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Planetary-scale tropopause folds in the southern subtropics

J.-L. Baray[1], V. Daniel[2], G. Ancellet[3] and B. Legras[2]

Abstract. Daily measurements of tropospheric ozone at La Reunion Island (55 E, 21 S) in July 1998 show that ozone layers are quasi-permanent in the troposphere between 6 and 10 km with values reaching 80 to 100 ppbv. Meridional cross sections of potential vorticity reveal that these layers are related to tropopause folds beneath the subtropical jet. Folding is persistent and extends over a considerable longitude range from mid-Atlantic to mid-Pacific. We suggest that this structure is due to the convergent flow associated to the descent branch of the Hadley circulation during austral winter.

1. Introduction

In the subtropics, the isentropic surfaces from 300 K to 370 K cut across the tropopause. Though stratosphere/ troposphere exchange is limited by the large potential vorticity jump (> 1 PVU; 1 PVU=10^{-6} K kg^{-1} m^2 s^{-1}) associated with the subtropical jet, synoptic scale instabilities in the upper troposphere can induce transport across the tropopause [*Chen*, 1995]. Experimental evidence already exists of a two-way exchange, using e.g. the water vapor distribution in the lowermost stratosphere [*Dessler et al.*, 1995] or ozone mixing ratios from aircraft observations [*Folkins and Appenzeller*, 1996; *Gouget et al.*, 1996]. However the previous conclusions are mainly based on single case studies. In this paper, we present the results of an intensive campaign of daily ozone soundings which has been conducted in the winter season at La Réunion Island and Johannesburg. In early winter ozone rich layers in the upper troposphere are not associated to biomass burning products [*Thompson et al.*, 1996] in the southern hemisphere. Complementary ozone profiles are also available in the mid troposphere up to 10 km at Johannesburg and Cape Town during the same period thanks to the programme MOZAIC (Measurements of OZone by Airbus In service airCraft) [*Marenco et al.*, 1998].

2. Campaign description

From July, 1st to July 31, 1998, 14 ozone soundings have been performed at La Réunion Island (21 S, 55 E) and 8 near Johannesburg, South Africa (26 S, 28 E) using ECC ozonesondes and meterological sensor from Vaisala. Balloon launches were scheduled according to potential vorticity maps calculated from ECMWF forecast, when the probability was high for a strong deformation of the potential vorticity surfaces. In addition to the ozonesondes, a tropospheric ozone DIAL lidar has been operated at La Réunion Island with nearly daily measurements during the whole month. Therefore, there is no bias towards anomalously large tropospheric ozone when the two dataset are combined. Vertical ozone profiles obtained with ECC and DIAL were in good agreement over the lidar vertical range, that is most of the tropical troposphere. Balloon soundings are also measuring temperatures and allow us to derive directly the ozone distribution as a function of potential temperature.

3. Campaign results

Figure 1 includes all the observations made by the lidar and the ozonesondes during the campaign at La Réunion. An ozone layer with mixing ratio reaching 80 to 100 ppbv is seen over most of the month within an altitude range of 5 to 12 km. These values are 50 ppbv above standard tropospheric values observed during spring time [*Baray et al.*, 1998]. The standard values of 30 to 50 ppbv are observed below 5 km and within the layer which, except on a few days, clearly separates the ozone layer from the tropopause below 16 km. The ozone enhancement in the mid-troposphere is similar to that found in northern hemisphere mid-latitude folds [*Browell*, 1987; *Ancellet et al.*, 1991], but the persistence over a whole month at a given location is strinkingly different from mid-latitude observations [*Beekmann et al.*, 1997]. The small spatial extent of the mid-latitude folds makes them difficult to detect even though the frequency of cyclogenesis may be as large as one event every three days within a ten degree circle. The easy detection of folds on the southern subtropical jet suggests a much larger spatial extent.

The ozone profiles measured during the same period at Johannesburg (not shown) exhibit the same features though the sampling frequency is lower than at La Réunion. The MOZAIC aircraft ozone measurements during the transit flights between Johannesburg (26 S, 28 E) and Cape Town (33 S, 19 E) show that ozone is present in large amounts only in the mid-troposphere at latitudes north of the subtropical jet, while ozone mixing ratios less than 50 ppbv are observed up to 10 km in Cape Town, south of the subtropical jet.

