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OZONE TRANSPORT DURING A CUT-OFF LOW EVENT STUDIED IN THE FRAME OF THE TOASTE PROGRAM

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Abstract

A study of ozone transfer to the troposphere has been performed during two phases of the evolution of a cut-off low using both ozone vertical profiles and objective analysis of the ECMWF to compute potential vorticity distributions and air mass trajectories. Ozone profiles were measured by a ground based lidar system at the Observatoire de Haute Provence (OHP, 43°55N, 5°42E). A stratospheric ozone transport into the troposphere has been observed during a tropopause fold which occured at the beginning of the cut-off low formation and during the erosion phase of the cut-off low. From the estimate of the maximum ozone content transfered to the troposphere, both mechanisms have the same order of magnitude of influence on the ozone flux to the troposphere. On a time scale of a few days, the correlation is very good between the potential vorticity and the ozone time evolution in the vicinity of the upper level frontal system.

1. Introduction

Air mass exchanges between the stratosphere and the troposphere must be understood to improve our knowledge of the tropospheric ozone budget. New progress in this field is dependent on the availability of experimental data of meteorological parameters and tracers like ozone. The european TOASTE experiment (Transport of Ozone and Stratosphere Troposphere Exchange) took place in 1990-1991 and aims at providing to modelling work a complete ensemble of experimental data obtained in meteorological systems which are likely to generate Stratosphere Troposphere Exchanges (STE). In this paper, we present ozone vertical profiles performed at the Observatoire de Haute Provence (OHP, 670 m, 43°55N, 5°42E) and meteorological analyses for one of the TOASTE case study to illustrate the impact of cut-off lows on STE. The role of cut-off lows is twofold: ozone transfer within the frontal system associated with the low and small scale mixing at the tropopause level over the whole surface of the low. The first mechanism was studied at the beginning of the TOASTE campaign (November 22nd to 25th, 1990) and the second one during the erosion phase of the cut-off low (November 27th to 30th, 1990).

2. The meteorological situation

The evolution of the meteorological situation during this campaign is illustrated by the 300 hPa maps of the geopotential heigths (Fig.1). They show that a low pressure system developed over France on November 22nd with the associated trough located over southern Spain at midnight. On November 23, a new low appeared south of Iceland causing a northward motion of the trough over Spain along a line going from Spain to Germany. The axis of the trough passed over the OHP during the afternoon of November 23rd and was directed on a line from Corsica to Paris. The circular motion of the two lows induced the formation of a large low pressure system over western Europe on November 24th. On the following days, this system moved southward and cut from the main jet stream on November 27th. The resulting cut-off low remained over France for 4 days before it reconnected to the general circulation flow.

3. Ozone Transfer within the frontal system

The ozone vertical distribution was measured by a UV DIAL lidar [Ancellet, 1989] almost continuously on November 23rd. The OHP lidar system uses two recording modes corresponding to two different altitude ranges: 4 - 7 km (analog mode), 7 - 13 km (photocounting mode). The maximum range is reduced to 11 km during daytime when the noise due the background light increases. Measurements within cloud layers are not included owing to the large aerosol interferences in the cloud. Although ozone concentrations larger than 1.0×10^{12} mol/cm^3 (100 ppb) have been measured during the night at 350 hPa (7.8 km), no clear evidence of ozone transport to the troposphere is shown on the lidar results. During the day, the time evolution resembles to a vertical cross section through a tropopause fold passing over the OHP near 18 UT (Fig.2). At the 450 hPa level (6 km) ozone values about 0.65×10^{12} mol/cm^3 (46 ppb) are not very high, but remain significantly larger than average values outside of the fold 0.4×10^{12} mol/cm^3 (30 ppb).

Using the European Center for Meteorological Weather Forecasting (ECMWF) analysis with the highest resolution 1.1°x1.1°, a vertical cross section of the isentropic potential vorticity (IPV) was calculated for the 18 UT time periods (Fig.3). The section was taken transverse to the minimum of the trough where the jet curvature is maximum. Air masses with high IPV ($> 1.2\times10^{-6}$ K m^2 s^{-1} kg^{-1} = 1.2 PV) supports the presence of a fold over the OHP extended down to 450 hPa. The resolution of the ECMWF analysis is still too coarse to fully resolve the fold below 450 hPa but IPV distribution is in good agreement with the ozone data between 450 hPa and 350 hPa. The ozone to IPV ratio is 38 ppb/PV at 450 hPa where IPV is 1.3 PV, and is 29 ppb/PV at 350 hPa where IPV is 3.4 PV. The air mass trajectories (Fig.4) shows clearly the stratospheric origin of the air masses, and indicates also that a large part of the air in the fold is transfered to the troposphere at low altitudes after turning around the developing low pressure system over Western Europe. This can also be supported by the presence of a dry (specific humidity of 150 ppmm) and stable layer (potential temperature gradient of 25 K/100 hPa) observed at 600 hPa on the November 26 by radiosoundings performed at Gibraltar.

