Decay of a cut-off low and contribution to stratosphere–troposphere exchange

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SUMMARY

We present a case study of the decay of a cut-off low over north-west Europe in June 1996, to establish how the stratospheric air initially contained within it was transferred to the troposphere. Two mechanisms for stratosphere–troposphere exchange are examined: direct convective erosion of the base of the low, and filamentation of the outer layers of the low along the flank of the polar jet stream. The approach taken relies on a combination of in-situ ozone and humidity measurements by MOZAIC (Measurement of Ozone and water vapour by Airbus In-service airCraft) aircraft and ozonesondes, and the European Centre for Medium-Range Weather Forecasts analyses. MOZAIC ozone is used to choose two analyses eight days apart at the genesis (14 June 1996) and decay (22 June 1996) of the low which have a consistent ozone/potential-vorticity relationship. Trajectories (both isentropic and three dimensional (3D)) between these two analyses reveal a consistent pattern; at the base of the low (310 K, 450 mb) all the trajectories attain tropospheric PV values whereas, at 320 K, those trajectories that leave the low experience a decrease in PV and those that do not leave the low retain their initial PV. We propose that air parcels leaving the low were stretched into thin filaments along the flank of the jet stream, which made them vulnerable to 3D mixing. A MOZAIC flight on 21 June 1996 provides direct evidence for this process.

Up to 22 June 1996 (by which time the low had lost its closed circulation) the satellite images showed very little convection beneath the corresponding PV anomaly. Mixing was only effective at the very base of the stratospheric air at 310 K. On 22 June the remaining remnant of high PV was advected into a region of deep convection over central and eastern Europe, mixing the remaining stratospheric air into the troposphere. Of the initial mass of $10^{15}$ kg of stratospheric air contained in the low, $6 \times 10^{14}$ kg was stripped into filaments along the jet and $4 \times 10^{14}$ kg remained to be mixed by convection during the period 22–23 June 1996.

KEYWORDS: Cut-off low Ozone Potential vorticity Trajectories Tropopause

1. INTRODUCTION

The composition of the lower stratosphere and upper troposphere is of considerable importance for several problems in atmospheric science, e.g. the depletion of the mid-latitude ozone layer, the radiative balance of the troposphere and the long-range transport of pollution. These two regions differ markedly in their inventory of minor constituents—the stratosphere is arid, but rich in ozone and nitric acid whereas the troposphere is moist and rich in hydrocarbons and other chemicals of surface origin. Mixing across their interface can have important chemical consequences, e.g. through the enhanced production of the OH radical (Bamber \textit{et al.} 1984). The long-term average exchange of mass between stratosphere and troposphere can be calculated (through continuity) from the meridional circulation of the stratosphere and mesosphere (Andrews and McIntyre 1976; Haynes \textit{et al.} 1991; Holton \textit{et al.} 1995), but the details of the exchange processes must be understood if their impact on the tropopause region itself is to be properly evaluated. This paper attempts to clarify the contribution to stratosphere–troposphere exchange of cut-off lows—features identified by previous work (e.g. WMO 1986; Price and Vaughan 1993) as important agents for mixing across the tropopause.

Cut-off lows are isolated cyclonic vortices which form as a result of meridional excursions of jet streams. They are synoptic-scale features, typically a thousand kilometres across (Price and Vaughan 1992). Within these vortices the tropopause is typically 2–3 km lower than in the surrounding atmosphere, forming a bowl of stratospheric air

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isolated horizontally from the polar stratospheric reservoir at the same potential temperature. Thus, cut-off lows appear as isolated regions of high potential vorticity on an isentropic surface which intersects the mid-latitude tropopause (Hoskins et al. 1985). Over a period of a few days the cut-off low decays, with the stratospheric air originally trapped in it either returning to the polar stratosphere or mixing into the troposphere. Cut-off lows are therefore of potential importance for stratosphere–troposphere exchange (Price and Vaughan 1993). Two mechanisms are possible for mixing the stratospheric air into the troposphere—isentropic filamentation of air away from the low followed by mixing outside it, or mixing across the tropopause within the low itself (either by convective penetration or clear-air turbulence). The purpose of this paper is to examine the relative contribution of these two mechanisms to the decay of a cut-off low which formed over the Atlantic in June 1996 during the TOASTE-C (Transport of Ozone and Stratosphere–Troposphere Exchange-C) campaign. Convection, especially over land, is more vigorous in summer than in winter so that a summer campaign is more likely to observe vertical mixing contributing to the decay of cut-off lows.

