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TRANSPORT INTO THE TROPOSPHERE IN A TROPOPAUSE FOLD / CUT-OFF LOW SYSTEM

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ABSTRACT

A tropopause fold developed on the western flank of a trough in the 300mb flow on 6th October 1990. Radiosonde ascents over western Europe showed very dry stable layers beneath the jet stream in the potential temperature range 310-315K. These were evident on profiles from 12h on the 6th to 00h on the 8th October. ECMWF model assimilations were examined for this period to determine how well the model represented the radiosonde observations. Humidity fields were found to give better agreement than potential vorticity, probably because the PV is affected by the limited vertical resolution of the model.

Isentropic trajectories were calculated for the air in the fold as represented by the ECMWF assimilation at 00h on 7th. Those on the western edge of the fold split from the main flow and transferred to the troposphere, while those on the eastern side ended up in the cut-off low. A lower bound of 1.1×10^{14} kg is estimated for the amount of stratospheric air transferred into the troposphere by this fold.

1. INTRODUCTION

The synoptic development of the tropopause fold/cut-off low system began over the Atlantic on 6th October 1990, as a trough in the 300 mb flow propagated eastwards, extending southward as it did so. By 00h on the 7th (fig.1a) it lay over the UK, with a northerly jet streak over Ireland containing peak winds in excess of 60 ms^{-1}. By 12h on the 7th (fig.1b) the trough had extended down to 45°N and formed a small cut-off region, which enlarged and moved southwards on the 8th. This cut-off low remained over the western Mediterranean until 00h on 12th October.

This study is aimed at determining the evolution of the fold from radiosonde profiles, and using this information to determine how well the ECMWF operational assimilation represented the fold. The assimilation fields are then used to estimate the amount of stratospheric air irreversibly transferred into the troposphere by the fold.

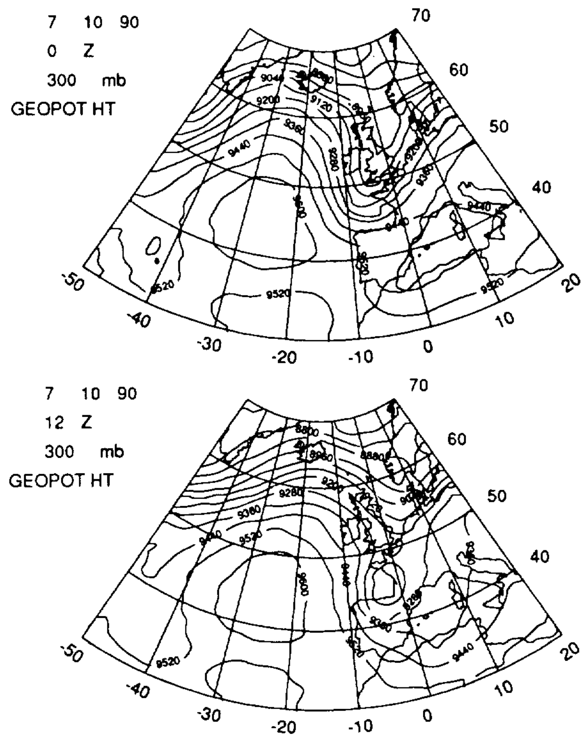

Fig.1: 300 mb geopotential height charts, 00h and 12h, October 7th 1990.

2. IDENTIFICATION OF THE TROPOPAUSE FOLD IN RADIOSONDE DATA

One of the characteristics of tropopause folds (indeed, the characteristic by which they were originally identified) is the presence of a very dry stable layer in the free troposphere at potential temperatures around 310-320K (i.e. those that span the midlatitude troposphere and polar lower stratosphere). This corresponds to the frontal zone beneath the polar jet stream, and therefore slopes downward on the equatorward side of the jet. Typically, folds occur on the western flank of deepening troughs in the upper tropospheric flow (Danielsen 1968), as occurred on 6-8 October 1990.

