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## ► To cite this version:

P. Krecl, C. S. Haley, J. Stegman, S. M. Brohede, Gwenaël Berthet. Retrieving the vertical distribution of stratospheric OCIO from Odin/OSIRIS limb-scattered sunlight measurements. *Atmospheric Chemistry and Physics Discussions*, 2005, 5 (3), pp.2989-3046. hal-00327907

**HAL Id: hal-00327907**

**<https://hal.science/hal-00327907>**

Submitted on 18 Jun 2008

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**Retrieval of OCIO  
profiles from OSIRIS  
limb observations**

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# Retrieving the vertical distribution of stratospheric OCIO from Odin/OSIRIS limb-scattered sunlight measurements

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Received: 28 February 2005 – Accepted: 29 March 2005 – Published: 13 May 2005

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## Abstract

The first vertical profiles of stratospheric OCIO retrieved from Odin/OSIRIS limb-scattered sunlight radiances are presented. The retrieval method is based on a two-step approach, using differential optical absorption spectroscopy combined with the maximum a posteriori estimator. The details of the spectral window selection, spectral corrections and inversion technique are discussed. The results show that OCIO can be detected inside the South polar vortex region between about 12 and 20 km altitude with a 2–5 km height resolution and an estimated retrieval error better than 60% at the peak. OCIO concentrations are consistent with chemical transport model simulations and show the expected relation to the atmospheric conditions in the lower stratosphere in the austral spring 2002. This unique data set of OCIO profiles is very promising to study the stratospheric chlorine activation in both polar regions.

## 1. Introduction

Since the dramatic ozone destruction over Antarctica was discovered by Farman et al. in 1985, laboratory and model studies in combination with stratospheric observations have improved the scientific understanding of the complex and interactive processes behind this annual depletion (review of historical research in Solomon, 1999). Moreover, these studies have revealed that a less severe stratospheric ozone loss occurs over the Arctic region during springtime (WMO, 2003). Stratospheric ozone is destroyed in the polar regions by several catalytic cycles involving reactive halogen species, primarily chlorine and bromine. Polar stratospheric clouds (PSCs), which are formed during the cold and dark winter, play a crucial role in the so-called chlorine activation. This activation refers to the conversion of chlorine reservoir gases (including HCl and ClONO<sub>2</sub>) into the more reactive forms (ClO and ClOOCl) by heterogeneous reactions occurring on the surface of the PSC particles. One of the consequences of the chlorine activation is the formation of chlorine dioxide (OCIO) mainly by the reaction

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that occurs in the lower stratosphere. OClO is rapidly photolyzed producing ClO and O,



leading to a null cycle when atomic oxygen combines with molecular oxygen to reform ozone. Even though OClO is not directly involved in the ozone destruction, its concentration is a quantitative indicator of the degree of chlorine activation at solar zenith angles (SZA) lower than 92° (Sessler et al., 1995).

10 The presence of OClO in the atmosphere was first detected at McMurdo Station (Antarctica) by Solomon et al. (1987) during the austral spring in 1986. Since then, total column densities of OClO have been derived from ground-based, airborne, and satellite measurements in the Arctic and Antarctic regions (e.g., Sanders et al., 1989; Schiller et al., 1990; Perner et al., 1991; Brandtjen et al., 1994; Wagner et al., 2001).  
15 Though measurements of OClO total column amounts are important, the OClO vertical distribution is required to improve the model computations of the ozone destruction due to the BrO/ClO reaction. It is also important to increase the confidence in the assumed relation between the stratospheric levels of BrO and OClO in the model calculations. Despite the relevance of these profiles, OClO vertical concentrations have been only  
20 measured in a few balloon campaigns in northern Scandinavia (e.g., Pommereau and Piquard, 1994; Renard et al., 1997; Payan et al., 1999; Rivi re et al., 2003).