The formation of cut-off lows can be described in the dynamical context summarized by Thorncroft et al. (1993). They presented two paradigms for baroclinic wave development, depending on whether the large-scale background shear is cyclonic or anticyclonic. In this context, an extrusion of stratospheric polar air to mid-latitudes is presented as a horizontal process visualized as the development of potential vorticity (PV) on an isentropic surface. Depending on the background shear, the extrusion develops either by rolling up cyclonically into a cut-off low or by evolving into a streamer of high potential vorticity curving anticyclonically to low latitudes. The latter is stretched by the large-scale shear, often giving rise to local instabilities which themselves develop as cut-off lows; this process has been clearly demonstrated in Meteosat water-vapour images by Appenzeller and Davies (1992) and Appenzeller et al. (1996). Because high PV serves as a definition of stratospheric air, the evolution of isolated PV-rich regions is a natural tool for examining the mixing of stratospheric and tropospheric air along isentropic surfaces.

An alternative viewpoint (pursued, for instance, by Price and Vaughan (1993)) emphasizes the vertical structure of the cut-off low and considers mixing across rather than along isentropic surfaces. This view defines a cut-off low by its closed circulation, which isolates it horizontally from the rest of the atmosphere, rather than as a PV anomaly (note that not all isolated PV anomalies have a closed circulation, as will be shown later). Examination of PV is still required to define the tropopause within the cut-off low—the closed circulation generally extends down to the mid-troposphere where the air within the vortex is tropospheric. Thus, when calculating the mass of stratospheric air within a cut-off low (see section 7) the PV definition must be adopted. Exchange of air between stratosphere and troposphere in this model occurs by convective erosion across the tropopause (vertically), turbulence near the jet stream (horizontally) and tropopause folding. The value of this model when compared with the isentropic viewpoint presented earlier is its natural inclusion of diabatic processes, especially convection.

Convection influences the development of a cut-off low in two ways (Wirth 1995): erosion of the lower stratosphere by convective mixing if the clouds penetrate sufficiently high (Ancellet et al. 1994; Wirth and Egger 1998); and the effect of latent-heat release in the lower troposphere in removing the thermal anomaly that is the direct progenitor (via the thermal–wind equation) of the closed circulation. As the tropospheric core of the low warms up, the geopotential gradient across the tropopause weakens and the outer layers of the cut-off low are lost to the surrounding flow. This stripping, which
is examined further in section 5 of this paper, occurs most readily if the low is embedded in a region with background shear, and for the case discussed here occurred as the cut-off low appeared (on synoptic charts) to be absorbed back into the polar stratosphere.

Critical to estimates of stratosphere–troposphere exchange in cut-off lows and similar systems is a definition of the tropopause. Unfortunately, there is no single PV value which defines the transition from troposphere to stratosphere; values ranging from 1.5 PVU* (WMO 1986) to 3 PVU (Hoerling et al. 1993) may be found in the literature, with the most popular value somewhere near 2 PVU. This is a conceptual problem rather than simply one of definition; the tropopause region marks a zone where the air is intermediate in dynamical and chemical properties between the troposphere and stratosphere. For instance, the humidity of the lowest kilometre of the mid-latitude stratosphere is well in excess of the 4–6 ppmv (parts per million by volume) typical of the rest of the stratosphere (Dessler et al. 1995). In this paper we generally consider PV values greater than 2 PVU to be stratospheric and those between 1 and 2 to be intermediate in character. Since the emphasis of this paper is on the relative contribution of horizontal and vertical mixing to the decay of a cut-off low/PV anomaly, such simple definitions are adequate, and follow previous practice in this respect (Holton et al. 1995).

The cut-off low chosen for this study developed from the elongation of an upper-air trough over the central Atlantic on 14–15 June 1996. It remained an isolated feature and tracked slowly eastwards until it was re-absorbed into a trough in the polar flow between 19–22 June. Trajectory calculations have been used to investigate the fate of air initially contained within the low. The evolution of PV and humidity along these trajectories has been compared with in-situ measurements of ozone and humidity by aircraft and ozonesondes. The two viewpoints discussed above have been compared by calculating the amount of air estimated to leave it through filamentation, in contrast to that subjected to convective erosion and mixing.