4. Meteorological PV analysis

Ertel potential vorticity (PV) has been calculated from ECMWF analysis retrieved with horizontal resolution T213 and 31 levels in the vertical. Figure 2 shows a meridional cross section of PV on July 17 with a corresponding ozone profile taken at La Réunion on the same day. The tropopause is easily seen as the surface bounding small tro-

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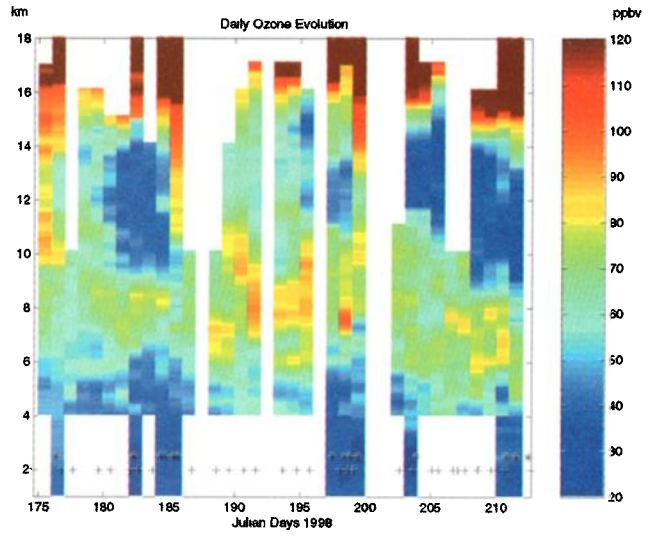


Figure 1. Evolution of the tropospheric profile of ozone mixing ratio over La Réunion during July 1998. This figure combines lidar and ECC soundings on a daily basis. Crosses at the bottom indicate lidar observations and stars indicate balloon soundings.

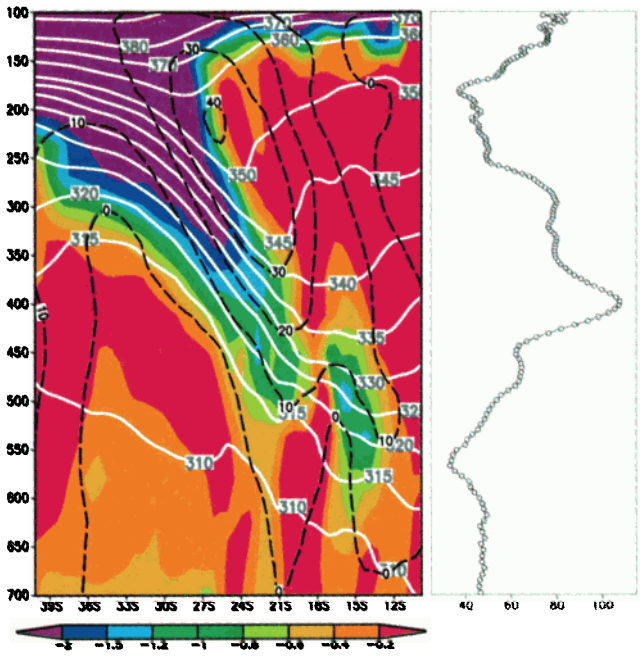


Figure 2. a) Meridional cross-section at 55 E on July 17, 1998, at 00h UT between 10 S and 40 S in latitude and between 700 hPa and 100 hPa in the vertical. PV is shown in color according to the bottom scale in PVU. Contours of potential temperature are shown in solid line with an interval of 5 K. Contours of zonal winds are shown in dashed lines with an interval of 10 m.s^{-1}. b) Vertical ozone profile in ppbv measured by lidar at La Réunion (21 S) at 01h23 UT on the same day.

pospheric PV gradients and large stratospheric gradients. A strong fold is located beneath the jet with isentropic layers between 315 K and 345 K plunging within the troposphere. The entrainment of stratospheric air within the fold, marked by high values of potential vorticity, is in good agreement with the ozone layer observed above La Réunion. The ozone maximum at 400 hPa almost coincides with the center of the fold at 21 S, and ozone values less than 50 ppb between 270 and 170 hPa corresponds to PV as low as 0.2 PVu. Error on low PV value estimates are obviously larger in the tropics where the planetary vorticity remains low. The existence of a stratospheric intrusion is confirmed by three-dimensional trajectory calculations (not shown).

