



## Abstract

This paper reports on an increase of ozone event observed over Kerguelen (49.4° S, 70.3° E) in relationship with large-scale isentropic transport. It is evidenced from ground-based observations, together with satellite global observations and assimilated fields.

The study is based on the analyses of the first ozonesonde experiment never recorded at the Kerguelen site in the framework of a French campaign called ROCK that took place from April to August 2008.

Comparisons and interpretations of the observed event are supported by co-localised SAOZ observations, by global mapping of tracers ( $O_3$ ,  $N_2O$  and columns of  $O_3$ ) from Aura/MLS and Aura/OMI experiments, and by model simulations of Ertel Potential Vorticity initialised by ECMWF (European Centre for Medium-Range Weather Forecasts) data reanalyses.

Satellite and ground-based observational data revealed a consistent increase of ozone in the local stratosphere by mid-April 2008. Additionally, Ozone ( $O_3$ ) and nitrous oxide ( $N_2O$ ) profiles obtained during January–May 2008 by the Microwave Lamb Sounder (MLS) aboard the Aura satellite are assimilated into MOCAGE (MOdèle de Chimie Atmosphérique à Grande Echelle), a global three-dimensional chemistry transport model of Météo-France. The assimilated total  $O_3$  values are consistent with SAOZ ground observations (within  $\pm 5\%$ ), and isentropic distributions of  $O_3$  are matching well with maps of advected potential vorticity (APV) derived from the MIMOSA model, a high-resolution advection transport model, and from ECMWF reanalysis.

The studied event seems to be related to isentropic transport of air masses that took place simultaneously in the lower- and middle-stratosphere, respectively from the polar region and from tropics to the mid-latitudes.

In fact, the studied ozone increase by mid April 2008 results simultaneously: (1) from an equator-ward departure of polar air masses characterised with a high-ozone layer in the lower stratosphere (nearby the 475K isentropic level), and (2) from a reverse

ACPD

10, 17727–17751, 2010

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



isentropic transport from tropics to mid- and high-latitudes in the upper stratosphere (nearby the 700 K level). The increase of ozone observed over Kerguelen from the 16-April ozonesonde profile is then attributed to a concomitant isentropic transport of ozone in two stratospheric layers: the tropical air moving southward and reaches over Kerguelen in the upper stratosphere, and the polar air passing over the same area but in the lower stratosphere.

## 1 Introduction

Stratospheric Ozone is mostly created by sunlight at tropical latitudes, and circulates through the Brewer-Dobson cell from tropics to mid-latitude- and polar-regions. In fact, due to interactions between planetary waves and the mean-zonal flow ozone is transported away from its production region. Additionally, in the winter stratosphere, erosion of the dynamical barriers such as the polar-vortex and the subtropical barrier by planetary-wave breaking, which results in the formation of filaments (*laminae*), also contributes to ozone distribution and balance.

The tropical stratosphere is a region where significant changes are expected to occur. It is also a region where many dynamical processes may take place and have effects on the chemical composition including ozone and other trace gases.

Recent observations showed that in the southern subtropics dynamical processes, such as isentropic exchanges in the tropical stratosphere through the subtropical barrier, take place (Portafaix et al., 2003; Semane et al., 2006; Sivakumar et al., 2004). These processes must play an important role in the transfer of energy, air masses and notably tracers between tropics and higher latitudes.

One of the most important issues in the understanding of transport processes in the stratosphere is an understanding of the climatic “chemical-radiative-dynamical” feedbacks. Indeed, improvement in parameterization of mechanisms by which air is transported in the stratosphere is crucial and requires careful attention and combined approaches. In that regard, Morel et al. (2005) have coupled a mechanistic model,

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



MSDOL (Monitoring of the Stratospheric Depletion of the Ozone Layer) (Bertaux et al., 1999), with a high-resolution advection model, MIMOSA (Modèle Isentropique du transport Méso-échelle de l'Ozone Stratosphérique par Advection) (Hauchecorne et al., 2002), to provide a consistent picture of the stratospheric large-scale circulation and simulate the fine-scale filaments generated by breaking planetary waves in the winter stratosphere. Recently, Bencherif et al. (2007) combined ground-based observations together with global tracer fields from Odin/SMR experiment assimilated into a three-dimensional chemistry transport model, MOCAGE-PALM, in order to examine effects of the polar vortex split and subsequent break-down on transport and mixing over tropics/subtropics during the 2002-major Stratospheric Sudden Warming (SSW). The 2002-SSW is an unprecedented major event in the Southern Hemisphere (SH). It has been extensively analyzed (see Journal of the Atmospheric Sciences, Special Issue, Vol. 62, 2005).

Still by now, ground-based measurements in the SH are very sparse, contrary to the Northern Hemisphere. Since 1998, a limited number of stations are operating in the SH tropics and subtropics under the SHADOZ (Southern Hemisphere Additional Ozonesondes) project (Thompson et al., 2003). In the mid-latitude regions of the SH, which is mainly made of oceans, the number of ground-based sites is very limited. The most equipped mid-latitude site to observe continuously stratospheric ozone in the SH is Lauder (45° S, 170° E), New-Zealand. Over that location, Brinksma et al. (1998) reported about a low-ozone event that occurred during austral winter (August 1997). They showed that the observed ozone reduction resulted of an isentropic transport process.

The present study reports on a large-scale transport event detected from ground-based observations at Kerguelen (i.e., co-localised ozonesonde and SAOZ experiments), and confirmed by satellite global observations and assimilated fields. It aims to examine that end-of-austral-summer event with emphasis on stratospheric ozone variations and link with large-scale isentropic transport. The study is based on the first ozonesonde experiment never recorded at the Kerguelen site on 16 April 2008.

**Analysis of a rapid increase of stratospheric ozone**

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Comparisons and interpretations are supported by co-localised SAOZ observations, by global mapping of tracers ( $O_3$ ,  $N_2O$  and columns of  $O_3$ ) from both MLS (Microwave Limb Sounder) and OMI (Ozone Monitoring Instrument) instruments onboard the Aura satellite, and by model simulations of EPV (Ertel Potential Vorticity) initialised by ECMWF (European Centre for Medium Range Weather Forecasts) data reanalyses.

The paper is outlined as follows: Sect. 2 presents the observations as well as the diagnosis tools used in this study; in Sect. 3, we present the main results concerning this study including observations, modelling and assimilation. Summary and conclusions are given in Sect. 4.