To estimate the number of ozone molecules that can be transfered to the troposphere, one can use the ozone content of the fold which is derived from the lidar measurements, and the horizontal distribution of the IPV on the 450 hPa surface to determine the horizontal extent of the fold. On a 1 or 2 day time scale, the ozone to IPV ratio can be taken constant in the free troposphere between 40°N and 50°N since ozone can be considered as a passive tracer within the fold. Therefore the area covered by air masses with IPV larger than 1 PV represents the possible extent of the fold which is approximately located in a 500 km x 2200 km rectangle (Fig.5). Using a 2 km vertical width for the intruded air mass where ozone is of the order of 0.55×10^{12} mol/cm^3, one obtains a value of 1.2×10^{33} molecules which can be transfered to the troposphere. This value is 3 times smaller than a similar estimate for a tropopause fold observed at the OHP during the spring period [Ancellet et al, 1991]. Although it is difficult to derive a general behavior from some case studies in March and in November, it supports the seasonal variation of the climatological mean of the stratospheric air flux proposed by Danielsen which shows a spring flux 4 times larger than the fall flux [Danielsen et al, 1977].

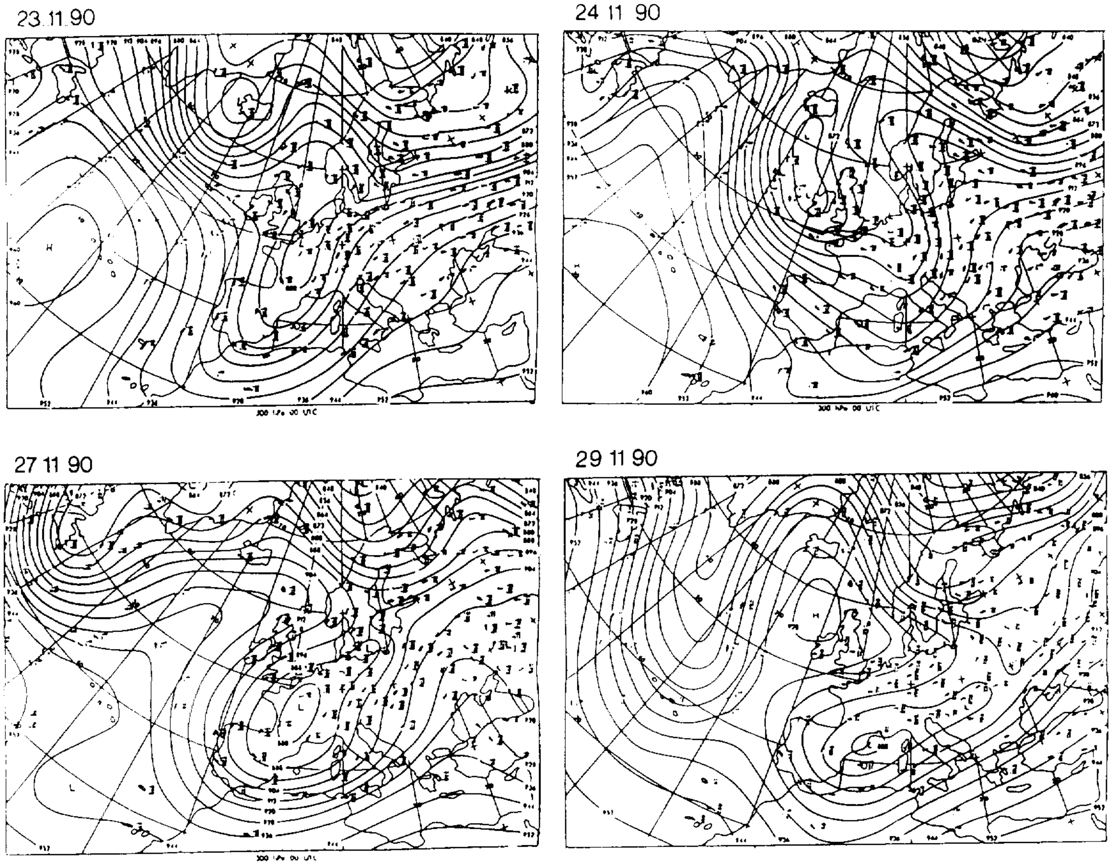


Fig.1 : Meteorological maps of the geopotential height and the wind vector on the 300 hPa surface from November 23rd 00 UT to November 29th 00 UT.