Other maps plotted every 12 hours during July 1998 show that the fold is quasi-permanent though its latitudinal extent varies from day to day. The longitudinal extent has been be investigated by plotting three-dimensional maps of the fold boundary, defined here as the surface of constant PV=-1.2 PVU, that is the value at the ozone maxima in Figure 2. The striking result is that for most of the days in July 1998, the fold extends, essentially without break, from mid-Atlantic to Central Pacific. Figure 3 shows a remarkable situation on July 25 where the flow is almost zonal and the fold extends eastward from 0 over 200°of longitude. Figure 4 shows that the probability distribution of the latitudinal extent of the fold over the longitudinal range of Figure 3 is almost linear from 0 to 3.5°. On the contrary, it was found that the probability of no-folding is 84% in the longitude range 0-160 W. These results are weakly sensitive to the precise PV surface considered. The monthly average probability distribution over July 1998 still exhibits large number of folds: 30% of the sections between 0 and 200 E and 40% between 30 E and 80 E with more than one degree in latitude extent.

On other dates, the frontal structure is modulated by travelling anticyclones on the northern side of the jet associated with cyclonic perturbations on its southern flank but the longitudinal size of the front is always much larger than the size of an individual perturbation and persists in the wake of the perturbations.

5. Relation with the Hadley circulation

The extension of the fold and its zonal character calls for a specific explanation which differs from that applying to mid-latitude frontogenesis where the main role is played by the confluent circulation induced by a baroclinic wave

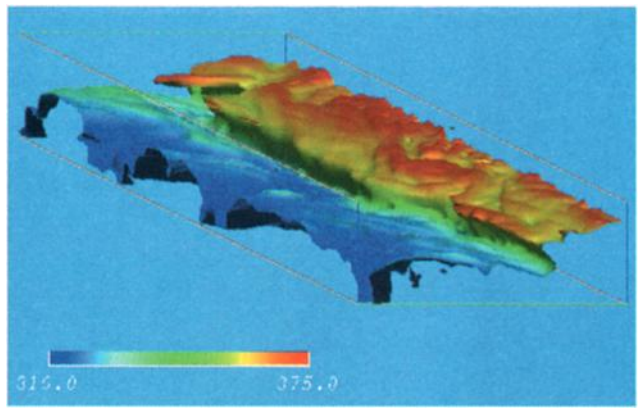


Figure 3. Three-dimensional map of the tropopause defined as the surface PV = -1.2 PVU on July 25, 1998 at 00h UT. The surface is shown within a box extending from 0 to 200 E in longitude, from 5 S to 45 S in latitude and from 600 to 30 hPa in the vertical. Color indicates the potential temperature according to the scale in the lower left corner.

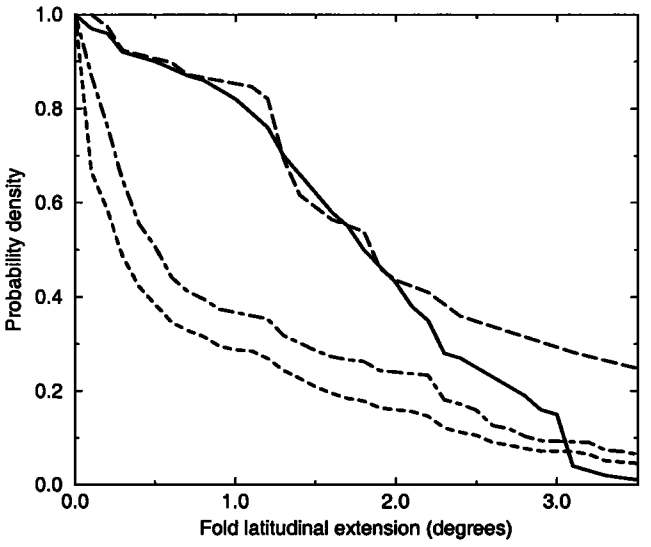


Figure 4. Probability density of the latitudinal extent of the fold measured as the distance between the two turning points of the S-shaped contour for PV = -1.2 PVU. The measure is performed on meridional sections every 2 degres in lontitude. $P(y)$ is the number of sections for which the fold is larger than y divided by the number N of sections. The value $y = 0$ corresponds to no-fold cases and cases where the contour is visually vertical, that is the frontier between fold and no-fold cases. Solid line: probability density for $N = 100$ sections on July 25, 1998 at 00h TU between 0 and 200 E; the number of no-fold sections is zero. Long-dashed line: same as previously but for PV = -2 PVU. Dot-dashed line: probability density for $N = 3000$ sections between 0 and 200 E and from July 1 to July 30 at 00h TU. Short-dashed line: probability density for $N = 750$ sections between 30 and 80 E and from July 1 to July 30 at 00h TU