2. EVOLUTION OF THE CUT-OFF LOW: SYNOPTIC VIEWPOINT

The evolution of the cut-off low at 300 mb began with an elongating trough over the mid-Atlantic near 40°N on 14 June, with a strong jet stream on its western side above a pronounced tropopause fold. The low detached at approximately 1800 UTC on 15 June and tracked slowly eastwards as an isolated feature. Throughout this period a stationary trough lay over northern Europe in the region 0–20°E. As the cut-off low approached this trough it gradually disappeared as a distinct feature, losing its closed circulation on 21 June. Henceforth, for brevity, we will use the notation 14/06 to refer to a field at 0600 UTC on 14 June, mutatis mutandis.

The evolution of the low as a PV feature is shown in Fig. 1 for the 320 K isentropic surface, derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses on a 1.125° grid (and obtained from the NILU† database, Norway). On 14/06 the trough appeared as a region of high PV (>2 PVU) reaching from 60°N to 43°N along 40°W. A region of stratospheric PV (PV >2 PVU) became cut off from the main trough on 15/18 (not shown), and remained a coherent feature for some seven days while gradually tracking eastwards. From 19 June onwards the anomaly decreased in area and in peak PV, as the cut-off low dissipated, but it remained a separate entity until the 22 June—well after the closed circulation at 300 mb had ceased. Figure 1(g), therefore, depicts a PV anomaly being advected with the large-scale flow rather than a cut-off low per se. On 20 June (Fig. 1(c)) the low assumed an

* Potential vorticity units: 1 PVU = 10^{-6} K m^2 kg^{-1} s^{-1}.
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Figure 1. Isentropic potential-vorticity maps on the 320 K potential-temperature surface derived from the ECMWF T106 analyses for (a) 0600 UTC 14 June, (b) 1200 UTC 19 June, (c) 12 UTC 20 June, (d) 1800 UTC 20 June, (e) 0000 UTC 21 June, (f) 1200 UTC 21 June, and (g) 0600 UTC 22 June 1996. The units are PVU (1 PVU = $10^{-6}$ K m$^2$ kg$^{-1}$ s$^{-1}$). Also shown are the MOZAIC flight paths for 0600 UTC 14 June, 1200 UTC 21 June and 0600 UTC 22 June. Arrows on the flight path in (f) denote the flight segment depicted in Fig. 7.
elongated shape; this was a time when a large mass of air left the low as a filament along the flank of the jet stream, as discussed later.

3. Trajectory Analyses

In this section, eight-day forward isentropic and 3D trajectories initiated in the low are used to examine the fate of the air contained within it. The evolution of PV and specific humidity along the trajectories will be used to estimate the degree to which stratospheric air was mixed into the troposphere. Isentropic trajectories have the advantage that they depend only on the horizontal component of the assimilated winds, whereas 3D trajectories require the less accurate vertical velocity field. In the very dry air of the lower stratosphere, radiative time-scales are very long and the isentropic assumption is likely to be valid over an eight-day period. For trajectories transferring to the troposphere, however, diabatic processes cannot be neglected. We therefore present both isentropic and 3D trajectories to verify the main results. The trajectories are based on six-hourly ECMWF analyses on a 1.125° grid, obtained on isentropic and standard isobaric surfaces. The calculations assume linear interpolation in time and use an Adams–Bashforth integration scheme with variable time step.

The underlying hypothesis of the trajectory analysis is that a parcel of stratospheric air, that loses its PV and gains moisture along a trajectory, has transferred into the troposphere. Unfortunately, there are two restrictions on applying this method—one is the limited resolution of the analyses, which cannot capture fine-scale filamentation (see later), the other is uncertainty about the relative accuracy of successive analyses, especially in the vicinity of the tropopause and in a data-sparse region like the central Atlantic. We therefore turn to an independent indicator of the quality of the analyses—ozone measurements on board commercial airliners.

(a) Comparison of ECMWF PV with MOZAIC ozone

Ozone in the lower stratosphere is positively correlated with PV, because both have been brought down from higher altitudes in the stratosphere (Danielsen 1985). Just above the tropopause the ratio of ozone to PV is generally in the range 40–50 ppbv (PVU)^{-1} (Beekmann et al. 1994). Ozone measurements in the lowermost stratosphere
are made regularly by commercial airliners fitted with instruments to measure ozone and water vapour as part of the MOZAIC (Measurement of Ozone and water vapour by Airbus In-service airCraft) programme (see Marenco et al. (1998) and the appendix). Five MOZAIC flights intercepted the cut-off low as they were flying over the Atlantic or southern Europe. Figure 1 shows the paths of three of them (shown in black) relative to the 320 K PV field. Note that the 320 K surface is used only as an indicative surface, since the altitude of the flights generally spanned a range of isentropic surfaces.