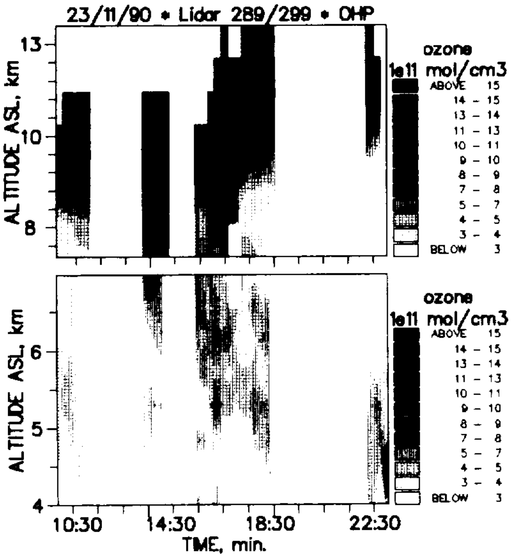


Fig.2 : Ozone concentration time series measured by lidar from 10:30 UT to 22:00 UT on Nonember 23rd. The lower and higher parts correspond respectively to the analog and photocounting recording mode

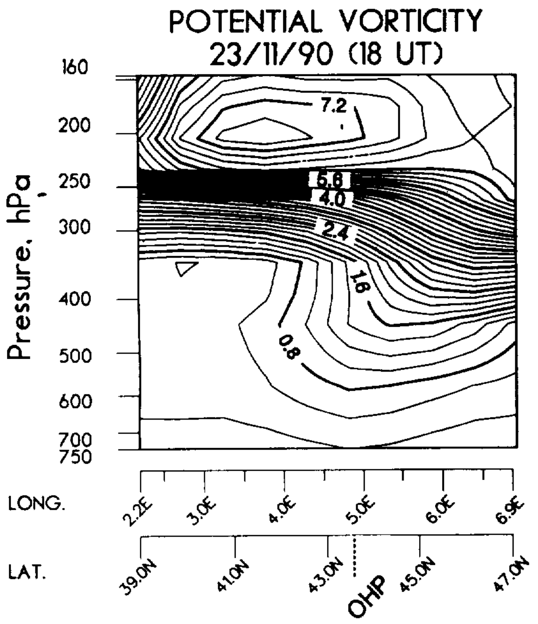


Fig.3 : Vertical cross section of the potential vorticity in PV units, for November 23rd at 18 UT.

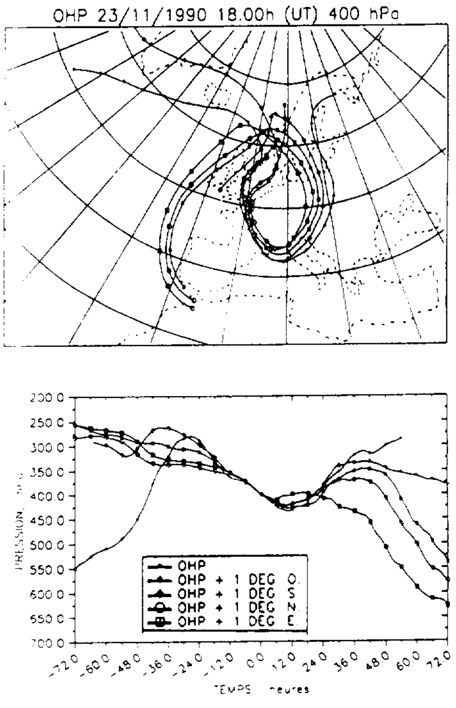


Fig.4 : Horizontal and vertical motions of air masses passing at 400 hPa above the OHP and above four points located 1° away from the OHP, for November 23rd at 18 UT.

