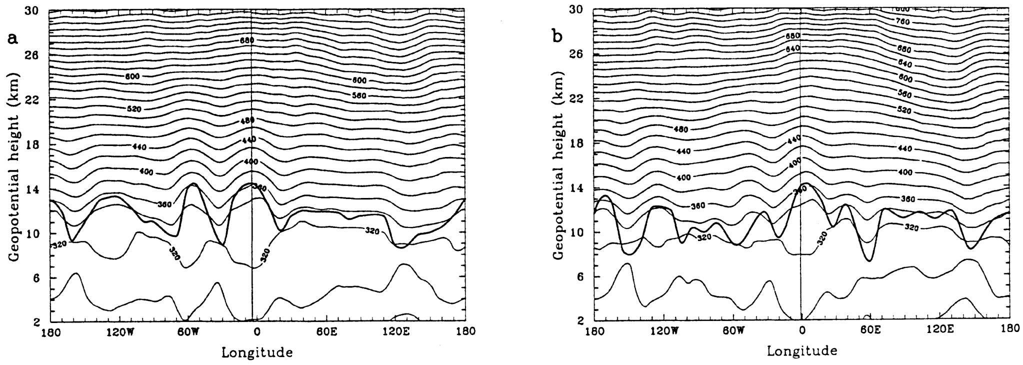

Fig. 6. Isentropes (thin lines) and 2.5 EPV units isoline (thick line), on a longitude/geopotential height cross-section (a) at 41°N for 27 November 2000, (b) at 45°N for 28 November 2000. The vertical lines indicate the positions of the observed minihole at the same days.

respectively). Isentropic surfaces are displaced upward above the tropopause and downwards below, as is the case in the occurrence of an anticyclonic IPV flow anomaly (Hoskins et al., 1985). The uplift of the isentropic surfaces is the main cause of the minihole in the case under study. However, it is also seen in Fig. 6 that the uplift is similar in amplitude for both days and thus cannot explain the minihole intensification on the later day. This is a confirmation that on days 28 and 29, the fact that the upper part of the air column is inside the vortex gives rise to the very exceptional minihole.

4. Conclusion

TOMS maps exhibit the evolution of an ozone minihole from 27 November to 30 November 2000 with an unusual reduction in total ozone over western Europe on 28 and 29 November.

The mechanism of its formation was studied with the help of ECMWF analysis, air-mass trajectory calculations and ozone in-situ measurements performed at the same place and day as the minihole. Inspection of isentropic surfaces confirms the role of the quasi-adiabatic uplift of air masses in the minihole formation, as has been shown by other authors. We also showed, using forward trajectories, that the minihole was not a material entity, but a consequence of a local distortion of the flow. In this case, the horizontal advection of air masses with low ozone content must be discarded as the main mechanism for minihole formation. With the data provided by an ozonosonde launched from Payerne, we confirmed the main role played by the uplift of isentropic surfaces. This was performed with an original approach that consists of comparing the ozone mixing-ratio profile in the minihole with a standard ozone profile, the mixing-ratio profiles being plotted as a function of potential temperature. The result is that both profiles are almost coincident in the lower stratosphere below 540 K, a result consistent with the quasi-adiabatic uplift. Above this level the profiles are very different during the intense phase of the minihole, and we explained this by the fact that, at that time, the minihole was situated, at high altitudes, inside the polar vortex.

To summarize, the very deep minihole observed on 29 November 2000 is not the consequence of the advection of a bubble of air of low ozone content air. It was created mainly by the local uplift of isentropic surfaces, and intensified in the encounter with the polar vortex.

5. Acknowledgements

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