Consistency between the PV analyses and ozone measurements was investigated by comparing the ozone with PV interpolated (in space and time) along the flight path. The two analyses in Figs. 1(a) and 1(g) were found to agree particularly well with the ozone measurements (Figs. 2(a) and 2(b)). There are some discrepancies due to the different resolution of the data; ozone measurements have a horizontal resolution of
Figure 3. Results of trajectory calculations initialized at 0000 UTC 17 June 1996. Locations on the 310 K surface of (a) the end points of back-trajectories at 0600 UTC 14 June, (b) the initial positions, and (c) the end points of forward trajectories at 0600 UTC 22 June at 310 K. (d), (e) and (f) as (a), (b) and (c), but on the 320 K surface. In each case the locations are superimposed on the corresponding potential-vorticity chart (PVU). (g) and (h) show the final locations for the 3D trajectories initialized at 0000 UTC 17 June at 450 mb and 300 mb, respectively.
Figure 3. Continued.
Figure 3. Continued.

1 km compared with around 200 km for the PV (note that the PV in Fig. 2 varies on length-scales much smaller than 200 km because of vertical excursions by the aircraft). The slopes of the O₃/PV regression observed during the sampling of the low on 14 and 22 June were, respectively, 52 ppbv/PVU and 46 ppbv/PVU, in good agreement with climatology (Beekmann et al. 1994). Correlation coefficients exceeded 0.95 in both cases. For the other three flights in this period (19, 20 and 21 June) the slopes and correlation coefficient were (44, 0.87), (48, 0.87) and (26, 0.83), respectively—showing that the ECMWF analyses for these times were less consistent with the MOZAIC ozone.

We have therefore used the analyses of 14/06 and 22/06 as the start and end times of trajectory calculations aimed at determining the fate of stratospheric air initially contained in the low. Bearing in mind the smaller O₃/PV slope at 22/06 than at 14/06, the PV in the second analysis was slightly larger for a given ozone concentration than in the first analysis. Hence, if there were no change in ozone along a trajectory (i.e. no mixing, as ozone is chemically inactive in the stratosphere at these altitudes), the calculations ought to show a small increase in PV between the two analyses. A decrease in PV is therefore suggestive of diabatic processes or mixing.
(b) Isentropic and 3D trajectories

Isentropic trajectories were calculated at 310 K and 320 K, and 3D trajectories were initialized at 450 and 300 mb (corresponding approximately to the starting pressures of the isentropic trajectories). They were started in the region of high PV at the base of the trough at 14/06, at positions defined by calculating a set of backward trajectories from a grid of points (1° × 1°) contained in the low at 17/00. 80 trajectories were calculated at 310 K and 450 mb, and 125 at 320 K and 300 mb. The initial (14/06), intermediate (17/00) and final (22/06) positions of the air parcels are given in Figs. 3(a)–(f) for the isentropic case, and the final positions only in Figs. 3(g)–(h) for the 3D case. The PV change along the trajectories is shown in Figs. 4(a) and 4(b) for the isentropic case and 4(c) and 4(d) for the 3D case. The change in specific humidity (not shown) was consistent with that in PV; a decrease in PV was accompanied by moistening.

At 310 K and 450 mb, the trajectory end points clustered in two main groups (Figs. 3(c) and (g)): one beneath the cut-off low over the western Mediterranean and the other around 55°N, 40°E over Russia. Some of these trajectories started with PV between 1 and 2 PVU (Figs. 4(a) and (c)), but by 22 June nearly all had moistened and reduced in PV to less than 1 PVU. Thus, they transferred from a region intermediate between stratosphere and troposphere to the troposphere proper. For the isentropic case there is a clear distinction in PV between the two groups, with the trajectories that left the low having uniformly lower PV. This is less clear in the 3D case, in contrast to the results at 320 K.