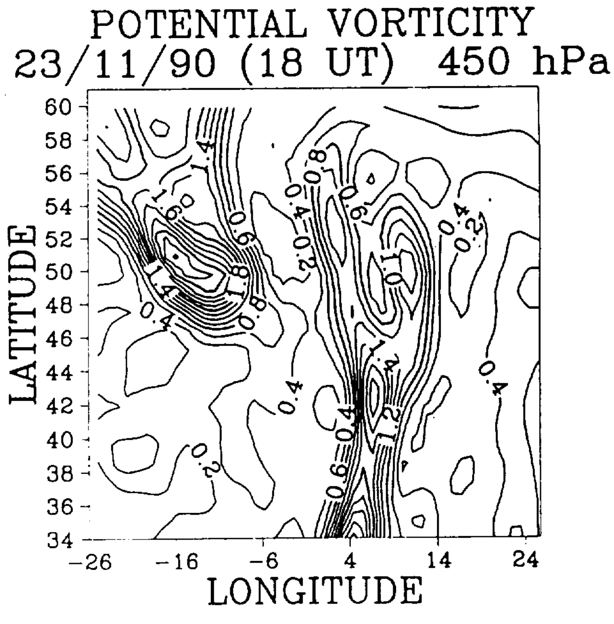
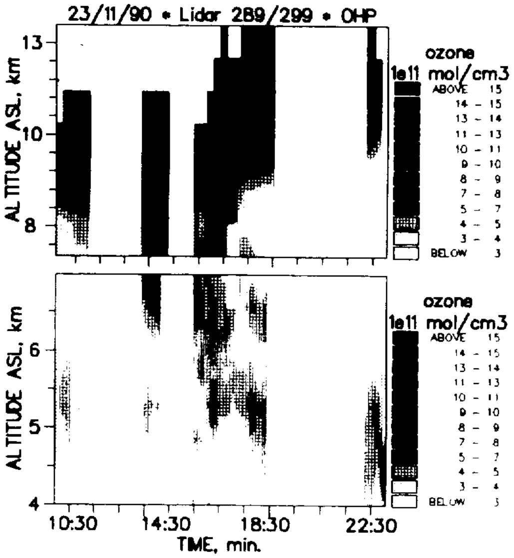


Fig.5 : Potential vorticity in PV unit on the 450 hPa surface on November 23rd 18 UT.

4. Evolution of the cut-off low

Ozone was measured on November 27th after 16:00 UT and on November 29 th in the afternoon, two time periods for which the OHP was located within the cut-off low. A continuous coverage was not possible owing to the large cloudiness level and rainfall within the low. The ozone temporal evolutions for these two days indicate a large ozone



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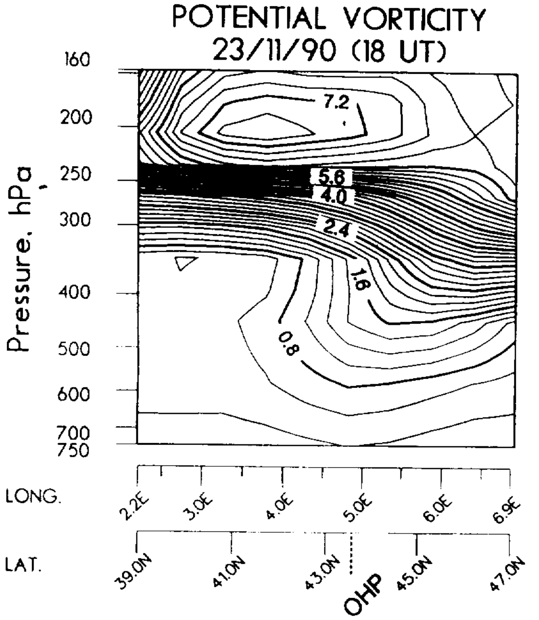

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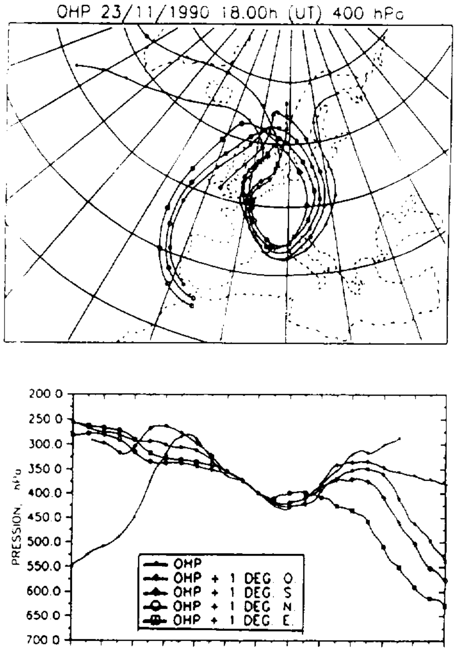