## 2 Datasets and diagnosis tool

### 2.1 Atmospheric observations at Kerguelen

Kerguelen (referred hereinafter as KER) is a French site located at  $49.4^\circ$  South in latitude and  $70.3^\circ$  East in longitude. In addition to daily meteorological observations (upper air data: pressure, temperature and humidity) made by Météo-France, a SAOZ (Système d'Acquisition par Observations Zénithales) system has been operating at KER on routine basis since 1996 in the framework of the NDACC (Network for Detection of Atmospheric Composition Change). The SAOZ is a passive UV-visible spectrometer that allows continuous measurements of total ozone ( $O_3$ ) and nitrogen dioxide ( $NO_2$ ) columns on daily basis at sunset and sunrise (Pommereau and Goutail, 1988). In this issue, we focus on total ozone records from SAOZ obtained by early- and mid-April 2008. Daily total ozone values measured by SAOZ at KER back to January 1996 (~13 years of daily continuous observations) are downloaded from the Ether database (<http://ether.ipsl.jussieu.fr>), the French centre for atmospheric data and services. Monthly means of total ozone are computed from the SAOZ daily data and used for comparison with the daily values observed during the studied period.

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Recently, as part of the International Polar Year, Reunion University and Météo-France set up a balloon radiosonde campaign called ROCK (Radiosondage Ozone Complémentaire aux Kerguelen). The ROCK campaign intended to obtain the first ozone profiles over KER location. 12 balloons were successfully launched during the campaign: from April to September 2008. The balloon-sonde equipment used during the ROCK campaign is similar to that of Reunion Island. It consists of a Väisälä radiosonde RS92 to measure Pressure, Temperature and Relative Humidity profiles, and an electrochemical concentration cell (ECC) to measure the associated partial pressure of ozone. Figure 1a shows ozone and temperature profiles from the first balloon-sonde recorded on 16 April 2008 at KER. It illustrates a tropopause at  $\sim 11.5$  km height, while the local ozonopause appears  $\sim 1$  km below. The most noticeable features from the ozone partial pressure profile are (i) the layering structures in the lower stratosphere (in the 13–16 km altitude range) and (ii) the strong maximum that appears just above, i.e., at  $\sim 17$ – $19$  km height ( $\sim 18$  mPa). In order to emphasize the ozone anomaly, we use the Fortuin & Kelder ozone climatology (Fortuin and Kelder, 1998) to derive climatological ozone profiles for three separate latitudinal belts ( $15^\circ$ – $25^\circ$ ;  $45^\circ$ – $55^\circ$  and  $75^\circ$ – $85^\circ$ ) of the SH. Fortuin & Kelder ozone climatology is based on ozonesonde and satellite measurements over the period 1980–1991. The 16-April  $O_3$  profile over KER, together with the above-mentioned climatological and latitudinal profiles are depicted on Fig. 1b. From the  $45^\circ$ – $55^\circ$  S latitude-band climatological profile the maximum of  $O_3$  (in partial pressure) appears at 23–26 km altitude range, while this climatological maximum of  $O_3$  over the  $75^\circ$ – $85^\circ$  latitude-band appears in the 17–21 km altitude range. As mentioned above, the observed ozone profile over KER (on 16-April) shows the ozone maximum at 17.3 km, (i.e., 19.15 mPa). Indeed, the maximum of  $O_3$  recorded above KER is overlapping with the maximum of climatological  $O_3$  derived for the polar latitude-band ( $75^\circ$ – $85^\circ$  South). This suggests that, by that time (mid April), stratospheric air masses over KER may originally come from polar region.

In the present study, we examine the possibility of an isentropic exchange in the southern stratosphere in relationship with ozone variations notably over KER. In that

**Analysis of a rapid increase of stratospheric ozone**

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



regard, ozone profiles collected during the ROCK campaign are used together with daily total ozone records obtained by SAOZ from January to May 2008. Moreover, the co-located ground-based ozone datasets are compared with observations from Aura/OMI overpasses and from the Aura/MLS hemispherical fields assimilated by the MOCAGE-PALM assimilation system during the same period, i.e., January–May 2008.

## 2.2 Aura/MLS and MOCAGE-PALM assimilation

The Aura satellite was launched on 15 July 2004 and placed into a near-polar Earth orbit at  $\sim 705$  km, with an inclination of  $98^\circ$  and an ascending node at 13:45 h. It makes about 14 orbits per day. The MLS instrument aboard Aura uses the microwave limb sounding technique to measure chemical constituents and dynamical tracers from the upper troposphere up to the lower mesosphere. It provides 3500 profiles per day within the  $\pm 82^\circ$  latitudinal range. Aura/MLS ozone profiles are obtained from measurements of a 240-GHz radiometer and they are retrieved with a horizontal resolution of 165 km and a typical vertical resolution of about 2.7 km in the stratosphere (Froidevaux et al., 2006; Jackson, 2007; Stajner et al., 2008; Feng et al., 2008). Ozone profiles from Aura/MLS observations are retrieved from 316 hPa to less than 0.01 hPa. However, only the data between 215 and 0.02 hPa are recommended (Froidevaux et al., 2008; Liu et al., 2010). Precision is around 20–50 ppbv (parts per billion by volume) and 0.1–0.2 ppmv in the 215.4–22 hPa and 21.5–0.46 hPa vertical ranges and, respectively (Waters et al., 2006). In order to examine total ozone variations in relation with this study, we use the Aura/MLS observations (version 2.2) from 1 January to 31 May 2008, in the Southern Hemisphere. Aura/MLS version 2.2 profiles have been validated in several studies (e.g., Jiang et al., 2007; Livesey et al., 2008; Froidevaux et al., 2008).

For the present work, total  $O_3$  fields have been deduced from the assimilation of Aura/MLS  $O_3$  profiles into the MOCAGE-PALM assimilation system for the period from 1 January to 31 May 2008. The MOCAGE-PALM system is jointly developed between Météo-France and CERFACS (Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique) (Massart et al., 2005; El Amraoui et al., 2008a). It

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



has demonstrated the capability to overcome the possible deficiencies of the model in connection with different chemical parameterizations (e.g., El Amraoui et al., 2008a). In the chemical data assimilation the observational and model errors are accounted for and can be verified, a posteriori, by considering observations minus forecast (OMF) statistics or  $\chi^2$  test (El Amraoui et al., 2004).

MOCAGE (MODèle de Chimie Atmosphérique à Grande Echelle) is a 3-D chemistry transport model. It is forced by meteorological fields (wind and temperature) from ARPEGE: the operational model of Météo-France (Courtier et al. 1991). The horizontal resolution of the used version of MOCAGE is  $2^\circ \times 2^\circ$  and the transport scheme is semi-lagrangian. It includes 47 hybrid ( $\sigma$ ,  $p$ ) levels from the surface up to 5 hPa, and has a vertical resolution of  $\sim 800$  m nearby the tropopause-lower stratosphere region.

The assimilation module is PALM (Projet dAssimilation par Logiciel Multi-mthode), a modular and flexible software developed at CERFACS <http://www.cerfacs.fr/~palm> which consists of elementary components that exchange data (Lagarde et al., 2001). The technique implemented within PALM and used for the assimilation of O3 profiles is the 3D-FGAT (First Guess at Appropriate Time) variational method. The assimilation system MOCAGE-PALM has been used to assess the quality of satellite ozone measurements (Massart et al., 2007). It has also been proven to be useful to overcome the possible deficiencies of the model. In this context, its assimilation product has been used in many atmospheric studies in relation to ozone loss in the Arctic vortex (El Amraoui et al., 2008a), to transport of ozone and large scale exchange between tropics and mid-latitude regions (Bencherif et al., 2007), to the stratosphere-troposphere exchanges (Semane et al., 2007; El Amraoui et al., 2010), and to the exchange between the polar vortex and the mid-latitudes (El Amraoui et al., 2008b).