The need for global coverage and high vertical resolution of atmospheric information led to the development of the atmospheric limb-scattering technique. In this complex viewing geometry, sunlight scattered from the Earth's limb is continuously measured  
25 on the sunlit atmosphere at different tangent heights. Some recently launched satellite instruments measure limb radiances with the objective of retrieving the vertical distribution of trace gases, including OClO. The Optical Spectrograph and InfraRed Imager System (OSIRIS) onboard the Odin satellite (Llewellyn et al., 2004) and the Scanning

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Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) on the ENVISAT spacecraft (Bovensmann et al., 1999) were specially designed to measure limb-scattered sunlight radiances with a near-global coverage and high vertical resolution (1–3 km). Two other instruments, the Global Ozone Monitoring by Occulta-  
tion of Stars (GOMOS) also onboard ENVISAT (Bertaux et al., 1991) and the Strato-  
spheric Aerosol and Gas Experiment III (SAGE III) on the Meteor-3M platform (Mc-  
Cormick et al., 1991), are primarily occultation instruments, but also have a limb-scatter  
measurement capability.

This paper reports the first OCIO number density profiles retrieved from OSIRIS limb-  
scattered radiances using differential optical absorption spectroscopy (DOAS) (Platt,  
1994) combined with an optimal estimation (OE) method, more specifically the maxi-  
mum a posteriori (MAP) estimator (Rodgers, 2000). After a summary of OSIRIS and  
Odin characteristics is given, the retrieval algorithm is described together with some  
sensitivity studies of the calculated OCIO effective column densities (ECD). OSIRIS  
OCIO profiles are then compared with simulations from a chemical transport model  
and some balloon measurements performed in the past. Results for high chlorine ac-  
tivation conditions in the austral spring 2002 are presented together with an outlook of  
the future work to be done.

## 2. OSIRIS instrument

The Odin satellite has a joint aeronomy and astronomy mission (Murtagh et al., 2002),  
sharing the main instrument which is an advanced Submillimetre and Millimetre Ra-  
diometer (SMR) (Frisk et al., 2003). For the aeronomy mission, the payload is com-  
plemented by another passive remote sensing instrument, OSIRIS (Llewellyn et al.,  
2004). Odin was launched in February 2001 into a 600 km circular Sun-synchronous  
near terminator orbit with the ascending node at 18:00 local solar time (LST). The  
coaligned instruments scan the terrestrial limb between 7 and 70 km tangent height  
in the stratospheric mode or between 7 and 110 km for the stratospheric-mesospheric

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mode at a rate of  $0.75 \text{ km s}^{-1}$  through nodding of the spacecraft. Odin completes about 15 orbits per day and, when operated in the stratospheric mode, approximately 65 scans are carried out per orbit. The inclination of Odin's orbit is  $97.8^\circ$ , limiting the latitudinal coverage to between  $82.2^\circ \text{ N}$  and  $82.2^\circ \text{ S}$  when viewing in the orbit plane. An off-plane mode is occasionally used to provide better global coverage, for example during the ozone 'hole' period. OSIRIS consists of two optically independent components: the Optical Spectrograph (OS) and the Infrared Imager (IRI). The spectrograph uses a charged-coupled device that provides a spectral coverage from 280 to 800 nm with a resolution (FWHM) of approximately 1 nm. The instantaneous field of view is 1 km in the vertical and 40 km in the horizontal at the tangent point. This study is focused on the OS, since chlorine dioxide absorbs in the UV-visible region. Table 1 summarizes the mission, spectral intervals (frequency or wavelength) and target species for the instruments onboard Odin.

### 3. Methodology

The two-step method developed by Haley et al. (2004) is used to derive OCIO vertical number density profiles from OS limb-scattered sunlight measurements in the near-UV and violet regions of the solar spectrum. The first step is the spectral analysis of the OS measurements to calculate the OCIO ECD profiles by applying the DOAS technique. The second step is the inversion of these ECD profiles to obtain the number density profiles using a non-linear iterative version of the MAP estimator coupled with the LIMBTRAN (Griffioen and Oikarinen, 2000) radiative transfer model. Figure 1 shows a schematic description of the retrieval algorithm.

