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Identification of Dynamical Processes at the Tropopause during the Decay of a Cutoff Low Using High-Resolution Airborne Lidar Ozone Measurements

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ABSTRACT

In June 1996, an airborne ozone lidar was successfully used to observe the decay of a cutoff low over southern Europe. This weather system was tracked during several days and sampled with an 8-km horizontal resolution. Most of the measurements took place in the 4–12-km altitude range and ozone-rich layers with a vertical thickness often less than 500 m were seen. Ozone vertical cross sections were obtained at the edges of the cutoff low or in frontal regions next to it. Using complementary data it is shown that these bidimensional cross sections characterize the ozone spatial field well. Two main features of the ozone distribution are large variability of the ozone tropopause and the presence of numerous ozone-rich layers within the troposphere. This paper focuses on the first feature. Observed ozone tropopauses compare well with potential vorticity ones derived from ECMWF analyses. The magnitude of the ozone to potential vorticity ratio also indicates that no significant diabatic mechanism contributes to the ozone transfer from the stratosphere to the troposphere above 325 K. An analysis of the evolution of the ozone vertical gradient in the upper troposphere (80–120 ppb) and lowermost stratosphere (120–200 ppb) is used to illustrate its usefulness as a diagnostic tool of dynamical processes. Large differences are found between air masses near and within the cutoff low. Vertical stretching induced by the PV anomaly cannot completely account for them. Differential advection in frontal regions and convective erosion on the eastern edge of the cutoff low tend to sharpen the vertical ozone gradient. On the contrary, clear sky turbulent mixing tends to smooth it. Convective erosion is also likely to transfer ozone from the stratosphere to the troposphere. This is corroborated by ozone vertical cross sections sampling tropospheric air masses three days after the decay of the cutoff low.

1. Introduction

The chemical, dynamical, and radiative balance of the atmosphere is extremely sensitive to the chemical composition of the 8–15-km atmospheric layer. Therefore, perturbations due to human activities must be carefully studied in this altitude range. The upper part of this atmospheric layer, the lower stratosphere, is a strong ozone source to the upper troposphere. The lower part of this atmospheric layer, the upper troposphere, is the main source region to the stratosphere for gases involved in ozone chemical destruction and in stratospheric water vapor budget.

The classical view of the Brewer circulation assumes transport to the stratosphere across the tropical tropopause through convection followed by poleward mean

transport circulation and transport to the troposphere at midlatitudes by a combination of diabatic subsidence in the stratosphere and frontogenesis in the troposphere (Holton et al. 1995). In order to better understand this global-scale circulation, intrusions of stratospheric air into the midtroposphere resulting from instabilities of the polar front must be well characterized to quantify the tropospheric ozone budget and the atmospheric's oxidizing capacity over Europe (Kley et al. 1997). Quasi-isentropic deformations of the midlatitude tropopause are very common but may not significantly contribute to chemical tracer exchanges. These intrusions must be stretched to small-scale features in order to achieve an efficient irreversible mixing (Appenzeller and Davies 1992). Instabilities in the jet streams on an isentropic surface may lead to long streamers extending over several thousands of kilometers coupling the subtropical region and the midlatitudes (Langford and Reid 1998). Breakup of these long streamers occurs at intermediate scales between synoptic-scale (>1000 km) and small-scale features (<100 km) where turbulence and radiative processes can mix stratospheric and tropospheric air.

Experimental investigations of air parcels at these intermediate scales are still necessary in order to validate