### 2.3 Potential vorticity and MIMOSA model

The MIMOSA (Modèle Isentropique du transport Méso-échelle de l'Ozone Stratosphérique par Advection) (Hauchecorne et al., 2002) is a high-resolution EPV (Ertel Potential Vorticity) contour advection model. It allows diagnosing the origin of air

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



masses. It uses the European Centre for Medium-Range Weather Forecasts (ECMWF) operational data to reproduce Advected Potential Vorticity (APV) fields on isentropic surfaces. Despite the resultant APV is a “quasi-passive PV”, it allows to depict a consistent plot of the fine-scale filaments generated by breaking planetary waves in the stratosphere. Indeed, behaving as a dynamical tracer in the absence of diabatic effects, the APV is used to study isentropic transport events in the stratosphere (Hoskins et al., 1985; Holton et al., 1995; Heese et al., 2001; Bencherif et al., 2003; Portafaix et al., 2003; Sivakumar et al., 2004; Semane et al., 2006; Bencherif et al., 2007).

In the present study we use the MIMOSA model in order to investigate isentropic transport during the O<sub>3</sub>-increase event observed over KER.

### 3 Observational, assimilation and model results

#### 3.1 Total ozone over Kerguelen

There are numerous ways to measure ozone in the atmosphere, but they fall broadly into two categories: measurements of ozone total column ozone and measurements of the vertical profile of ozone. Regular measurements of total ozone are available from a network of surface stations, mostly in the NH mid-latitudes, with reasonable coverage extending back to the 1960s. On the global scale, continuous total ozone data are available from satellite measurements since 1979. The column abundance of ozone can be derived from differential absorption measurements in the ultraviolet Huggins band, where ozone exhibits strong absorption features. The ratio of the intensity of direct sunlight at two wavelengths in the 300–320 nm range is a measure of the total abundance of ozone in a column through the atmosphere. This forms the basic operating principle for a variety of optical instruments that monitor atmospheric ozone. In addition to Dobson and Brewer spectrometers, SAOZ is a well-known ground-based ozone-monitoring instrument. It is a UV-visible zenith-sky grating spectrometer (Pommereau and Goutail, 1988) that enables deriving columns of ozone in the Chappuis

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



band (in the 470–540 nm spectral window). SAOZ Retrievals from a real-time spectral analysis are converted into preliminary total vertical columns by the use of standard air-mass factors (Sarkissian et al., 1995).

We use for the present study total ozone records obtained at KER by a SAOZ system that has been operating since 1996. The study focuses on the January–May 2008 period. Figure 2 illustrates monthly climatological total ozone variations as derived from KER-SAOZ daily records, together with the 2008 SAOZ daily observations. The minimum of the annual ozone variation appears over KER by March and it is about 290 DU. The 2008 ozone values show that from March there is an increase trend in the total ozone day-to-day variations. These variations are in form of alternative maxima and minima of total ozone during March and April 2008, whose amplitudes exceed the monthly climatological values. For comparison, daily Aura/OMI columns of ozone are also superimposed (blue line) on Fig. 2a. Except some little discrepancies Fig. 2b shows that daily variations of total ozone recorded by SAOZ and Aura/OMI are similar during the studied period. Yet, on the global, Aura/OMI ozone daily values are slightly lower than SAOZ ones (less than 6%). More interestingly, we also compare ground-based observations obtained by SAOZ at KER with Aura/MLS total ozone derived from the MOCAGE-PALM assimilation system and interpolated to KER location.

O<sub>3</sub> MLS observations are assimilated within the MOCAGE-PALM assimilation system in terms of vertical profiles. The total columns corresponding to the assimilated products are then calculated using the vertical integration of the assimilated O<sub>3</sub> profiles and by taking into account vertical profiles of both the pressure and the air density.

Assimilated MLS and SAOZ ozone values are depicted on Fig. 2b together with the monthly climatological values, for the same period, i.e., January–May 2008.

Interestingly, from the total ozone time-evolution (see Fig. 2b), we note that assimilated values show qualitative and quantitative agreement with SAOZ observations. Indeed, discrepancy between SAOZ observations and MOCAGE-PALM assimilation values is within  $\pm 5\%$ . In addition, the figure evidences that the MOCAGE-PALM assimilation system is able to retrieve much of total ozone variations over KER during the

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



whole period on a daily basis.

From these comparisons between the ground-based observations (by SAOZ) and global values derived from Aura/OMI overpasses and from Aura/MLS assimilated fields (by MOCAGE-PALM) we find a pretty good agreement. In fact, the three measures show very similar daily variations of total ozone over Kerguelen. This period of study is characterized by a decreasing phase in total ozone that ends by about mid-March, followed by a reverse-phase with ozone increase. In fact, by mid-March we notice from the three datasets an increase in the amplitude of daily total ozone variations, with alternative minimum and maximum values as low as  $\sim 245$  Dobson Unit (DU), and as high as  $\sim 343$  DU. From early April, we find the largest increase of ozone during the studied period, i.e., more than  $\sim 100$  DU increase of total ozone within about 2 weeks.

The ozone profile recorded on 16 April at KER (see Fig. 1) is in agreement with the observed total ozone over KER. It also illustrates a significant ozone increase in the lower stratosphere, in the 16–24 km height range (between the  $\sim 400$  K and the  $\sim 650$  K isentropic levels). Additionally, from a given ozonesonde profile one can infer an estimate of the corresponding total ozone by adding a residual amount based on the SBUV (Solar Backscattered UltraViolet) monthly average ozone climatology performed by McPeters et al. (1997). The residual term corresponds to the total ozone amount above the balloon burst altitude. By applying this method to the 16-April ozone profile, the corresponding total ozone is estimated about 339 DU. This is in good agreement with the sunrise SAOZ observation on the same day (348.5 DU), within less than 10 DU ( $\sim 2.9\%$ ) difference.

### 3.2 Evidence of isentropic transport from polar region to mid-latitudes

In this subsection we aim to investigate the role of isentropic transport of polar air northward from polar region to mid-latitudes, in conjunction with similar transport in the reverse way from tropics, that both contributed to the rapid and prominent increase of stratospheric ozone on April 2008 over KER.

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Figure 3 shows the ozone and nitrous oxide ( $\text{N}_2\text{O}$ ) mixing ratio fields from Aura/MLS observations on 16 April 2008 as assimilated by MOCAGE-PALM onto the 475-K potential temperature surface.