[*Keyser and Shapiro*, 1986]. This mechanism cannot explain how the fold remains in the wake of the perturbation since this latter travels eastward less rapidly than the jet along which the fold is advected. We rather require a stationary forcing upstream of the domain where the jet fold is observed. Figure 5 shows the divergence of the analysed wind at 200 hPa which has been averaged over the whole month of July 1998 since the instantaneous maps are dominated by small-scale noise. Strong negative values of the divergence are observed in a latitude band between 20 S and 30 S over the jet in particular in the Atlantic near 20 S and 5 W. This convergence is a mark of the descending branch of the Hadley circulation associated with the Asian monsoon return flow. The magnitude reaches 10^{-5} s^{-1} over a fairly large region. As a matter of comparison, a confluence of the same magnitude is able to generate a front within two days [*Keyser and Pecnick*, 1985].

6. Concluding remarks

Daily survey of ozone profile above La Réunion and meteorological data from ECMWF analysis reveal the persistence and the large spatial extent of frontogenesis beneath the austral winter subtropical jet. Although the validity of mesoscale analysis is sometimes questioned in the southern hemisphere, the consistency between ozone observations and the analysis is a strong favorable indication. If the phenomenon is associated, as we believe, with the descending branch of the Hadley circulation, it is likely to reproduce with the same intensity during each austral winter when the Asian monsoon circulation is well established. Preliminary investigations show that the phenomenon has no counterpart in the northern hemisphere winter. Further investigations are required to link the convergence to frontogenesis. We have only shown that the average convergence has the required magnitude. It is likely that the shear between the upper tropospheric jet and the surface easterlies may play a role too. It is unclear how much exchange between the stratosphere and the troposphere is induced by the fold since the deformation of the tropopopause can be reversible to some extent. We can, however, infer that by its size and its persistence, the fold offers considerable potential for exchange. This effect has to be estimated by studying the small-scales that escape to our present analysis [*Langford and Reid*, 1998] and to be compared with the often advocated role of biomass burning.

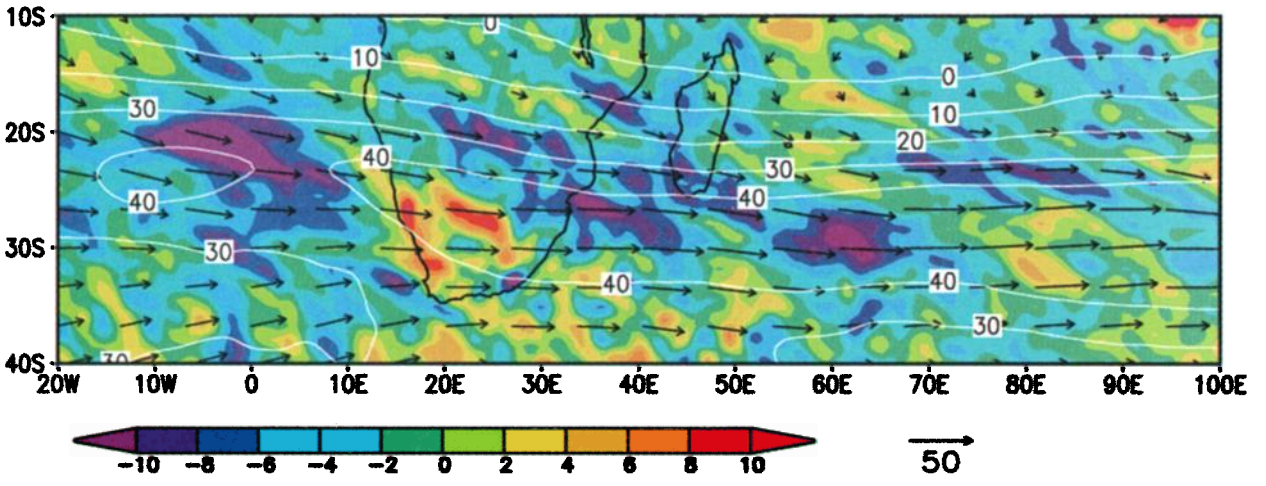


Figure 5. Divergence of the horizontal wind at 200 hPa calculated from the ECMWF analysis and averaged over July 1998. Unit: 10^{-6} s^{-1}. Solid contours: average zonal wind in m s^{-1}. Arrows: averaged horizontal wind in m s^{-1}.

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