At 320 K and 300 mb (Figs. 4(b) and (d)), most of the trajectories started with PV values in the range 2–5 PVU, and at 22/06 the same two groups of trajectory end points are found as at 310 K. This time, however, there is a clear difference in PV between the two groups for both isentropic and 3D trajectories. The first group, corresponding to the cut-off-low remnant over the western Mediterranean (squares in Figs. 4(b) and 4(d)), has retained its stratospheric PV. The second group over Russia (asterisks in Figs. 4(b) and 4(d)) has lost PV; it now contains PV values intermediate between troposphere and stratosphere (1–2 PVU), as well as values less than 1 PVU which are typically tropospheric.

The consistency between the 3D and isentropic trajectories suggests that the pattern outlined above is not simply due to errors in the trajectory calculations. Thus, the acquisition of tropospheric characteristics by trajectories leaving the low must be due to diabatic processes, mixing, or inadequate model resolution as the air in the cut-off low elongated into thin filaments along the jet. Further consideration of this problem is presented in section 5. Firstly, however, we investigate the evidence for convective erosion of the low, since this has a direct bearing on the validity of the trajectory calculations.

4. Convective erosion: Use of satellite imagery and radiosondes

To evaluate the extent of convection beneath the PV anomaly, visible and infrared AVHRR images for midday from the NOAA-12 satellite were studied for the period 15–22 June. No significant convection was observed while the low was over the Atlantic. Figure 5(a) shows the AVHRR visible satellite photograph for 1331 UTC on 19 June, with the region with PV greater than 2 PVU at 320 K outlined in white. Of interest in this picture is the typical 'roll-up' of the vortex as air from different origins is mixed within the cut-off region; much of the high cloud in the vortex appears to be frontal debris. Some deep convection is evident in the low around (46°N, 15°W), and along
its south-eastern edge near \((45^\circ N, 11^\circ W)\); this is clearer on the corresponding infrared image. Generally, though, the low is free of deep convection.

On 20 June (Fig. 5(b)), the PV anomaly had moved eastwards and its centre was now approximately 500 km west of Brittany. A tongue of high PV extending eastwards over the English Channel represents air in the process of leaving the low; this is the air that is later stretched into a thin filament along the jet. The position of the jet stream is given by the cirrus line extending from southern England to Germany.

On 21 June (Fig. 5(c)), the PV anomaly was over northern Spain. Convection is visible in its north-eastern quadrant, indicating the potential for tropopause erosion there. By 22 June the PV anomaly was moving rapidly eastward, reaching Corsica and northern Italy by midday (Fig. 5(d)). Again, most of the convection occurs on the north-eastern side of the low over land. Subsequent to this, however, the PV anomaly moved to a region of extensive deep convection—it reached the eastern Adriatic coast by 22/18 and disappeared on the 320 K surface soon after.
Radiosonde temperature profiles along the path of the low at La Coruña (43.3°N, 8.4°W), Santander (43.4°N, 3.81°W), Bordeaux (44.5°N, 0.4°W), Nimes (43.8°N, 4.4°E) and Udine (46.0°N, 13.2°E) were studied to determine the likely depth of the convection. Most of the sondes did not indicate the potential for deep convection in the low, consistent with the satellite images. Exceptions were seen at Bordeaux and Santander on 21 June (Figs. 6(a) and (b)) where the equivalent potential temperature $\theta_e$ at the surface was 317 and 316 K, and the tropopause potential temperature 317 and 311 K respectively. Convection at Bordeaux would have remained in the troposphere, whereas there is potential for tropopause erosion at Santander. Note, however, that $\theta_e$ decreased very quickly in the boundary layer at Santander, reaching 307 K at 990 mb. It seems unlikely, therefore, that the clouds in Fig. 5(c) were responsible for extensive erosion of the tropopause (note also the ozonesonde ascents discussed in section 6).

In the region into which the residual PV anomaly moved on 22 June, conditions were very different. Extensive deep convection was visible on the satellite images in this region, with a $\theta_e$ of 332 K at the surface at Udine (Fig. 6(c)) for instance. It is
Figure 5. Visible satellite images from the AVHRR instrument on the NOAA-12 satellite around midday on (a) 19 June, (b) 20 June, (c) 21 June and (d) 22 June 1996. The closed dashed lines mark the 2 PVU contour around the cut-off low at 320 K.
Figure 5. Continued.
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Figure 6. Tephigrams for (a) Bordeaux at 1200 UTC 21 June, (b) Santander at 1200 UTC 21 June, and (c) Udine at 1200 UTC 22 June 1996. The thick solid lines are temperature profiles and the dashed lines are dew-point profiles. The thin curving lines are saturated adiabats.
reasonable to assume, therefore, that any air below 330 K still trapped in the cut-off low at 22/18 would rapidly be mixed into the troposphere by the deep convection.