Since ozone life-time in the lower stratosphere goes from a few days to several months, it can be considered as a transport tracer. From plot (b) of Fig. 3, it comes on the overall that ozone is high over polar region and low in tropics. It can also be seen from this plot that the polar ozone is not bordered to the polar region. There are some filamentary structures with large scale extensions up to subtropics (nearby the  $30^\circ\text{S}$  latitude circle). With regard to the situation over Kerguelen (indicated on the map by the cross “x” symbol), the site seems undergoing an air mass of high ozone.

Moreover,  $\text{N}_2\text{O}$  is a long-lived species (over 100 years in the lower stratosphere). It is used as a good dynamical tracer and enables underlining isentropic transport and its latitudinal extension. Indeed, Fig. 3a ( $\text{N}_2\text{O}$  field on 16 April, derived from Aura/MLS assimilated observations) shows concordant (as the  $\text{O}_3$  map) large-scale transport features. Furthermore,  $\text{N}_2\text{O}$  distribution offers great advantage to illustrate isentropic transport and exchange between low-, mid-latitudes and polar region. In fact, it is well illustrated that high- $\text{N}_2\text{O}$  air-masses (originally from tropics) have moved pole-ward; while, on the opposite, low- $\text{N}_2\text{O}$  air-masses moved equator-ward. It should be noted that, in a general way, the low- $\text{N}_2\text{O}$  distributions appear to be in accordance with high- $\text{O}_3$  values (and vice versa). In fact,  $\text{O}_3$  and  $\text{N}_2\text{O}$  fields give complementary pictures and illustrate well the large-scale transport event.

As mentioned above, EPV is conservative parameter and hence, in the absence of diabatic effects, EPV behaves as a dynamical tracer on isentropic surfaces. It is indeed a useful tool for understanding transport processes in the stratosphere (Hoskins et al., 1985). Usually, the polar vortex is identified by high absolute EPV values, and delimited by a strong EPV gradient; while, on the opposite, the tropical stratospheric reservoir is identified by low absolute EPV values, and delimited by subtropical barriers.

Figure 4a depicts the 16-April distribution of EPV computed from ECMWF analyses for the 475K isentropic level. Broadly the tropical air can be identified by absolute

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



EPV values less than 13 PVU (in the red-yellow colour palette), and the polar air is identifiable by absolute EPV values higher than 22 PVU (in the blue colour palette). It is clear from Fig. 4a that a polar air-masse is pulled out off the vortex edge region with a large longitudinal and latitudinal extension up to subtropics. The departure place of that polar filament is situated over KER (star \* symbol). We also plotted on Fig. 4b the corresponding map of ECMWF ozone mixing ratio. Seemingly, the excursion of that polar filament is folded together with O<sub>3</sub> rich filament from the vortex. This is also in agreement with ozone distribution from Aura/MLS data assimilated with MOCAGE-PALM (see Fig. 3b).

In fact, Figs. 3 and 4 illustrate consistent pictures of air masse transport in the lower stratosphere during that O<sub>3</sub>-high event over KER. They evidence a large-scale transport of stratospheric ozone from polar edge towards mid- and low-latitude regions. Since EPV is an effective dynamical tracer, comparison between EPV (from ECMWF analyses) and chemical tracers (O<sub>3</sub>, N<sub>2</sub>O) maps obtained from Aura/MLS assimilated fields suggests that O<sub>3</sub>/N<sub>2</sub>O distributions that occurred during the event are dynamically driven.

However, by taking into account the altitude range (16–24 km) of the O<sub>3</sub>-increase recorded by the 16-April balloon-sonde experiment (Fig. 1), the evidenced isentropic transport in the lower stratosphere could not explain alone the observed increase in total ozone as observed by ground-based and global measurements (SAOZ, Aura/OMI and Aura/MLS) (Fig. 2).

In order to investigate air masse and ozone transport higher in the stratosphere, we examine here below the situation onto the 700-K isentropic surface.

The upper plots of Fig. 5 shows snapshots of ozone mixing ratio from Aura/MLS assimilated by MOCAGE-PALM onto the 700-K isentropic surface for the following selected days prior to and during the rapid O<sub>3</sub>-increase event over KER: 5, 11, 16 and 17 April 2008. Unlike the lower stratosphere (LS), namely at the 475-K isentropic level depicted on Fig. 3, on the 700-K surface the polar region is characterized by a minimum of ozone ( $\leq 3$  ppmv), while ozone maxima appear over low- and mid-latitude

**Analysis of a rapid increase of stratospheric ozone**

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



regions ( $\geq 8$  ppmv). By early April, ozone values over KER appear to be intermediate ( $\sim 5$  ppmv). Moreover, a “tongue” of high- $O_3$  initially (4 April) located over south of the Latin America subcontinent, seems moving eastward and surrounding a polar filament of low- $O_3$ . Within less than a week (11 April), the vortex shape changed and became more elliptic than circular, while the “tongue” of high- $O_3$  was still moving eastward and crossed the Atlantic Ocean. It is seen from the 16- and 17-April ozone maps (Fig. 5) that this ozone “tongue” had been transported over KER and contributed increasing the amount of total ozone over the site. As illustrated by the lower plots of Fig. 5, the same features are noticeable from MIMOSA-maps of APV fields obtained on the same isentropic surface (700 K) and for the same days (4, 11, 16 and 17 April). Actually, a low-APV pattern moving eastward and southward from southern America to KER is well simulated by the MIMOSA model, suggesting that the  $O_3$ -increase over KER by mid-April 2008 resulted from transport of air masses originally from tropics.

To sum up this section, the observed rapid increase of stratospheric ozone over KER by late austral summer (April 2008) mainly resulted from large-scale transport processes. The  $O_3$ -high is reported from many observations (ground-based and satellites). In fact, our analyses show that this particular  $O_3$ -high event is a combination of two transport processes: one in the LS and the other in the upper layer. This study suggests that in the LS (475 K), air masses and ozone have been isentropically pulled out of the edge of the polar vortex into mid- and low-latitude regions. Simultaneously, in the upper stratosphere (700 K), Fig. 5 highlights a transport process, but in the reverse way, i.e., from tropics to mid- and high-latitudes.

## 4 Conclusions

In this paper, we investigated the first ozone profile obtained with balloon-sonde at Kerguelen, a French overseas territory in the southern Indian Ocean. The balloon-sonde was launched on 16 April 2008 within a collaborative research project between Reunion Island University and Météo-France, in the framework of the International

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Analysis of a rapid increase of stratospheric ozone**

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Polar Year. That observation is supplemented by co-localized daily total ozone column records made on a routine basis by a SAOZ system. It is a UV-visible spectrometer that has been operating at KER since 1996 in the framework of the NDACC-SAOZ network. Both ozone profile (Fig. 1) and SAOZ daily records (Fig. 2) evidenced a rapid and prominent increase of stratospheric ozone during April 2008: more than ~100 DU increase of total ozone within about 2 weeks. A good agreement is found from comparison between ground-based and Aura/OMI total ozone values, and the latter seem slightly lower (less than 6%) than SAOZ values (Fig. 2). Additionally, for the purpose of the present issue, O<sub>3</sub> and N<sub>2</sub>O observations from Aura/MLS experiment are assimilated using the three-dimensional chemistry transport model of Météo-France MOCAGE-PALM assimilation system (El Amraoui et al., 2008a; Massart et al., 2005), for the period from January to May 2008. From those assimilations exercise, daily total ozone columns are derived over KER location. It is found that MLS/MOCAGE total ozone values are consistent with the SAOZ observations (within ±5%), and hence the MOCAGE-PALM assimilation system is able to retrieve much of total ozone day-to-day variations.