#### 3.1. Spectral analysis

In the late seventies, DOAS was introduced as a method to detect atmospheric trace-gas concentrations from measurements in the UV and visible spectral regions (e.g.,

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Noxon, 1975; Noxon et al., 1979, and Platt et al., 1979). This technique uses narrow molecular absorption bands of trace species, which are molecule-specific, to deduce their absorption strength. A detailed description of DOAS applied to scattered sunlight limb radiances follows.

5 Absorption spectroscopic techniques employ the Beer-Lambert-Bouguer Law to determine the concentrations of gas species. This law describes the pure absorption of electromagnetic radiation by a single species in a homogeneous medium at a specific wavelength, and has to be modified when applied to limb-scattered sunlight measurements. It is necessary to add the contribution of Rayleigh and Mie scattering, and to  
 10 consider multiple absorbers over a spectral region. Thus, the optical depth  $\tau$  at tangent height  $h_t$  and wavelength  $\lambda$  can be expressed as

$$\tau(\lambda, h_t) = \ln \left[ \frac{I_o(\lambda)}{I(\lambda, h_t)} \right] = \sum_i \sigma_i(\lambda) c_i(h_t) + \tau_R(\lambda, h_t) + \tau_M(\lambda, h_t), \quad (1)$$

where  $I(\lambda, h_t)$  is the measured intensity,  $I_o(\lambda)$  is the unattenuated reference intensity,  $\sigma_i(\lambda)$  is the wavelength dependent absorption cross section of the  $i$ th species,  $c_i(h_t)$   
 15 is the effective column density of the  $i$ th species as measured in the direction of the line of sight (LOS),  $\tau_R(\lambda, h_t)$  is the Rayleigh optical depth, and  $\tau_M(\lambda, h_t)$  is the Mie optical depth. Note that in the limb viewing geometry,  $I_o$  represents a scattered solar spectrum free from molecular absorption and Rayleigh and Mie extinctions. Since such  
 20 a spectrum is not available from OS measurements, a limb-scattered spectrum from a high tangent height within the same scan is used. This reference is expected to contain little trace gas absorption, thus maximizing the differential absorption features while minimizing the interference with the solar Fraunhofer lines. The average of limb-scattered spectra between 40 and 70 km from each scan is used as the reference to reduce noise.

25 The basic principle of DOAS is to calculate the so-called differential absorption, that is the rapidly varying part of the total absorption. Hence, the absorption cross sections

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are split into two components:

$$\sigma_i(\lambda) = \sigma_i^S(\lambda) + \sigma_i'(\lambda), \quad (2)$$

where  $\sigma_i^S(\lambda)$  represents broad spectral features and the differential cross sections,  $\sigma_i'(\lambda)$ , show narrow spectral features containing the ‘fingerprints’ of the absorbers. Introducing Eq (2) into Eq. (1), and separating the rapidly and slowly varying components leads to

$$\tau(\lambda, h_t) = \underbrace{\sum_i \sigma_i'(\lambda) c_i(h_t)}_{\text{rapid}, \tau'} + \underbrace{\sum_i \sigma_i^S(\lambda) c_i(h_t) + \tau_R(\lambda, h_t) + \tau_M(\lambda, h_t)}_{\text{slow}, \tau^S}, \quad (3)$$

where the first term of the right-hand side is the differential optical depth (DOD), and the other three terms represent the slowly varying components of the optical depth  $\tau^S$ . Considering only the differential component of Eq. (3), the differential optical depth  $\tau'$  is defined as

$$\tau'(\lambda, h_t) = \sum_i \sigma_i'(\lambda) c_i(h_t). \quad (4)$$

The observed DOD  $\tau'_{obs}$  can then be modelled with Eq. (4), i.e.

$$\tau'_{obs}(\lambda, h_t) \approx \sum_i \sigma_i'(\lambda) c_i(h_t) + E_{\tau'_{obs}}(\lambda, h_t), \quad (5)$$

where  $E_{\tau'_{obs}}(\lambda, h_t)$  is the error in the observed DOD resulting from the measurement error (noise) of OS. Employing the error propagation formula, the standard deviation of this error,  $\varepsilon_{\tau'_{obs}}(\lambda, h_t)$ , is approximated by

$$\varepsilon_{\tau'_{obs}}(\lambda, h_t) = \sqrt{\left[ \frac{\varepsilon_{I_o}(\lambda)}{I_o(\lambda)} \right]^2 + \left[ \frac{\varepsilon_I(\lambda, h_t)}{I(\lambda, h_t)} \right]^2}, \quad (6)$$

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where  $\varepsilon_{I_o}(\lambda)$  is the estimated error of the reference spectrum and  $\varepsilon_I(\lambda, h_t)$  is the estimated error in the spectrum  $I(\lambda, h_t)$ .