The conclusion drawn from this analysis is that convective mixing played a minor role in eroding the PV anomaly at 320 K until 22 June, after which very extensive mixing occurred up to 330 K. Trajectory calculations at 320 K (or their 3D equivalent) should therefore give a reliable indication of the fate of the air initially contained in the cut-off low until 22/12. The trajectories at 310 K all showed a decrease in PV to normal tropospheric values, and are obviously less reliable than those at 320 K—but since their PV was already less than 1 PVU by 21/00, convection over the land was not the deciding factor.

5. Filamentation of Stratospheric Air Near the Jet Stream

The trajectories presented in section 3(b) suggest that air leaving the cut-off low after 19 June was spun into a thin filament along the flank of the jet stream, possibly rolling up downstream in the trough that developed over Russia. The jet stream is a region where very sharp horizontal gradients in ozone have previously been reported (Shapiro 1978, 1980). Ozone measurements obtained by an aircraft flying orthogonal to a jet stream were presented by Vaughan and Tuck (1984); they showed enormous variability on the cyclonic side of the core, indicating the close interleaving of filaments of air of very different origin. In the present case the opportunity to observe such filaments was afforded by a MOZAIC flight from Vienna to Tokyo on 21 June when air parcels leaving the cut-off-low were streaming into the jet. Indeed, a pronounced filamentary structure was observed near to (53.5°N, 26°W) during a near-isentropic
flight segment at 327 K. The location of this filament is indicated relative to the 320 K surface in Fig. 1(f), and the MOZAIC measurements are shown in Fig. 7. Shortly after 13.5 decimal hours UTC there was a sudden jump in the ozone mixing ratio, from 70 to 240 ppbv, immediately prior to a small vertical excursion by the aircraft. Because the ozone structure was not correlated with potential temperature, it cannot be attributed to vertical motion and must, therefore, represent a horizontal filament of elevated ozone. A second filament was seen around 13.7 UTC, when the plane was descending slightly.

The ECMWF potential vorticity interpolated to the aircraft track (Fig. 7) varies more gradually. It increases steadily to 4 PVU just after the location of the first filament, then decreases slightly thereafter. The tropopause appears as a sharp jump in PV at around 13.25 UTC, so both filaments were located in the stratosphere according to the ECMWF analysis. The MOZAIC ozone, however, shows much finer-scale structure, with the aircraft registering tropospheric ozone concentrations up to 13.5 UTC and after 13.8 UTC. The two peaks with stratospheric values in Fig. 7 lasted 5.5 and 2.7 min, respectively—corresponding to horizontal distances of 86 and 43 km with the aircraft ground speed of 260 m s$^{-1}$. However, the aircraft was flying at 40° to the wind, so if the filaments were aligned along the wind (as seems probable) their widths would be 55 and 27.5 km respectively—far too narrow to be represented in the ECMWF analyses.

Isentropic back-trajectories were conducted at 330 K from the location of this flight segment. The results showed that the filamentary structure was observed at the confluence of air from the main trough with that from the cut-off low. Indeed, the calculations showed that the first ozone peak in Fig. 7 left the cut-off low on 20 June, while the second came from the Arctic down the western side of the main trough. Given the resolution of the meteorological analyses this result has illustrative value only—but it does support the hypothesis that air leaving the cut-off low was stretched into thin filaments along the jet stream. The loss of PV along trajectories leaving the low, demonstrated in Fig. 4, was at least partly due to the inability of the model to represent

Figure 7. Measurements of ozone (ppbv, solid line), relative humidity (%, dot-dash line) and potential temperature (K, dashed line) from the MOZAIC database for the flight segment between 1300 UTC and 1400 UTC 21 June 1996 (see Fig. 1(f) for the location of the segment). Also shown is the potential vorticity interpolated onto the flight track from the ECMWF T106 analysis at 1200 UTC 21 June (dotted line).
the filamentation, but it is worth examining the in-situ data for evidence of real mixing along the flank of the jet.