In order to examine the large-scale transport during the studied O<sub>3</sub>-high over KER, ECMWF analyses and a high-resolution advection transport model called MIMOSA are used and compared to MLS/MOCAGE O<sub>3</sub> and N<sub>2</sub>O distributions. Even though the advected potential vorticity is not the true Ertel Potential Vorticity but a quasi-passive potential vorticity, it gives a consistent picture of the fine-scale filaments in the stratosphere (Hauchecorne et al., 2002). It is used to investigate the origins of air masses and pathways of isentropic transport.

By combining observations and assimilation fields along with ECMWF analysis and APV maps it comes out that the observed rapid increase of O<sub>3</sub>-high over Kerguelen by late austral summer (April 2008) has mainly resulted from large-scale transport processes. The studied event seems to be related to isentropic transport of air masses that took place simultaneously in the lower- and middle-stratosphere, respectively from the polar region and from tropics to the mid-latitudes.

*Acknowledgements.* The LACy (Laboratoire de l'Atmosphère et des Cyclones) is supported by INSU (Institut National des Sciences de l'Univers), a CNRS institut, and by the Regional Council of Reunion (Conseil Régional de La Réunion). The present work is conjointly part of the Regional COMPTRAST programme and the IPY/ROCK campaign. We are grateful to the Météo-France radiosonde team at Kerguelen for their operational help during the campaign. We would like to acknowledge ECMWF for providing analyses and the French data centre for atmospheric chemistry (<http://ether.ipsl.jussieu.fr>), for providing daily SAOZ data and APV-MIMOSA maps and data. We also acknowledge the TOMS, OMI and MLS teams for providing ozone global observations.



The publication of this article is financed by CNRS-INSU.

## References

- Bencherif, H., Portafaix, T., Baray, J.-L., Morel, B., Baldy, S., Leveau, J., Hauchecorne, A., Keckhut, P., Moorgawa, A., Michaelis, M. M., and Diab, R.: LIDAR observations of lower stratospheric aerosols over South Africa linked to large scale transport across the southern subtropical barrier, *J. Atmos. Solar- Terrestrial Phys.*, 65(6), 707–715, 2003.
- Bencherif, H., El Amraoui, L., Semane, N., Massart, S., Vidyaranya D. C., Hauchecorne, A., and Peuch, V.-H.: Examination of the 2002 major warming in the Southern Hemisphere using ground-based and Odin/SMR assimilated data: stratospheric ozone distributions and tropic/mid-latitude exchange, *Can. J. Phys.*, 85, 1287–1300, 2007.
- Bertaux, J. L., Hauchecorne, A., Mangin, A., Cot, C., Théodore, B., Talagrand, O., Fussen, D., Simon, P. C., Kyrölä, E., Roscoe, H., Hembise, O., and Brasseur, G. P.: The Msdol

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Analysis of a rapid increase of stratospheric ozone**

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Project: Assimilation Of Gomos Ozone Data In A 3-D Chemistry-Transport Model, Phys. Chem. Earth, 24(5), 435–437, 1999.

Brinksma, E. J., Meijer, Y. J., Connor, B. J., Manney, G. L., Bergwer, J. B., Bodeker, G. E., Boyd, I. S., Liley, J. B., Hogervorst, W., Hovenier, J. W., Livesey, N. J., and Swart, D. P. J.: Analysis of Record-Low Ozone Values During the 1997 Winter over Lauder, New Zealand, Geophys. Res. Lett., 25(15), 2785–2788, 1998.

Courtier, P., Freyrier, C., Geleyn, J.-F. Rabier, F. and Rochas, M.: The ARPEGE project at Météo-France, in: Workshop on numerical methods in atmospheric models, Vol. 2, 193–231, 1991.

El Amraoui, L., Ricaud, P., Urban, J., Théodore, B., Hauchecorne, A., Lautié, N., de La Noë, J., Guirlet, M., Le Flochmën, E., Murtagh, D., Dupuy, E., Frisk, U., and d'Andon, O. F.: Assimilation of Odin/SMR O<sub>3</sub> and N<sub>2</sub>O measurements in a three-dimensional chemistry transport model, J. Geophys. Res., 109, D22304, doi:10.1029/2004JD004796, 2004.

El Amraoui, L., Peuch, V.-H., Ricaud, P., Massart, S., Urban, J., Semane, N., Teyssdre, H., Cariolle, D., and Karcher, F.: Ozone loss in the 2002/2003 Arctic Vortex deduced from the Assimilation of Odin/SMR O<sub>3</sub> and N<sub>2</sub>O measurements: N<sub>2</sub>O as a dynamical tracer, Q. J. Roy. Meteor. Soc., 134, 217–228, 2008a.

El Amraoui, L., Semane, N., Peuch, V.-H., and Santee, M. L.: Investigation of dynamical processes in the polar stratospheric vortex during the unusually cold winter 2004/2005, Geophys. Res. Lett., 35, L03803, doi:10.1029/2007GL031251, 2008b.

El Amraoui, L., Attié, J.-L., Semane, N., Claeysman, M., Peuch, V.-H., Warner, J., Ricaud, P., Cammas, J.-P., Piacentini, A., Josse, B., Cariolle, D., Massart, S., and Bencherif, H.: Midlatitude stratospheretroposphere exchange as diagnosed by MLS O<sub>3</sub> and MOPITT CO assimilated fields, Atmos. Chem. Phys., 10, 2175–2194, doi:10.5194/acp-10-2175-2010, 2010.

Feng, W., Chipperfield, M. P., Roscoe, H. K., Remedios, J. J., Waterfall, A. M., Stiller, G. P., Glatthor, N., Höpfner, M., and Wang, D.-Y.: Three-Dimensional Model Study of the Antarctic Ozone Hole in 2002 and Comparison with 2000, J. Atmos. Sci., 62, 822–837, 2005.

Fortuin, J. P. F. and Kelder, H.: An ozone climatology based on ozonesonde and satellite measurements, J. Geophys. Res., 103, 31709–31734, 1998.

Froidevaux, L., Livesey, N. J., Read, W. G., Jiang, Y. B., Jimenez, C. C., Filipiak, M. J., Schwartz, M. J., Santee, M. L., Pumphrey, H. C., Jiang, J. H., Wu, D. L., Manney, G. L., Drouin, B. J., Waters, J. W., Fetzer, E. J., Bernath, P. F., Boone, C. D., Walker, K. A., Jucks, K. W., Toon, G. C., Margitan, J. J., Sen, B., Webster, C. R., Christensen, L. E., Elkins, J. W., Atlas, E., Lueb,

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



R. A., and Hendersho, R.: Early validation analyses of atmospheric profiles from EOS MLS on the Aura Satellite, *IEEE Trans. Geosc. Remote Sens.*, 44(5), 1106–1121, 2006.