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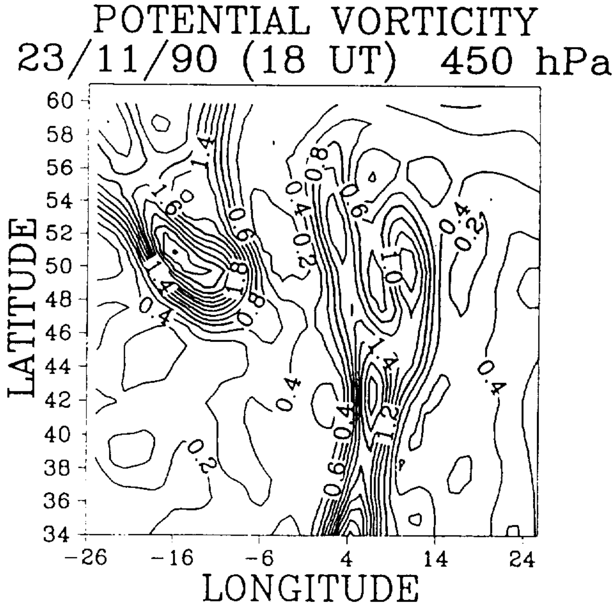

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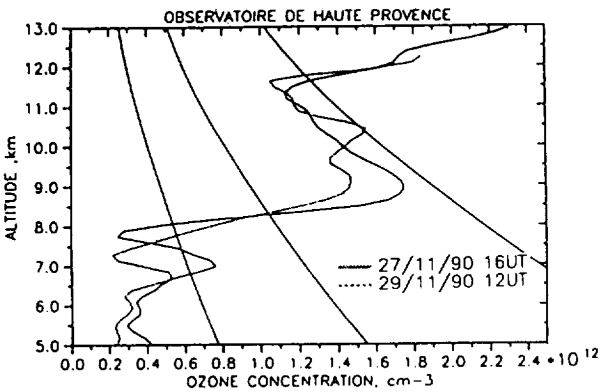

Fig.6 : One hour average ozone profiles measured on November 27th at 16 UT and November 29th at 12 UT.

gradient remaining at 8 km which corresponds to the tropopause altitude measured for these two days at the nearby Nîmes radiosounding station. The one hour average ozone profiles for November 27th at 18 UT and November 29th at noon (Fig.6) shows that the ozone gradient at 8 km is weaker on November 29th than on November 27th while the position of the OHP respect to the center of the low is similar for these two time periods. The tropospheric ozone values between 6 and 8 km on November 27th may be slightly overestimated due to the presence of a cloud layer at 7 km. As a consequence ozone transfer to the troposphere by small scale processes cannot be accurately estimated from the ozone change in this region, but we can use the ozone decrease above the tropopause (between 8.5 and 10.5 km) to estimate this effect during the evolution of the low. The ozone transferred to the troposphere from November 27th to November 29th corresponds then to the variation of the integrated ozone between 8.5 km and 10.5 km assuming that small scale mixing at the upper boundary remains small. Indeed the ozone gradient measured by the lidar at 10.5 km does not change significantly during the two day time period. It is not surprising since the climatological mean of the exchange coefficient in the low stratosphere is generally of 3-4 times smaller than at the tropopause level [Warneck, 1988]. In addition this ozone variation is not related to a tropopause altitude change, since the latter remains constant during these two days.

The ozone flux through the tropopause is then of the order 2.8 10^{12} $cm^{-2}s^{-1}$ associated to an integrated ozone decrease of 4 10^{16} cm^{-2}. If one extends this flux to the 1500 x 1000 km surface of the cut-off low, one obtains a value of 1.0 10^{33} molecules transfered to the troposphere in two days. The contribution to the stratospheric air flux is then of the same order of magnitude or even larger than a direct transfer of ozone present in tropopause folds.

5. Conclusion

In this work, stratospheric ozone transfer to the troposphere was studied using both ozone vertical profiles and objective analysis of the ECMWF model to derive potential vorticity distribution and air mass trajectories. We have shown by this study that:

- the ozone variations observed in the vicinity of frontal systems are well correlated with potential vorticity variations, supporting similar results obtained over continental U.S. [Browell, 1987]. The ozone to potential vorticity ratio of the order of 30 ppb/PV for air masses with potential vorticity larger than 1.2 PV is in good agreement with the November climatological mean of the this ratio obtained from the 1984-1990 OHP ozone data set considering air masses of similar potential vorticity [Beekmann, 1992].
- the ozone potentially transfered from the tropopause fold in the region of maximum jet stream curvature and the ensuing cut-off low development can increase the tropospheric ozone content of 1.2 10^{33} molecules in a two or three day time scale.
- the small scale mixing taking place at the tropopause level within the observed cut-off low reduces the ozone gradient and leads to an ozone transfer almost equivalent to the transfer by tropopause folding.

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