A mixture of stratospheric and tropospheric air contains elevated values of ozone and water vapour together. The relative humidity measured by MOZAIIC is shown in Fig. 7. The sensor's quoted precision is 7% in RH in the upper troposphere, with a response time of up to 3 min (Helten et al. 1998). As the aircraft entered the first ozone maximum the RH fell to 35%, then remained at this value as the ozone peak passed, before increasing steadily through the second peak. The time constant of the sensor precludes an accurate measurement in the peaks—but in the region between the two ozone peaks where the ozone mixing ratio was 122 ppbv, the RH measurement of 45% (specific humidity 70 ppmm*) should be reliable. This air therefore has the mixed characteristics described above, the mixing presumably occurring owing to the increase in surface area as stratospheric filaments were stretched along the jet stream. This result suggests that a decrease in PV is to be expected for trajectories leaving the cut-off low.

6. FOLD EVENTS ASSOCIATED WITH THE LOW: OZONE SOUNDINGS ON 21 JUNE 1996

Although the MOZAIIC flights offer unrivalled measurements of the horizontal structure of the upper troposphere and lower stratosphere, they cannot at the same time measure the vertical structure. Such measurements were available from ozonesondes on 21 June 1996 at Toulouse (43°N, 1.3°E) at 1230 UTC and Madrid (40°N, 3.75°W) at 1030 UTC (Fig. 8). These ascents probed the southern flank of the cut-off low, around the time when some of the isentropic trajectories already presented at 310 K and 320 K reached Toulouse. The ozone profile there shows two maxima in the troposphere (Fig. 8(a)), one relatively sharp at 314 K (125 ppbv) and another thicker one around 320 K (115 ppbv), just below the tropopause at 323 K. These two ozone maxima are correlated with relative humidity minima (10–15%) and static stability peaks which confirm their stratospheric origin. They are separated by a wetter less stable and less ozone-rich layer, occurring at 315–317 K, the characteristics of which are more tropospheric. The alternative presence of stratospheric air and tropospheric air is indicative of interleaving of stratospheric and tropospheric air at the base of the low, reminiscent of tropopause folding.

Confirmation of interleaving on the southern edge of the low is provided by the Madrid sonde (Fig. 8(b)). A similar but less pronounced structure to that at Toulouse was observed at 320 K, with an ozone peak of 100 ppbv. This was again correlated with low relative humidity (10–15%) and elevated static stability, consistent with a stratospheric origin. A second ozone peak, of 85 ppbv at 310 K, is not as well correlated with humidity and stability, and may not be of stratospheric origin. As observed two hours later in Toulouse, the region around 315 K is clearly tropospheric, with less ozone (60 ppbv), lower stability and higher relative humidity (40%).

Two important conclusions may be drawn from the sonde measurements. Firstly, there is clearly some stratospheric air in the low below 320 K—this region has not completely mixed with the troposphere, confirming the conclusion of section 4. Secondly, the interleaving on the flank of the low offers enhanced opportunities for mixing by clear-air turbulence and for further filamentation because of the wind shear in this region. Since the ECMWF analyses did not resolve a folded structure we cannot confirm the presence of a fold, nor estimate its extent. However, clear-air turbulence in small

* Parts per million by mass.
folds around the flanks of the low offers a possible mechanism for the erosion of the bottom layer (around 310 K) between 14 and 21 June.