Froidevaux, L., Jiang, Y. B., Lambert, A., Livesey, N. J., Read, W. G., Waters, J. W., Browell, E. V., Hair, J. W., Avery, M. A., McGee, T. J., Twigg, L. W., Sumnicht, G. K., Jucks, K. W., Margitan, J. J., Sen, B., Stachnik, R. A., Toon, G. C., Bernath, P. F., Boone, C. D., Walker, K. A., Filipiak, M. J., Harwood, R. S., Fuller, R. A., Manney, G. L., Schwartz, M. J., Daffer, W. H., Drouin, B. J., Cofield, R. E., Cuddy, D. T., Jarnot, R. F., Knosp, B. W., Perun, V. S., Snyder, W. V., Stek, P. C., Thurstans, R. P., Wagner, P. A.: Validation of Aura Microwave Limb Sounder stratospheric ozone measurements, *J. Geophys. Res.*, 113, D15S20, doi:10.1029/2007JD008771, 2008.

Hauchecorne, A., Godin, S., Marchand, M., Heese, B., and Souprayen, C.: Quantification of the transport of chemical constituents from the polar vortex to midlatitudes in the lower stratosphere using the high-resolution advection model MIMOSA and effective diffusivity, *J. Geophys. Res.*, 107(D20), 8289, doi:10.1029/2001JD000491, 2002.

Heese, B., Godin, S., and Hauchecorne, A.: Forecast and simulation of stratospheric ozone filaments: A validation of a high-resolution PV advection model by airborne ozone lidar measurements in winter 1998–1999, *J. Geophys. Res.*, 106, 20 011–20 024, 2001.

Holton, J. R., Haynes, P. H., McIntyre, M. E., Douglass, A. R., Rood, R. B., and Pfister, L.: Stratosphere troposphere exchange, *Rev. Geophys.*, 33, 403–439, 1995.

Hoskins, B. J., McIntyre, M. E., and Robertson, A. W.: On the use and significance of isentropic potential vorticity maps, *Q. J. Roy. Meteor. Soc.*, 111, 877–946, 1985.

Jackson, D.: Assimilation of EOS MLS ozone observations in the Met Office Data Assimilation System, *Q. J. Roy. Meteor. Soc.*, 133, 1771–1788, 2007.

Jiang, Y. B., Froidevaux, L., Lambert, A., Livesey, N. J., Read, W. G., Waters, J. W., Bojkov, B., Leblanc, T., McDermid, I. S., Godin-Beekmann, S., Filipiak, M. J., Harwood, R. S., Fuller, R. A., Daffer, W. H., Drouin, B. J., Cofield, R. E., Cuddy, D. T., Jarnot, R. F., Knosp, B. W., Perun, V. S., Schwartz, M. J., Snyder, W. V., Stek, P. C., Thurstans, R. P., Wagner, P. A., Allaart, M., Andersen, S. B., Bodeker, G., Calpini, B., Claude, H., Coetzee, G., Davies, J., De Backer, H., Dier, H., Fujiwara, M., Johnson, B., Kelder, H., Leme, N. P., Konig-Langlo, G., Kyro, E., Laneve, G., Fook, L. S., Merrill, J., Morris, G., Newchurch, M., Oltmans, S., Parrondos, M. C., Posny, F., Schmidlin, F., Skrivankova, P., Stubi, R., Tarasick, D., Thompson, A., Thouret, V., Viatte, P., Vomel, H., von der Gathen, P., Yela, M., and Zabolck, G.: Validation of the Aura Microwave Limb Sounder Ozone by Ozonesonde and Lidar Measurements, *J. Geophys.*

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Res., 112, D24S34, doi:10.1029/2007JD008776, 2007.

Lagarde, T., Piacentini, A., and Thual, O.: A new representation of data assimilation methods: the PALM flow charting approach, *Q. J. Roy. Meteor. Soc.*, 127, 189–207, 2001.

Liu, X., Bhartia, P. K., Chance, K., Froidevaux, L., Spurr, R. J. D., and Kurosu, T. P.: Validation of Ozone Monitoring Instrument (OMI) ozone profiles and stratospheric ozone columns with Microwave Limb Sounder (MLS) measurements, *Atmos. Chem. Phys.*, 10, 2539–2549, doi:10.5194/acp-10-2539-2010, 2010.

Livesey, N. J., Filipiak, M. J., Froidevaux, L., Read, W. G., Lambert, A., Santee, M. L., Jiang, J. H., Pumphrey, H. C., Waters, J. W., Cofield, R. E., Cuddy, D. T., Daffer, W. H., Drouin, B. J., Fuller, R. A., Jarnot, R. F., Jiang, Y. B., Knosp, B. W., Li, Q. B., Perun, V. S., Schwartz, M. J., Snyder, W. V., Stek, P. C., Thurstans, R. P., Wagner, P. A., Avery, M., Browell, E. V., Cammas, J.-P., Christensen, L. E., Diskin, G. S., Gao, R.-S., Jost, H.-J., Loewenstein, M., Lopez, J. D., Nedelec, P., Osterman, G. B., Sachse, G. W., and Webster, C. R.: Validation of Aura Microwave Limb Sounder O<sub>3</sub> and CO observations in the upper troposphere and lower stratosphere, *J. Geophys. Res.*, 113, D15S02, doi:10.1029/2007JD008805, 2008.

Massart, S., Cariolle, D., and Peuch, V.-H.: Towards an improvement of the atmospheric ozone distribution and variability by assimilation of satellite data, *C. R. Geosciences*, 15, 1305–1310, 2005

Massart, S., Piacentini, A., Cariolle, D., El Amraoui, L., and Semane, N.: Assessment of the quality of the ozone measurements from the Odin/SMR instrument using data assimilation, *Can. J. Phys.*, 85, 1209–1223, doi:10.1139/P07-124, 2007.

Semane, N., Peuch, V.-H., Pradier, S., Desroziers, G., El Amraoui, L., Brousseau, P., Massart, S., Chapnik, B., and Peuch, A.: On the extraction of wind information from the assimilation of ozone profiles in MtoFrance 4-D-Var operational NWP suite, *Atmos. Chem. Phys.*, 9, 4855–4867, doi:10.5194/acp-9-4855-2009, 2009.

McPeters, R. D., Labow, G. J., and Johnson, B. J.: A satellite-derived ozone climatology for balloon-sonde estimation of total column ozone, *J. Geophys. Res.*, 102, D7, 8875–8885, 1997.

