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Mesoscale analysis of transport across the subtropical tropopause

Johanna Kowol–Santen and Gérard Ancellet
Service d'Aéronomie du CNRS, Paris

Abstract. An airborne ozone lidar has been operated on March 26 and 27, 1999 in order to document the ozone distribution near the subtropical jet (STJ) in the 5°W–15°W longitude band which corresponds to an area where the STJ accelerates and interacts strongly with mid–latitude cyclones. The two main features observed are a tropopause fold in the region where the STJ accelerates and an intrusion of subtropical tropospheric air into the mid–latitude lower stratosphere. A mesoscale meteorological model is applied with high vertical resolution in order to study the strong layering in the upper troposphere and lower stratosphere.

Introduction

The dynamical processes associated with the subtropical jet determine the transport across the subtropical tropopause modifying the budget of chemically reactive minor constituents in the lower stratosphere and upper troposphere.
To get a better insight especially in the transport of tropospheric tropical air into the mid–latitude stratosphere *Dessler et al.* [1995] have used water vapor profiles. More recently, ground based lidar observations with their good vertical and temporal resolution have revealed the occurrence of large scale tropopause folds at the southern hemispheric STJ [*Baray et al.*, 2000]. Ground based observations are however limited in their ability to document a true meridional distribution across the jet. Although there is already experimental evidence of transport across the subtropical tropopause neither the amount of exchange nor the possible importance of mesoscale dynamical mechanisms have as yet been well characterized.
This paper presents temporally and spatially high resolved airborne lidar measurements carried out in the subtropical upper troposphere and lower stratosphere. The high resolution of the measurements allows to identify large numbers of vertical layers in this area in a plane perpendicular to the jet. In order to analyze the underlying dynamical processes we perform mesoscale meteorological model simulations. It is in particular necessary to use a high vertical resolution of the model to capture the layered structure.

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The paper is structured as follows: In section 2 the aircraft campaign is presented. Section 3 describes the mesoscale model applied for the interpretation of the measurements. The results of potential vorticity and trajectory analysis are presented in section 4. Finally, conclusions and perspectives are given in section 5.

Campaign description

On March 26 and 27, four aircraft flights have been performed between France and the west coast of North Africa. An Airborne Lidar for Tropospheric Ozone (ALTO) measurements [*Ancellet and Ravetta*, 1998] was installed on board of a Mystère 20 aircraft to achieve a better temporal and spatial continuity in the analysis of the ozone distribution near the subtropical jet stream. The two flight tracks used in this paper are indicated by the thick black lines in Figure Figure 1. The meteorological situation under investigation was characterized by a strong interaction between the STJ and a mid–latitude low pressure system. The area where the subtropical jet accelerates was located between 20°N and 30°N, and east of 10°W with maximum wind speeds of more than 70 m/s at 200 hPa. A cut-off low formed over western Europe and drifted southward.

Model description

Méso–NH is a mesoscale non–hydrostatic anelastic equation model developed by Météo France and Centre National de Recherche Scientifique [*Anonymous*, 1999]. Key parameterizations applied for the presented simulation include a radiance scheme according to *Morcrette et al.* [1986], a mass conserving positive transport scheme, a convection parameterization according to *Kain and Fritsch* [1993], and a turbulence scheme following *Bougeault and Lacarrère* [1989]. The presented simulation was carried out with a horizontal resolution of 50 km on a Mercator conformal map projection with 90×90 grid points centered at 15°W and 32°N. In the vertical a terrain–following coordinate system [*Gal–Chen and Sommerville*, 1975] is used with 59 unequally spaced levels from the surface up to 21 km. A high vertical resolution of 300 m is applied for the upper troposphere and lower stratosphere, between 8.5 and 15 km. For initial and boundary conditions ECMWF analyses with a spectral resolution T213 and 50 hybrid levels are used. In order to simulate mesoscale dynamical processes two days before the measurements and to an-