Radiosonde ascents for this period from western European stations were examined for the presence of such layers. Air was deemed to be stratospheric if the potential vorticity, calculated from the radiosonde stability and ECMWF analysis absolute vorticity (see 3a) exceeded $1.5\times10^{-6}\ Km^2(kgs)^{-1}$. The results are shown in fig.2. They show that a fold began near Iceland at 12h on 6th, extended along the whole western edge of the trough from near Iceland to north-west Spain at 00h on 7th, then propagated around the cut-off low and dissipated over southern Spain early on 8th October. This analysis, of course, cannot give a complete picture of the fold since there were very few radiosonde ascents over the ocean, but it does serve to delineate its overall development, and gives a good estimate of its depth (about 800m near 500 mb and nearer 500 m at lower levels, especially during the dissipating phase).

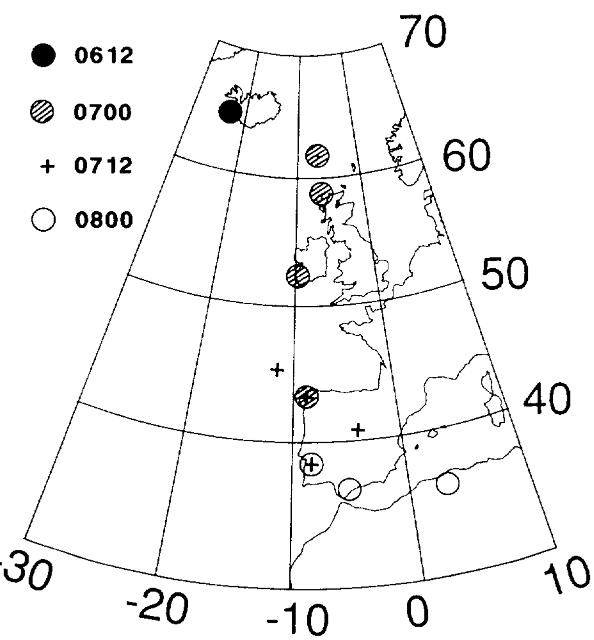

Fig.2: Extent and development of the fold as revealed at 12-hourly intervals by radiosonde profiles, from 12h on the 6th October (0612) to 00h on 8th (0800).

3. REPRESENTATION OF THE FOLD IN ECMWF ANALYSES

Model assimilation fields containing winds, temperature, geopotential height and specific humidity were available at 6-hourly intervals with a horizontal resolution of 1.5° and 12 vertical levels (1000, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70 and 50 mb), from 00h on 6th onwards.

a) Potential Vorticity

Stratospheric air is distinguished from tropospheric air by high values of potential vorticity ($> 2\times10^{-6}\ Km^2(kgs)^{-1}$). Isentropic maps of PV were derived from the model vorticity and static stability fields and compared with spot values derived using the radiosonde stability (sect. 2). The main PV anomaly propagating into the trough and the cut-off low was well represented on these charts, but the fold which formed its western edge was poorly defined: the model did not show high PV values dipping down sufficiently far into the troposphere. This may be attributed to its coarse vertical resolution: the fold was considerably thinner than the 2.5 km separating the model fields at 700 and 500mb.

b) Humidity fields

As previously mentioned, stratospheric air is also distinguished by being very dry. Specific humidity values were available directly from the model assimilation; thus, cross-sections of humidity perpendicular to the flow were examined for evidence of the fold. It was found that the model did indeed generate folded structures in its humidity assimilation between 310 and 315K, in the region below the jet stream, with tongues of very dry air (<100 ppmm) extending into the troposphere. The horizontal extent of these features is shown in fig.3. Several points may be made regarding these cross-sections:

i)The model began generating a fold at 12h on 6th, but did not show a tongue of very dry air extending into the

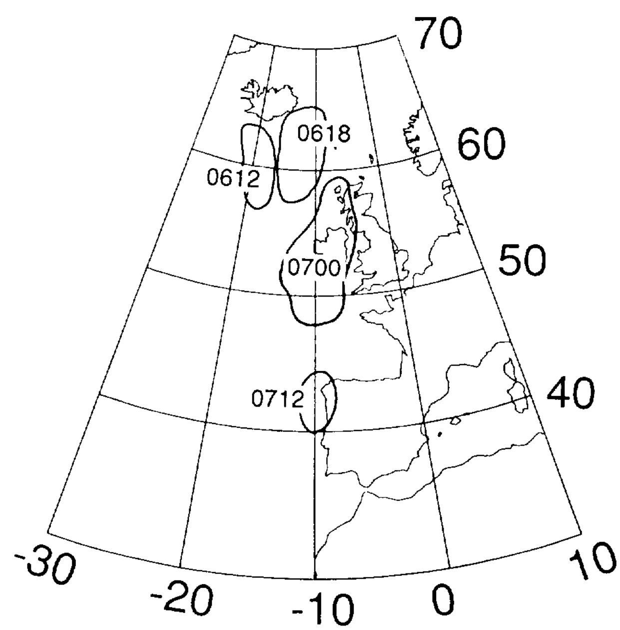

Fig.3: Development of the fold in the model humidity assimilations from 12h on 6th (0612) to 12h on 7th (0712).