The effective column densities of the  $i$  absorbers at each tangent height can be derived using a least squares (LSQ) fit of Eq. (5) with respect to  $c$ , i.e. by fitting the differential cross sections of the absorbers to the observed DOD. A residual analysis is carried out to assess the adequacy of the fit to the measured values. The fitting residual  $r$  is defined as the difference between the differential optical depth of the observed and modelled spectra at each tangent height  $h_t$  and wavelength  $\lambda$ :

$$r(\lambda, h_t) = \tau'_{obs}(\lambda, h_t) - \sum_i \sigma'_i(\lambda) c_i(h_t). \quad (7)$$

The residual gives a measure of the overall quality of the fit and would consist of only random noise for a perfect model and an ideal measurement. The root mean square (RMS) of the residuals at the tangent height  $h_t$  is determined by

$$r_{\text{RMS}}(h_t) = \sqrt{\frac{\sum_{j=1}^{\eta} r(\lambda_j, h_t)^2}{\eta}}, \quad (8)$$

where  $\eta$  is the number of pixels in the fitting region. A chi-squared test is also performed to determine if the fit to the DOD is consistent with the measured DOD within the estimated error of the measurements. The DOAS reduced chi-squared statistic  $\chi^2_{doas}$  is calculated as

$$\chi^2_{doas}(h_t) = \frac{\sum_{j=1}^{\eta} \left[ \frac{r(\lambda_j, h_t)}{\varepsilon'_{\tau'_{obs}}(\lambda_j, h_t)} \right]^2}{d}, \quad (9)$$

where  $d$  is the number of degrees of freedom (i.e., the number of pixels in the spectral window minus the number of parameters used in the fit). If the reduced chi-squared

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values are much larger than one, the observed DOD does not fit the calculated DOD within the measurement errors. Fits with  $\chi^2_{doas} > 4$  are excluded from the further analysis.

### 3.2. Selection of the fitting interval

5 The spectral absorption structure of OCIO, shown in Fig. 2, suggests that the differential absorption spectroscopy is an attractive way of detecting this gas in the near-UV and visible regions. Solomon et al. (1987) first retrieved OCIO column abundances in the wavelength range of 403–428 nm using a spectrograph covering the region from 400 to 453 nm. Spectroscopic measurements of OCIO have also been performed in the  
 10 near-UV region by other authors (e.g., Schiller et al., 1990; Perner et al., 1991, 1994; Brandtjen et al., 1994; Van Roozendaal et al., 1995; Wagner et al., 2001), with the window 363–391 nm being the most frequently employed.

In this study, the selection of the OCIO fitting window is restricted to the 355–427 nm wavelength interval. Wavelengths longer than 355 nm are chosen to avoid the imperfect  
 15 removal of ozone features due to the temperature dependence of its cross sections in the Huggins bands and the non-linearity problems due to large optical depths. Because of a strong  $N_2^+$  auroral emission at 427.8 nm and the weak cross sections of OCIO at longer wavelengths, wavelengths have to be shorter than 427 nm. In this study, three spectral regions were investigated as possible fitting windows to retrieve OCIO ECD:  
 20 363–391 nm, 403–427 nm, and 363–427 nm. Measurements in the 390.9–398.4 nm range are not included in the spectral fit due to the presence of a pair of deep Fraunhofer lines ( $\sim 393$  and  $\sim 397$  nm) and a strong  $N_2^+$  auroral emission at 391.4 nm. As seen in Fig. 2, other trace gases (i.e.,  $O_3$ ,  $NO_2$ ,  $O_4$  and BrO) absorb in the UV-visible region. Thus, their absorption cross sections are included along with OCIO in the fit.  
 25 Table 2 displays the number of pixels  $n$  of each window, excluded wavelength bands and interfering species in the different windows.