Morel, B., Bencherif, H., Keckhut, P., Portataix, T., Hauchecorne, A., and Baldy, S.: Fine-scale study of a thick stratospheric ozone lamina at the edge of the southern subtropical barrier. Part II: Numerical simulations with coupled dynamics models, *J. Geophys. Res.*, 110, D17101, doi:10.1029/2004JD005737, 2005.

Pommereau, J. P. and Goutail, F.: O<sub>3</sub> and NO<sub>2</sub> Ground-Based Measurements by Visible spec-

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



trometry during Arctic Winter and Spring 1988, *Geophys. Res. Lett.*, 891, 891–894, 1988.

Portafaix, T., Morel, B., Bencherif, H., Baldy, S., Godin-Beekmann, S., and Hauchecorne, A.: Fine-scale study of a thick stratospheric ozone lamina at the edge of the southern subtropical barrier, *J. Geophys. Res.*, 108(D6), 4196, doi:10.1029/2002JD002741, 2003.

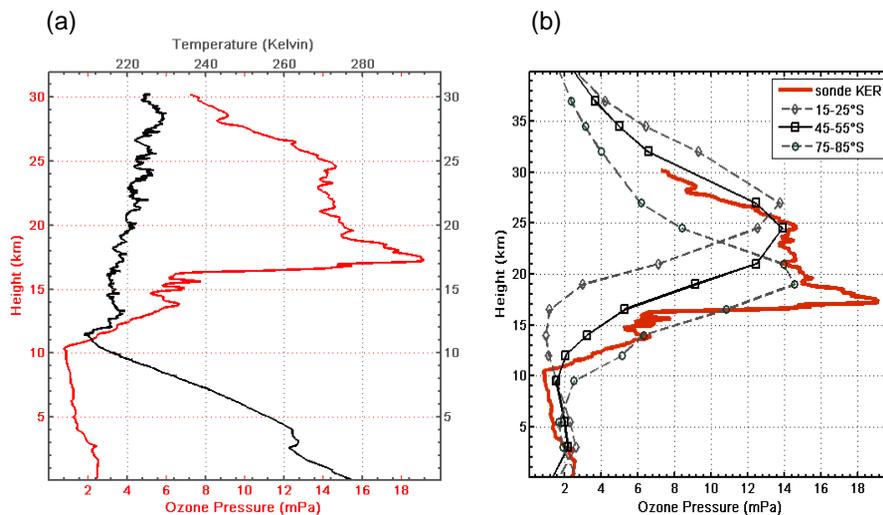
5 Sarkissian, A., Fish, D., Van Roozendaal, M., Gil, M., Chen, H. B., Wang, P., Pommereau, J. P., and Lenoble, J.: Ozone and NO<sub>2</sub> air-mass factors for zenith-sky spectrometers: Inter-comparison of calculations with different radiative transfer models, *Geophys. Res. Lett.*, 22, 1113–1116, 1995.

10 Semane, N., Bencherif, H., Morel, B., Hauchecorne, A., and Diab, R. D.: An unusual stratospheric ozone decrease in the Southern Hemisphere subtropics linked to isentropic air-mass transport as observed over Irene (25.5° S, 28.1° E) in mid-May 2002, *Atmos. Chem. Phys.*, 6, 1927–1936, doi:10.5194/acp-6-1927-2006, 2006.

Sivakumar, V., Morel, B., Bencherif, H., Baray, J. L., Baldy, S., Hauchecorne, A., and Rao, P. B.: Rayleigh lidar observation of a warm stratopause over a tropical site, Gadanki (13.5° N; 15 79.2° E), *Atmos. Chem. Phys.*, 4, 1989–1996, doi:10.5194/acp-4-1989-2004, 2004.

Stajner, I., Wargan, K., Pawson, S., Hayashi, H., Chang, L.-P., Hudman, R. C., Froidevaux, L., Livesey, N., Levelt, P. F., Thompson, A. M., Tarasick, D. W., Stübi, R., Andersen, S. B., Yela, M., König-Langlo, G., Schmidlin, F. J., and Witte, J. C.: Assimilated ozone from EOS- 20 Aura: Evaluation of the tropopause region and tropospheric columns, *J. Geophys. Res.*, 113, D16S32, doi:10.1029/2007JD008863, 2008.

Thompson, A. M., Witte, J. C., McPeters, R. D., Oltmans, S. J., Schmidlin, F. J., Logan, J. A., Fujiwara, M., Kirchhoff, V. W. J. H., Posny, F., Coetzee, G. J. R., Hoegger, B., Kawakami, S., Ogawa, T., Johnson, J. B., Vömel, H., and Labow, G.: Southern Hemisphere Additional Ozonesondes (SHADOZ) 1998-2000 tropical ozone climatology 1. Comparison with Total 25 25 Ozone Mapping Spectrometer (TOMS) and ground-based measurements, *J. Geophys. Res.*, 108, D2, 8238, doi:1029/2001JD000967, 2003.

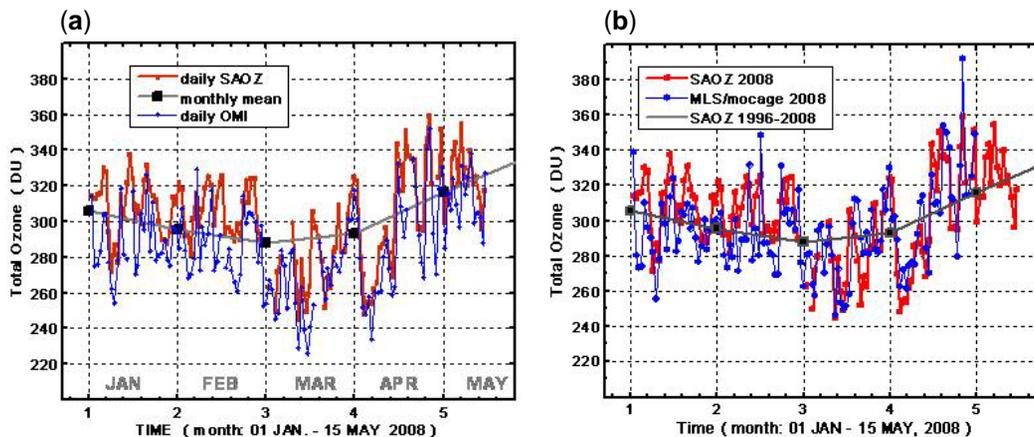


**Fig. 1.** (a) Vertical profiles of temperature (black line, in Kelvin) and ozone (red line, in mPa) obtained over Kerguelen ( $49.4^{\circ}$  S,  $70.3^{\circ}$  E) as measured by the first balloon-sonde with ozone ECC sensor on 16 April 2008. (b) Same ozone profile (partial pressure in mPa, red continuous thick line) superimposed together with climatological ozone profiles derived from Fortuin & Kelder ozone climatology for three separate latitudinal belts ( $15^{\circ}$ – $25^{\circ}$ ;  $45^{\circ}$ – $55^{\circ}$  and  $75^{\circ}$ – $85^{\circ}$ ) of the southern hemisphere (see legend).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.