troposphere - unlike the Keflavik radiosonde ascent at this time.

ii)The area of folded humidity contours propagated southwards more quickly than the PV anomaly, overtaking it by 12h on 7th.

iii)The model depicted a large fold at 18h on 6th, when radiosonde measurements would not have been available. This feature was larger than its counterpart at 12h. Thus, the dry tongues were not simply passive features of the assimilation, but were produced (or at least enhanced) by the model dynamics.

iv)No folds were produced in the model assimilation for 06h on 7th, and only a very small area of limited folding at 12h (at the time of a very prominent fold in the Coruna radiosonde ascent at 43.3°N, 8.4°W). During this period the base of the trough was cutting off and the fold (as shown by the radiosonde analysis) was propagating around the base of the low and dissipating. Thus the model humidity field did not represent the dissipating phase of the fold.

v)At 00h on 7th, the area of folded humidity contours extended over a considerably smaller latitude range than the fold depicted in the radiosonde analysis, which extended from just south of Iceland to Coruna.

vi)The model humidity field represented the fold more realisticaly than the derived PV. A similar result was shown in WMO (1986, Chapt.5). In fact, it appeared sufficiently realistic for the humidity field to be used to define the folded region at 00h on 7th October when estimating the amount of stratosphere-troposphere exchange in the episode.

The conclusion from this analysis is that the ECMWF assimilation represented the growth phase of the fold rather well (although, understandably, underestimating its extent), but that the decay phase was less well represented.

c) Trajectory analyses

Kinematic air parcel trajectories were carried out on the 310 and 315K surfaces for the air in the model-resolved fold at 00h on 7th. The results are summarised in fig.4 for 310K, where the horizontal locations of five groups of air parcels are shown at 00h on the 7th and after 24 and 48 hours. The evolution of these groups can be summarised as follows:

1)the westernmost group (no shading) began near 4.5 km altitude, and descended 700m before turning anticyclonically and rising. This group had descended by 2 km in the previous 24 hours.

2)trajectories immediately to the east of group 1 (diagonal shading), beginning near 4.8km, also descended by 700m,

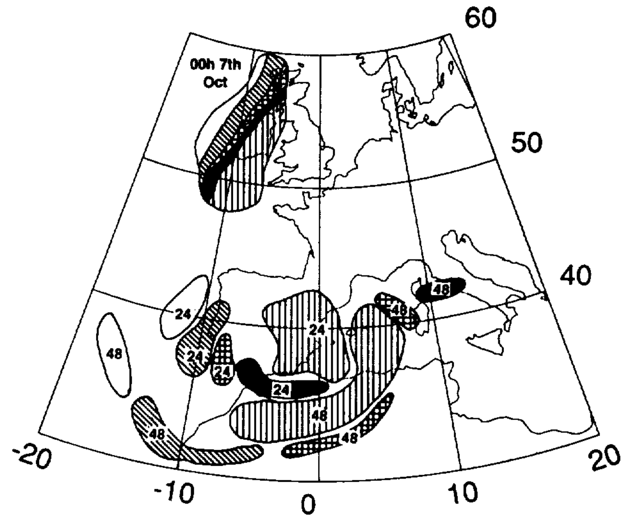

Fig. 4: Evolution of groups of trajectories over 48 hours, beginning in the model fold at 00h on 7th over Ireland. The shading differentiates between groups as defined in the text: group 1 (no shading) is the westernmost and group 5 (vertical hatching) the easternmost at 00h on 7th. The diagram shows end-points after 24 and 48 hours, identified by the appropriate numeral. Groups 1 and 2 transfer into the troposphere, groups 3 and 5 enter the cut-off low while group 4 continues flowing downstream beneath the jet.

but travelled southward towards the subtropics and continued to descend. Back-trajectories from this group showed that they had descended 2.2 km from their stratospheric origin at 00h on the 6th.