Figure 3 shows OCIO ECD profiles, reduced chi squared and residual RMS values retrieved from OS spectra (scan 8567046, measured on 19 September 2002) in the

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three spectral regions. The wavelength interval 403–427 nm presents larger OCIO ECD compared with the others at almost all the tangent heights. The mean residual RMS values are  $1.8 \times 10^{-3}$ ,  $1.0 \times 10^{-3}$ , and  $1.6 \times 10^{-3}$  in the 363–391, 403–427, and 363–427 nm regions respectively with generally larger residual RMS values at lower tangent heights.  $\chi^2_{doas}$  values in the 403–427 nm window are smaller or at most comparable with the values obtained in the other windows at all tangent heights, ranging between 1 and 2. The estimated accuracy of the OCIO ECD at the peak is 12%, 14% and 19% in the 363–391, 403–427, and 363–427 nm windows, respectively.

Since a good reduced chi squared and small residual RMS may not mean necessarily that the fit and/or the fitting function are good, a visual examination of the residuals is performed to identify remaining patterns or systematic structures. Figure 4 presents the fitting residual values of the same scan shown in Fig. 3 at a tangent height of 16.8 km. Although the residuals in the 403–427 nm region show some systematic structures, their values are small compared with the residuals of the other windows. These findings are confirmed with the results obtained when processing other OS spectra measured on 19–20 September 2002 inside the polar vortex area. A significant cross correlation between OCIO and BrO absorption cross sections for wavelengths shorter than 380 nm could, to some extent, explain the larger residual structures found in the 363–391 and 363–427 nm intervals and the large difference in ECD.

Negative OCIO ECD were frequently found at latitudes outside the polar vortex area at all tangent heights and at high tangent heights (above 25 km) within the vortex for spectra measured on 19–20 September 2002. This is consistent with the negative OCIO abundances observed by other authors (e.g., Solomon et al., 1987; Pommereau and Piquard, 1994) outside the chlorine activation area, and is due to the low OCIO concentrations. The frequency of occurrence and the magnitude of these negative ECD values are smaller in the range 403–427 nm compared to the values calculated in the other windows. A possible explanation could be the smaller residual structures observed in this spectral window, indicating a better fit.

Based on these results, the window 403–427 nm has been chosen to retrieve OCIO

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in this study.

### 3.3. Spectral corrections

Systematic structures in the residual spectra can be caused by the Ring effect,  $I_o$  effect, polarization sensitivity of the instrument, effect of instrument resolution and sampling, wavelength shifts, as well as temperature dependence of the absorption cross sections. In this section, the sensitivity of the derived OCIO effective columns to these issues is analyzed by applying different spectral corrections to the OS spectra and absorption cross sections. The spectra were chosen from 122 scans, measured on 19–20 September 2002 inside the chlorine activation area, at tangent heights between 10 and 30 km. This study was carried out in a sequence of several steps as follows:

- i The variables OCIO ECD, relative ECD error (i.e., the ECD error divided by its corresponding ECD), reduced chi squared, and residual RMS are derived when no correction is used in the retrieval process (run 1).
- ii The same variables are calculated when the first spectral correction is taken into account (run 2).
- iii For each variable, the results of run 1 are subtracted from the results of run 2.
- iv These differences are then classified as positive or negative increments. Differences larger than 100% or smaller than –100% represent only a few percent of the total number of measurements and were discarded from this analysis.
- v The relative frequencies (i.e., the number of measurements following this condition divided by the total number of measurements) of the positive and negative differences are calculated for each variable.
- vi The mean values of the positive and negative increments are computed separately for OCIO ECD, relative ECD error, reduced chi squared, and residual RMS.

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vii After analyzing the results obtained in steps v) and vi), it is decided if the spectral correction is included or not in the subsequent runs.