**Fig. 2.** Time evolution of total ozone derived from daily SAOZ observations (SR and SS daily averages, red lines), from 1 January to 15 May 2008. The grey lines with square symbols represent the corresponding monthly climatological total ozone values derived from daily SAOZ observations at Kerguelen over the 1996–2008 period. The blue solid line on plot (a) depicts the Aura/OMI daily values; while it depicts on plot (b) the Aura/MLS values for Kerguelen assimilated by the MOCAGE-PALM system (from 1 January to 30 April 2008).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

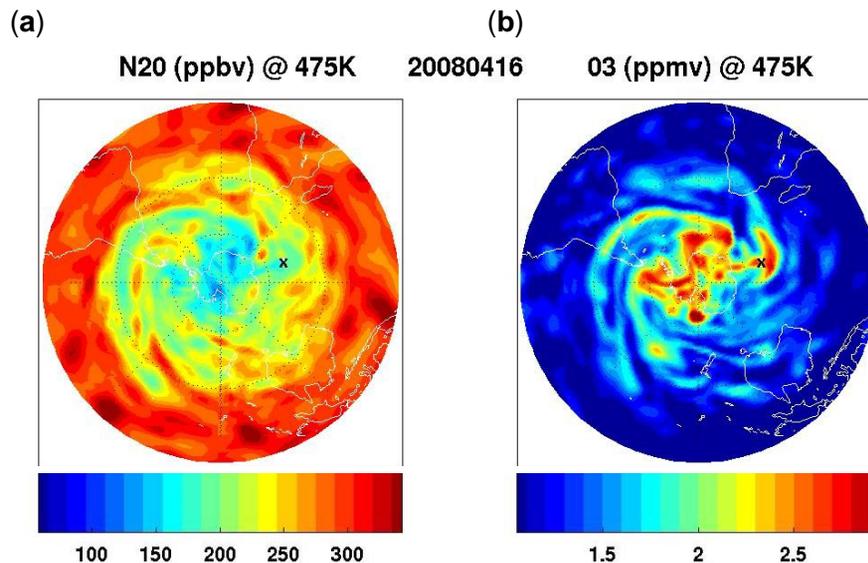
Printer-friendly Version

Interactive Discussion



**Analysis of a rapid increase of stratospheric ozone**

H. Bencherif et al.



**Fig. 3.** Maps of mixing ratios of (a) nitrous oxide (N<sub>2</sub>O) (in ppbv) and (b) of ozone (O<sub>3</sub>) (in ppmv) from Aura/MLS observations assimilated by the MOCAGE-PALM system for 16 April 2008, in the lower stratosphere, onto the 475-K isentropic surface. The cross × symbol indicates the Kerguelen location, and the concentric circles depict, from the centre of the map, the 60°- and 30°-latitudes of the Southern Hemisphere.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

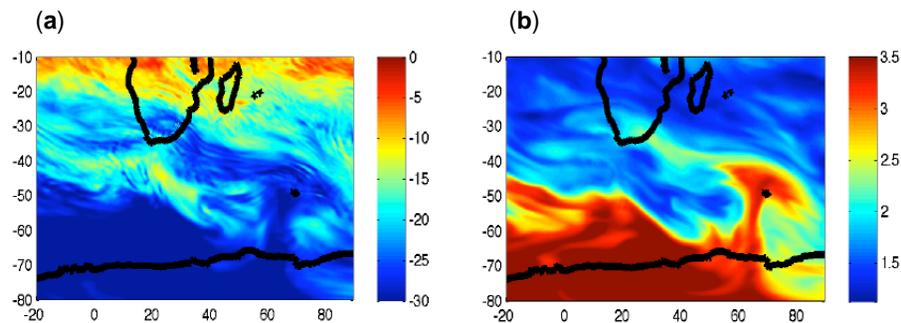
Printer-friendly Version

Interactive Discussion



**Analysis of a rapid increase of stratospheric ozone**

H. Bencherif et al.



**Fig. 4.** (a) PV map (in PVU) and (b) ozone mixing ratio (in ppmv) onto the 475-K isentropic level, as obtained from ECMWF analyses for 16 April 2008, 06:00 UT. The star \* symbol indicates the Kerguelen location.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

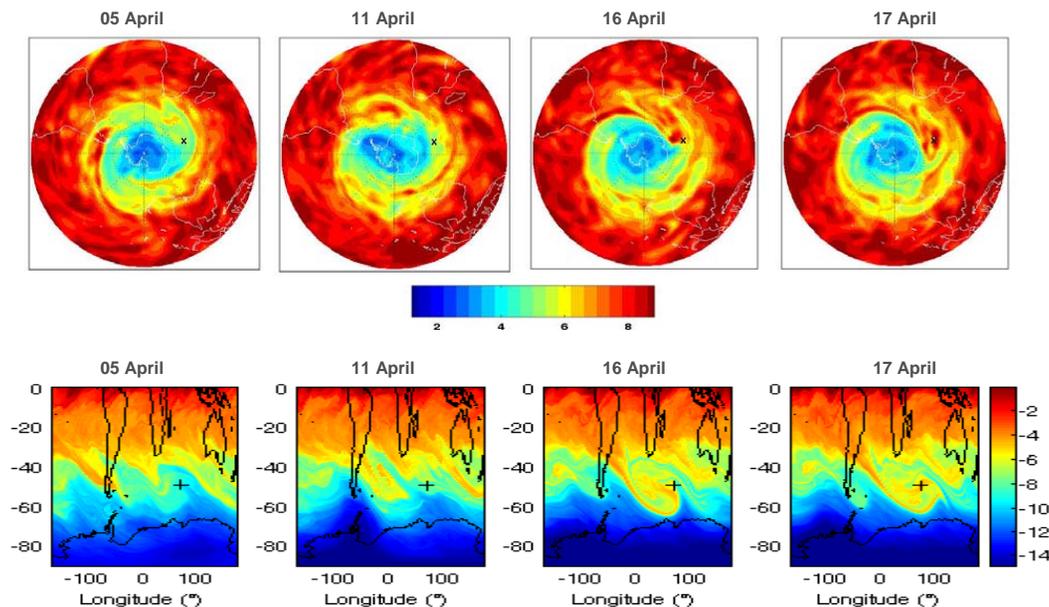
Printer-friendly Version

Interactive Discussion



## Analysis of a rapid increase of stratospheric ozone

H. Bencherif et al.



**Fig. 5.** Upper plots: Maps of ozone mixing ratio (in ppmv) as derived from MOCAGE-PALM assimilation system using Aura/MLS observations, during April 2008, onto the 700-K isentropic level for selected dates: 5, 11, 16 and 17 April. Lower plots: Same as for the upper plots, but for Advection Potential Vorticity (APV) derived from the high-resolution MIMOSA model. The cross symbols indicate the Kerguelen location, and the concentric circles on the upper plots depict, from the centre of the map, the 60°- and 30°-latitudes of the Southern Hemisphere.