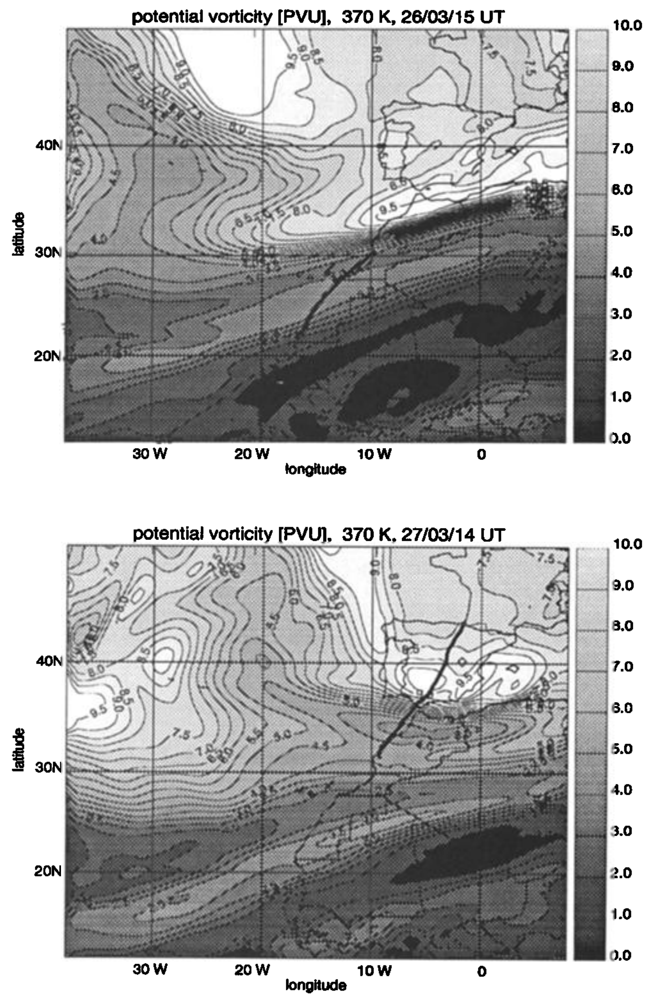

Figure 1. Méso–NH potential vorticity at 370 K on March 26 at 15 UTC (upper frame) and March 27 at 14 UTC (lower frame). The bold lines mark the flight tracks from Agadir to Nouhadibou on March 26 and from Agadir to Biarritz on March 27. PV values in heavy grey areas are less than 2 PVU.

alyze the temporal evolution of the observed features the model was initialized on March 24, 1999 at 0 UTC and run for a time period of 96 hours.

For the study of exchange across the subtropical tropopause two passive tracers were implemented into the model according to the potential vorticity distribution: a stratospheric tracer was initialized for PV$\geq$2 PVU and a tropospheric tracer for PV$<$ 2 PVU.

Three–dimensional trajectory calculations were performed using the wind fields from Méso–NH with a temporal resolution of one hour. The parcel positions are updated every ten minutes by interpolating the modeled winds and advecting the parcels with a two–step iteration in three dimensions. The evolution of potential vorticity is calculated along the trajectories. Large ensembles of trajectories can then be used to quantify the exchange across the tropopause.

Considering the numerical and methodical differences between these two techniques one may place more confidence in the soundness of the flux estimates when the difference between the results remains small [*Wirth and Egger*, 1999].

Potential vorticity and trajectory analysis

Figure 1 shows the potential vorticity field at 370 K on March 26 at 15 UTC and March 27 at 14 UTC as calculated using Méso–NH results and the associated flight tracks.On March 26 the aircraft crossed the STJ. The ozone vertical cross section along the flight track is presented in Figure Figure 2. During the first thirty minutes of this flight the ozone distribution exhibits a layer of high ozone (200–250 ppb) between ~9.5 and 11.0 km. On the cyclonic edge of the jet the isentropic potential vorticity shows strong gradients (Fig. 1). Vertical cross sections of potential vorticity across the frontal zone as well as along the flight track confirm the enfolding of the PV–layers 1 to 5 PVU down to ~9 km on the cyclonic side of the STJ (Fig. 2). This shows the good quality of the Méso–NH analysis.

Backward trajectories calculated in this area show confluence of air parcels advected southeastbound from the North Atlantic and northeastbound from the subtropics. The area of confluence indicates the region of upper tropospheric frontogenesis which is prerequisite to the formation of tropopause folds [*Keyser and Shapiro*, 1986]. The area of frontogenesis is larger than observed at the mid–latitudes and extends over up to 3000 km. But, it remains smaller than the planetary–scale tropopause folds observed by *Baray et al.* [2000] in the Indian Ocean near the southern hemispheric STJ.