3)to the east of group 2, a strip of trajectories beginning at 5.4 km entered the cut-off low near 4.8 km early on 9th October (cross-hatched shading). These had descended by 2 km in the previous 24 hours,

4)further east again, trajectories originating near 5.7 km continued downstream beneath the jet at an altitude of 4.5-4.8 km (solid shading). These had descended by 1.9 km in the previous 24 hours.

5)the easternmost (and largest) group (vertical shading) had returned to the stratosphere in the base of the cut-off low by 00h on the 8th. All these trajectories started at heights between 5.8 and 6.1 km, and had descended by 1.5 km or less in the past 24 hours (700 m in the case of the easternmost trajectories near the Irish coast). Their heights within the cut-off low varied between 5 and 5.5 km. Some of them left the low in a second folding event at 06h on the 8th, associated with the injection of group 3 into the low 12 hours later.

The extent of the fold at 00h on 8th as shown on fig.4

closely matches the radiosonde observations (fig.2), lending support to the trajectory calculations. Additionally, isobaric specific humidity fields for 700mb at 12h on the 8th and 00h on the 9th (ie 36 and 48 hours along the trajectories) showed low humidity values near 35°N and 30°N respectively - corresponding to the group 2 trajectories at 310K.

d) Estimate of the irreversible STE in the fold.

The trajectories in groups 1 and 2 represent irreversible transfer of air from stratosphere to troposphere (air in the other groups returned, at least initially, into the stratosphere on the eastern side of the trough or in the cut-off low). The area of these regions at 00h on 7th was 120,000 and 140,000 km^2 respectively. The depth of the fold for the group 2 trajectories may be directly measured from the Valentia and Stornoway radiosonde profiles at 00h; this yields 550m (at 500 mb). The group 1 trajectories passed near a ship at 46°N, 11°W 12 hours later, where the fold was 450 m deep (at 650 mb); this was taken as the depth of this region at 00h. Group 1 therefore contained 4.3×10^{13} kg and group 2, 6.7×10^{13} of air: a total irreversible transfer of 1.1×10^{14} kg.In fact, the radiosondes show that the fold was about twice as long as the model representation, suggesting that this figure should be increased, perhaps by a factor of around 2. It is also entirely likely that the true fold extended westwards of that shown by the model, again increasing the estimate of the mass of air transferred.

An estimate of the total amount of ozone transferred may be made by reference to the PV in groups 1 and 2. According to Beekmann et al (1992) the ratio between ozone mixing ratio and PV in the lower stratosphere is about 40 ppb/PV unit. From the radiosonde-derived PV fields at 00h and 12h, the PV in group 2 was estimated as 2.9 PV units and that in group 1 as 1.8 PV units. Thus the total no. ozone molecules contained in these two regions was 2.2×10^{32} - an excess of 8×10^{31} molecules over a normal tropospheric background of 50 ppbv (Beekmann et al, 1992).

4. CONCLUSIONS

The main objective of this case study was to study the potential application of ECMWF operational analysis fields to the study of stratosphere-troposphere exchange, and in particular tropopause folds. By using cross-sections from the model, specific humidity fields and an extensive trajectory analysis, it was seen that the model did resolve the growth phase of a fold which developed in a southward plunge of the polar jet stream over Ireland. Representation of the dissipating phase was less satisfactory. Careful analysis of radiosonde data is clearly essential when studying folds with the ECMWF model.

The value of around 2×10^{14} kg of stratospheric air irreversibly transferred into the tropospheric in this event is rather small compared to previous studies (e.g 6×10^{14} kg by Reiter and Mahlman, 1965). However, further potential for stratosphere-troposphere exchange is revealed by the trajectories in categories 3 and 5: some of the air which formed the base of the cut-off low had passed through the fold. Small-scale mixing is prevalent in baroclinic zones due to the low Richardson number, so that air returning to the stratosphere contains a mixture of the two air masses - exactly as observed in the base of a cut-off low by Bamber et al (1983). Furthermore, the injection of group 3 trajectories into the low was connected with a second fold along its western flank and the transfer of further air parcels into the troposphere.

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