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Atmospheric Environment 39 (2005) 6537–6549
ATMOSPHERIC ENVIRONMENT
www.elsevier.com/locate/atmosenv

Extratropical case study of stratosphere–troposphere exchange using multivariate analyses from mozaic aircraft data

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Received 21 March 2005; received in revised form 30 June 2005; accepted 13 July 2005

Abstract

A multivariate analysis methodology, applied to ozone, water vapour and potential temperature data collected from MOZAIC aircraft allowed to identify and to quantify three types of air masses directly linked to stratosphere-troposphere exchanges (STE). These air masses occurred in February 1997 over the North Atlantic during the development of a Rossby wave, which is manifested in the form of four different structures, namely trough, ridge, streamer and cut-off low (COL). Here a study is conducted on 20 isobaric (i.e. at 230 hPa) flights crossing all these upper-level structures. It is shown that the first type of air mass corresponds to a mixed zone between the stratosphere and the troposphere when the tropopause is poorly defined and when there exist medium values and weak gradients of ozone, potential temperature and humidity. The second type of air mass reveals an irreversible transport from the troposphere to the stratosphere for all these structures leading to a "wet" stratosphere with high values of water vapour. The third type of air mass corresponds to the classical stratosphere with high values of ozone and low values of water vapour. The comparison with the model results of Kowol-Santen et al. (2000) shows that these first two air masses are directly linked to either diabatic processes or turbulent diffusion depending on the orientation and the type of the structure. The western side of the trough (with no mixing zone on the eastern side) and the ridge are dominated by clear air turbulence (CAT). On the other hand, the decay of the COL seems to be the result of strong convection on its northern and eastern flanks. Concerning the decay of the streamer, it is found to be due to both diabatic and turbulent processes. The above results suggest that the existence of a mixing zone during STE seems to be a more realistic concept instead of that where the tropopause is considered as a surface.

Keywords: MOZAIC; Stratosphere–troposphere exchange; Trough and ridge; Cut-off low; Streamer; Multivariate analyses

1. Introduction

Between mid- and high-latitudes, one of the main stratosphere-troposphere exchange (STE) processes is the formation of a tropopause folding associated with upper level troughs and cut-off low (COL) systems (Reed, 1955; Hoskins et al., 1985; Keiser and Shapiro., 1986; Vaughan et al., 1994, Holton et al., 1995). COLs are closed cyclonic circulations in the upper-level flow (i.e. around 300 hPa) resulting from the equatorward excursion of a trough. In dynamical terms, COLs constitute isolated regions of high potential vorticity (PV) on isentropic surfaces which span the troposphere and the lowermost stratosphere (Hoskins et al., 1985); this way COLs can have an important role for STE

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1352-2310/$ - see front matter
doi:10.1016/j.atmosenv.2005.07.019

(Price and Vaughan, 1993). In addition, from the above dynamical view on isentropic surfaces, streamers are directly linked to the irreversible deformations of the PV contours; for example the Rossby-wave breaking (Hoskins et al., 1985; McIntyre, 1993) has been observed using satellite water vapour imagery (Appenzeller and Davies, 1992) and PV contour advection techniques (Norton, 1994; Plumb et al., 1994; Appenzeller et al., 1996).

The sub-synoptic irreversible mixing processes that can occur with the decay of a tropopause folding, a COL, and/or a streamer are: (1) convective clouds, which penetrate the tropopause, latent heat release in the lower troposphere or radiative effect from the top of the clouds; these processes are called diabatic (Wirth, 1995a); (2) turbulent diffusion by clear air turbulence (CAT) in the region of large wind shear, such as the jet stream (Shapiro, 1978); (3) the stretching and rolling up (Appenzeller et al., 1996), and the mixing occurring with molecular or turbulent diffusion or diabatic processes, and (4) the breaking of gravity and other particular waves around the tropopause (Danielsen et al., 1991). Diabatic processes and/or CAT are more efficient and faster than molecular diffusion. Nevertheless, the relative importance between CAT and diabatic processes is extremely variable and still not entirely clarified, and it also depends on the meteorological conditions (Price and Vaughan, 1993; Lamarque and Hess, 1994). Although much research has already been carried out on STE, identifying and quantifying these exchanges is, however, complex and requires the combination of dynamics and chemistry. As a result, the details of the STE processes remain poorly understood, especially the knowledge of bi-directional irreversible transports across the tropopause (e.g. stratospheric air mixing in the troposphere and vice versa).

The work described in this paper initially deals with the study of STE processes and their resulting air masses in a ridge, trough, streamer and COL. These upper-level structures took place in February 1997 over the North Atlantic and Western Europe. In order to quantify the exchange across the tropopause, Kowol-Santen et al., (2000, hereafter referred to as KS00) have already analysed this episode using two different methods: the Eulerian formulation of Wei (Wei, 1987) and the Lagragian trajectory analysis. Their estimations have been obtained by implementing the European Air Pollution Dispersion (EURAD) model system. In order to synthesize and compare between the experimental and model results, here we focus on 20 flights from the MOZAIC (Measurement of OZone and water vapour by Airbus In-service airCraft) programme that crossed the same as in KS00 trough and ridge, streamer and COL structures in February 1997 over the North Atlantic and Western Europe.

In this work, the MOZAIC database is presented in Section 2. The multivariate analyses (MA), such as Principal Components Analysis (PCA), Cluster Methods (CM) and Discriminant Analysis (DA), are shown in Section 3. The evolution of a trough into a streamer and a COL is studied in Section 4. In Section 5 the MA are then used to discriminate air masses based on 20 MOZAIC flights crossing the trough, ridge, streamer and the COL structures. In section 6 the MOZAIC data are compared with the model results of KS00 and finally conclusions are presented in section 7.

2. The MOZAIC database

The EC-funded MOZAIC programme was designed to collect in situ ozone and water vapour data by using automatic equipment installed on board five long-range Airbus A340 aircraft that fly regularly to many destinations around the world since August 1994 (Marenco et al., 1998). The aim of the programme is to build a large database of measurements in order to study the chemical and physical processes in the atmosphere and, hence, to help validate global chemistry transport models. Most of the MOZAIC data are recorded at northern mid-latitudes (i.e., Europe, North America, China and Japan) but the programme also provides data over the northern tropics (i.e. northern South America, Africa, and the Indo-Asian subcontinent) and some in the southern hemisphere, mostly Brazil and South Africa. For further details on MOZAIC see Marenco et al., (1998) and a map of coverage, which is periodically updated, can be found on the MOZAIC Website (http://www.aero.obs-mip.fr/mozaic/). The MOZAIC equipment at time intervals of every 4 s (corresponding typically to a flight distance of about 1 km) provide measurements of the aircraft position, atmospheric pressure, temperature, zonal and meridional wind, relative humidity (RH) with respect to liquid water, and ozone mixing ratio. For ozone, a dual beam UV absorption instrument (Thermo-Electron, model 49–103) is used with an estimated accuracy of 2 ppbv ± 2% (Thouret et al., 1998a). For water vapour, a capacitive RH sensor (Humicap -H, Vaisala) is used with an overall uncertainty of ±4–5% (Helten et al., 1998).

3. Methodology of MA

The MA applied in the present study include PCA, CM and Linear Discriminant Analysis (LDA). PCA is achieved by finding linear combinations (i.e., principal components) of the original variables, which account for as much as possible of the original total variance (Jolliffe, 1986). PCA is performed to obtain new