During the first part of the flight from Agadir to Biarritz on March 27 the measurements were made on the cyclonic edge of the STJ. The wind gradients at 200 hPa were weaker compared to those found during the previous day meandering towards southern Spain. In the second part of this flight, the aircraft entered the edge of a mid-latitude cut–off low. The isentropic potential vorticity (Fig. 1) exhibits a tongue of low PV ($<$ 4 PVU) between 30°N and 40°N. The analysis of the temporal evolution of this PV–anomaly together with 3D backward trajectories shows that it originates 4 days earlier at the east coast of North America. The development of an upper level ridge led to poleward transport of subtropical air. The upper level cyclogenesis and subsequent development of a cut–off low over south–western Europe interacted with this PV–anomaly on March 27 between 0 and 20°W.

In agreement with this northward isentropic transport of subtropical air and simultaneous southward transport of mid–latitude air the vertical distribution of ozone as observed by the airborne lidar (Fig. Figure 3) shows a layer of very low ozone (80–100 ppb) between ~11.5 and 13.5 km on the top of a stratospheric ozone layer (400 ppb). In contrast to mid-latitude potential vorticity anomalies where convective clouds de-

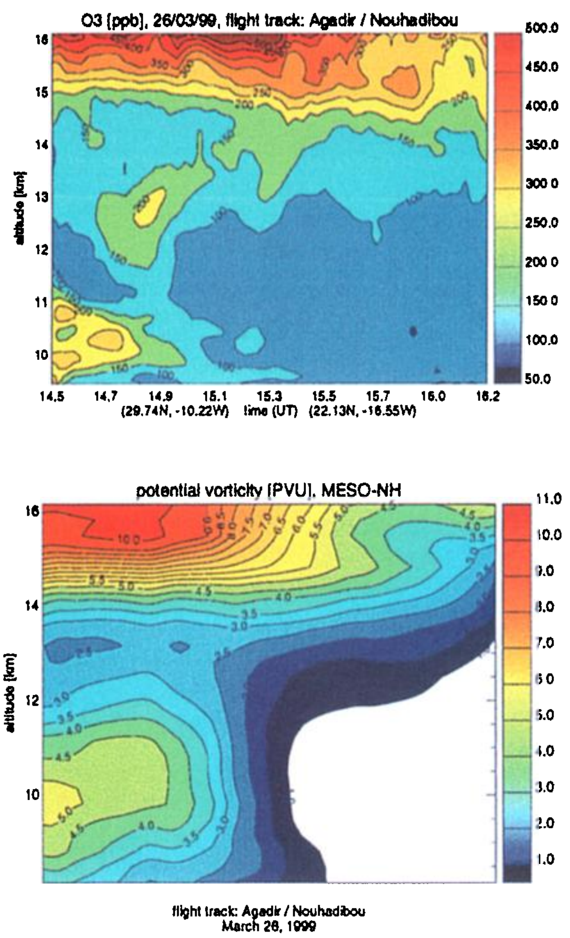

Figure 2. Vertical profile of the ozone mixing ratio (upper panel) and potential vorticity as calculated by Méso-NH (lower panel) along the flight track from Agadir to Nouhadibou on March 26, 1999.

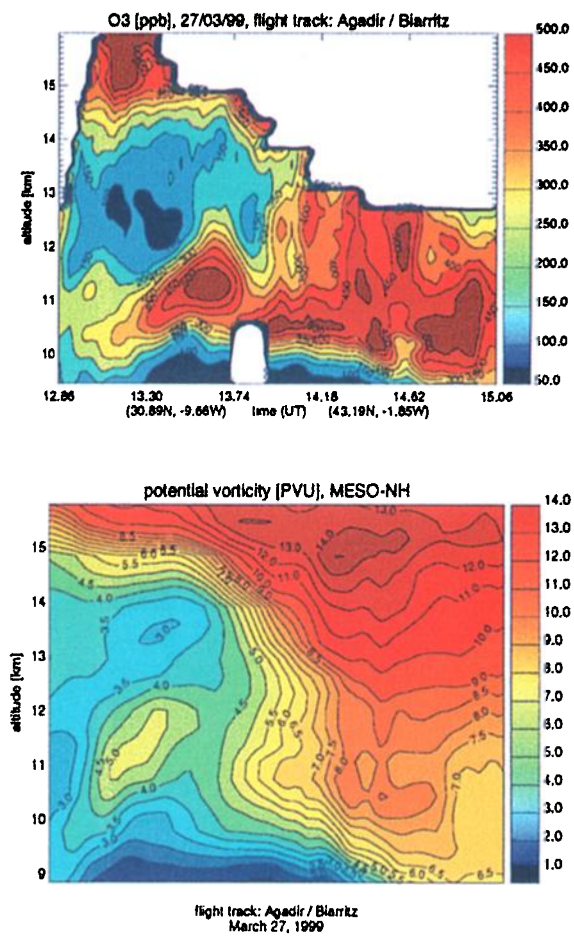

Figure 3. Vertical profiles of the ozone mixing ratio (upper panel) and potential vorticity as calculated by Méso-NH (lower panel) along the flight track from Agadir to Biarritz on March 27, 1999.