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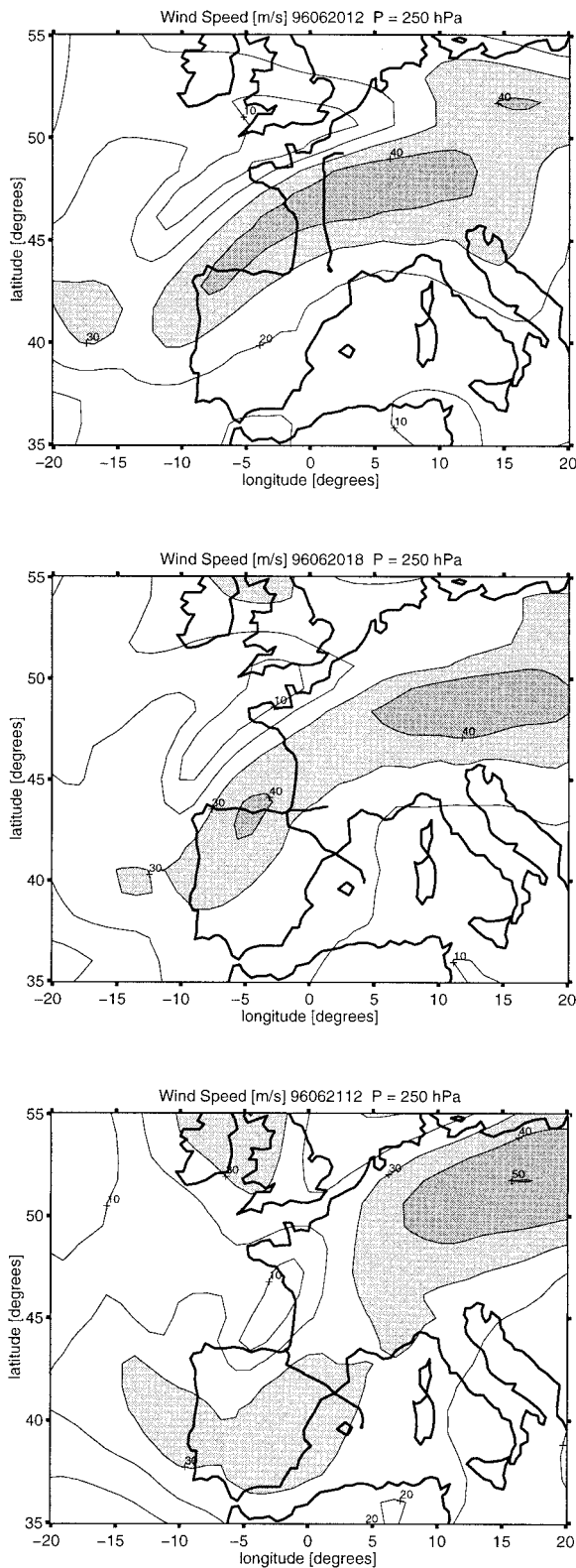


FIG. 3. Wind isotachs in $m s^{-1}$ at 250 hPa at 1200 and 1800 UTC 20 Jun and 1200 UTC 21 Jun. The shaded areas correspond to winds $> 30 m s^{-1}$. The wind is southeasterly in the shaded area. The COL corresponds to wind values less than $10 m s^{-1}$.

the upper troposphere (Bethan et al. 1998). However, spring ozone concentrations associated with these events do not exceed 50 ppb in the mid- and upper troposphere, while ozone concentrations, considered in this paper for the discussion of dynamical processes, are in the range 80–200 ppb.

2) OZONE DATASET

The ozone vertical cross sections are presented in Fig. 4 using isomixing ratio contours from 40 to 190 ppb. The contour line step is 10 ppb in the troposphere (40–80 ppb) and increases to 30 and 40 ppb in the tropopause region (80–190 ppb). The color in the area between two contour lines corresponds to the smallest contour value. The 1-h timescale given in Fig. 4 corresponds approximately to a distance of 300 km. The regions with missing data delineate air masses where clouds have been observed. A full strip of missing data is often indicative of convective clouds while missing data above 6 km are associated with altostratus or cirrus clouds. The horizontal distribution of these cloud layers can be derived from Meteosat images (Fig. 2). A UV absorption ozone monitor was mounted in the aircraft for this campaign. These ozone measurements have been included in the lidar cross sections to give the order of magnitude of ozone in the lower and midtroposphere for this meteorological event. Although a direct comparison between the two datasets is not possible, ozone variability in the lowest lidar altitude range compares well with ozone values provided by the ozone monitor. Most of the time, the ozone mixing ratio remains near 60 ppb at altitudes below 5 km suggesting a small impact of photochemical ozone production on the observed ozone distribution and variability in the lower troposphere. Indeed, ozone mixing ratios larger than 80 ppb were measured at 5 km only in the jet streak region at the eastern side with a connection to layers reaching the tropopause (see below).

In Fig. 4, the ozone vertical cross sections exhibit two main features: a variability in the vertical gradient at the tropopause and the occurrence of many ozone layers in the frontal zone around the COL. The ozone vertical gradient appears to be less defined in the return flow at the eastern side of the COL than in the northerly jet on the western side. This is due to larger ozone concentrations below the tropopause in the return flow and it can be interpreted as the effect of stratosphere–troposphere exchange in these air masses. This point will be further developed in section 4b. One could argue that the positive ozone gradient in the upper troposphere is related to ozone photochemical production. But this is very unlikely for this event due to the low ozone concentration in the lower layers. Furthermore, a high-resolution global model study recently showed that, in the upper troposphere, the stratospheric source of ozone increases with altitude, from 20 ppb at 5 km up to 80 ppb at the tropopause, while its photochemical source de-