7. Mass calculations

Having identified the processes contributing to stratosphere–troposphere exchange, we must now attempt to quantify the relative importance of these contributions. When the cut-off low was over the Atlantic, away from the background shear of the polar jet stream, the closed circulation defining it coincided with the edge of the PV anomaly. Since this anomaly delineated the stratospheric air within the low, the decrease of its mass is a measure of the extent of mixing and transport out of the low. This evolution is shown in Fig. 9 using two different PV thresholds to define the stratospheric air (the calculation follows the method of Vaughan and Timmis (1998)). The figure shows that the mass remained essentially constant until 20 June, when (as shown in Fig. 1(c)) air began to leave under the influence of the polar jet. About 60% of the mass had been lost by 0600 UTC on 22 June, prior to the onset of widespread deep convection. We therefore conclude that, in this case, over half of the mass of the low was lost by filamentation along the flank of the polar jet stream. Some, at least, of the stratospheric air leaving the low this way was mixed with surrounding tropospheric air, leading to a uniform decrease in potential vorticity along the trajectories to values (1–2 PVU) intermediate between troposphere and stratosphere (Fig. 4).
We have presented a case study of the evolution of a cut-off low which attempts to identify the mechanisms by which stratospheric air is transferred to the troposphere in such features. The cut-off low formed on 15 June 1996, and dissipated over Europe on 22 June. The evolution of PV and humidity along trajectories, as well as temperature profiles in the low on 21 June, confirmed that the air remaining in it was largely stratospheric above 312 K. Ozone profiles along its flank on 21 June also revealed stratospheric air down to 312 K. Large-scale mixing by convection did not start until 22 June, by which time over half the air in the low had been removed by filamentation along the flank of the polar jet stream to its north. The closed circulation of the cut-off low had ceased by then, with the remaining PV anomaly being passively advected with the flow. This remnant disappeared quickly from the ECMWF analyses after 1200 UTC on 22 June, due to vigorous mixing by the deep convection. The MOZAIK measurements on 21 June confirmed the presence of filamentation, exactly where trajectories leaving the cut-off low were located. These filaments contained relatively moist, ozone-rich air—direct evidence for mixing of stratospheric and tropospheric air. The subsequent fate of this air is difficult to determine because of the limited resolution of the ECMWF analyses, but the trajectories suggest that some, at least, was incorporated into a trough that formed over Russia on 22 June—with a distinctly lower PV than when it left the cut-off low. Together with the evidence for mixed air in the MOZAIK humidity and ozone, this suggests that the filamentation process, in enormously increasing the surface area of the stratospheric air, promotes the effectiveness of turbulence in mixing stratospheric and tropospheric air along the flank of the polar jet stream.

Near the base of the cut-off low (310 K in this case), the air was initially intermediate in character between stratosphere and troposphere (1–2 PVU). The trajectories show all of this air transferring to the troposphere (i.e. to levels where the PV was less than 1 PVU) by 21 June. Since there was little convection in the low over the ocean we suggest that the main agency here was tropopause folding along its flanks, both in removing air directly from the low and in promoting clear-air turbulence. We only have direct evidence for folding in the ozonesondes on 21 June, but note that the ECMWF analyses failed to capture these features, in contrast to the large fold that accompanied
the genesis of the low. The picture emerges then of rapid exchange of air into and out of the low at its lowest levels, while the main bulk of the low remained isolated until it entered the shear zone of the main polar jet on 20 June.

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APPENDIX

MOZAIC

The MOZAIC program (Measurements of Ozone and water vapour by Airbus In-service airCraft) was initiated in 1993 by European scientists, aircraft manufacturers and airlines to collect experimental data on ozone and water vapour concentrations in the atmosphere. It relies upon fully automatic devices installed on five long-range Airbus A340s in normal service, flying regularly all over the world since September 1994 (Marenco et al. 1998). O₃ and H₂O measurements are continuously recorded every 4 s during flight, i.e. 1 km horizontally, and 30 m vertically during the ascent and descent phases. Because the programme uses long-range aircraft travelling between continents, most of the data (90%) were collected at cruise levels (9–12 km) and at five constant and well defined pressure levels corresponding to 9.4, 10, 10.6, 11.2, and 11.8 km altitude.

The ozone analyser installed aboard MOZAIC aircraft is a dual-beam UV-absorption instrument (Thermo-Electron: Model 49-103). The response time is 4 s and the concentration is automatically corrected for pressure and temperature influences. The MOZAIC ozone sensors and their performances are described in Thouret et al. (1998). Their characteristics are: detection limit 2 ppbv and precision (2 ppbv +2%) (e.g. 2 ppbv at 10 ppbv O₃, 4 ppbv at 100 ppbv O₃). This corresponds to an upper limit on the error on measurements; studies of in-flight performance have shown better characteristics.

The humidity sensing device is an AD-FS2 thin-film sensor (Helten et al. 1998). The time response of the sensor in the lower/middle troposphere is 10 s, increasing to 1–3 min at 10–12 km altitude. The vertical resolution of humidity profiling during ascent and descent of the MOZAIC aircraft is better than 100 m in the lower part of the profile and around 500 m in the upper part of the profile. At cruise altitude the horizontal resolution of the humidity measurements is around 15–50 km. The mean total uncertainty of RH, as obtained over all MOZAIC-humidity measurements made in 1995, ranges from ±7% RH at a static air temperature of −55 °C (13 km) down to ±4% RH at −40 °C (10 km).

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