velop [*Ravetta and Ancellet*, 1999], the vertical ozone gradient at the tropopause (100–200 ppb) remained stable during the whole flight (Fig. 3). This confirms the strong dependence of the ozone vertical gradient on the development of convection. The observed subtropical tropospheric air mass extended in the horizontal over ~500 km which coincides with the tongue of low PV moving towards southern Spain (Fig. 1). Three-dimensional backward trajectories released at different altitudes along the flight track confirm the different origin of the sampled air masses. Parcels released between 170 and 230 hPa were advected eastwards within the tongue of low PV. Trajectories started above 170 hPa and below 230 hPa originate in the mid-latitude cyclone.

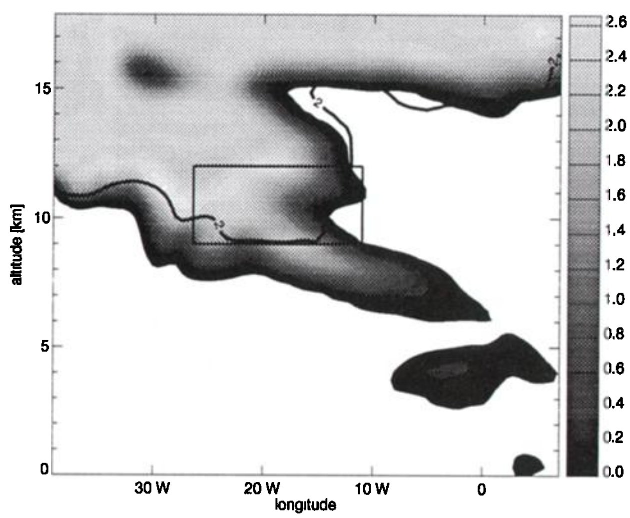

Figure 4. Vertical cross section of the stratospheric passive tracer distribution (arbitrary units) and the 2-PVU-surface (bold line) on March 27, 1999 at 12 UTC along 27°N. The box marks the area where forward trajectories were released (see text).

Conclusions and perspectives

The analysis of the ozone distribution at the northern hemispheric subtropical jet using high resolution airborne lidar measurements reveals strong layering in the tropopause region. The application of a mesoscale model with a high vertical resolution in the upper troposphere and lower stratosphere makes it possible to identify the different layers by their dynamical characterization. The question which remains is how much exchange between the mid-latitude lower stratosphere and the subtropical upper troposphere is induced by this interaction between the STJ and the mid-latitude low pressure system.

As we have shown that the mesoscale model is suitable to simulate the subtropical tropopause dynamics, we can now apply numerical methods based on this mesoscale model in order to analyze the exchange of air mass between troposphere and stratosphere. Figure Figure 4 shows as an example a vertical cross section of the stratospheric tracer along 27°N and of the 2-PVU-surface on March 27 at 12 UTC. The results reveal a downward transport of stratospheric air masses across the tropopause in particular at the tip of the fold. At the same time tropospheric air is transported into the stratosphere on the warm anticyclonic side in the thermal direct cell. Another approach is to use large ensembles of trajectories. An ensemble of 180 forward trajectories released along 27°N between 200 and 300 hPa (as indicated by the box in Fig. 4) shows also transport across the tropopause. 43% of the trajectories originating in the stratosphere become tropospheric within 6 hours. 7% of the trajectories enters the stratosphere. Both three-dimensional trajectory analysis and budget calculations of the passive tracer will be more thoroughly compared in a future work and the aim is to quantify the amount of air mass and ozone exchange between the mid-latitude lower stratosphere and the subtropical upper troposphere.

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Johanna Kowol-Santen and Gérard Ancellet, Service d'Aéronomie (UMR 7620), Université Pierre et Marie Curie, Tour 15 - 5ème étage, case 102, 4 Place Jussieu, 75252 Paris Cedex 05, France. (e-mail: kowol@aero.jussieu.fr, gerard.ancellet@aero.jussieu.fr)

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