The above procedure is employed to investigate the sensitivity of the OCIO ECD profiles to various spectral corrections: Rayleigh scattering, solar  $I_0$  effect, Ring effect, polarization, tilt effect, and wavelength shifts. Tables 3, 4, 5, and 6 display separately the positive and negative mean differences of the OCIO ECD, relative ECD error, residual RMS and  $\chi^2_{doas}$  respectively, together with the relative frequencies of these increments for each spectral correction. As an example, when the tilt correction is taken into account 71% of the OCIO ECD increments are positive with a mean increase of 11% while 26% of the increments are negative with an mean difference value of  $-10\%$  (see Table 3).

### 3.3.1. Rayleigh scattering

The spectral smoothing applied to obtain the differential quantities is performed by a second order closure polynomial in the 403–427 nm region. Rayleigh cross sections (from Bates, 1984) are included in the LSQ fit to complete the removal of this 4th order polynomial structure. This correction is especially important for the lower stratosphere where Rayleigh scattering is more efficient. The Rayleigh correction yields a mean increase of 27% in the OCIO ECD for 50% of the cases, while it reduces the residual RMS by 1% for almost all the cases. In light of this, this correction is included in the retrieval process.

### 3.3.2. Solar $I_0$ effect

The absorption cross sections of the trace gases used in the DOAS analysis are taken from the literature. OS spectra and laboratory absorption cross sections are measured at different spectral resolutions and using different light sources. In the case of limb-scattered sunlight measurements, the reference  $I_0$  spectrum is highly structured due to the presence of Fraunhofer lines whereas the  $I_0$  spectrum used to measure the

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laboratory cross sections is nearly unstructured. Thus, the usually highly resolved laboratory cross sections  $\sigma_i^{hr}$  have to be convolved to the OS resolution including the so-called solar  $I_o$  effect (Aliwell et al., 2002). For small optical depths, the solar  $I_o$ -corrected cross sections  $\sigma_i^*$  can be approximated as (Haley et al., 2004)

$$\sigma_i^*(\lambda) \approx \frac{\int_{-\infty}^{+\infty} g(\lambda', s_g) I_s^{hr}(\lambda - \lambda') \sigma_i^{hr}(\lambda - \lambda') d\lambda'}{\int_{-\infty}^{+\infty} g(\lambda', s_g) I_s^{hr}(\lambda - \lambda') d\lambda'}, \quad (10)$$

where  $I_s^{hr}$  is a solar exoatmospheric spectrum at a resolution identical to that of  $\sigma_i^{hr}$ ,  $g$  is the instrumental filter function and  $s_g$  is the standard deviation of  $g$ . The following high-resolution and temperature-dependent cross sections are  $I_o$  corrected and used in this study: a)  $O_3$  from Bogumil et al. (2003) at temperatures 203 K, 223 K, 243 K, 273 K and 293 K with quadratic interpolation and resolution (FWHM) of 0.52 nm at 415 nm, b)  $NO_2$  from Vandaele et al. (1998) at temperatures 200 K and 294 K with linear interpolation and resolution (FWHM) of 34 pm at 415 nm, c) OCIO from Kromminga et al. (2003) at temperatures 213 K, 223 K, 253 K, 273 K and 293 K with quadratic interpolation and resolution (FWHM) of 17 pm at 415 nm, and d)  $O_4$  from Greenblatt et al. (1990) at temperature 296 K and resolution (FWHM) of 0.56 nm. The difference between the uncorrected and  $I_o$ -corrected cross sections is larger for OCIO (up to 4%) than for the interfering species in this fitting region. Accounting for the  $I_o$  effect increases the OCIO effective columns by an average of 8% in 64% of the cases while a reduction of 1% is observed in the residual RMS and  $\chi_{dof}^2$  statistics. Moreover, the relative error decreases 8% in 69% of the cases. As a result, the  $I_o$ -corrected cross sections are used in this work.

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### 3.3.3. Ring effect

The solar radiation in the Earth's atmosphere undergoes inelastic scattering by Rotational Raman Scattering (RRS). This scattering results from interactions between molecular rotation and electromagnetic waves and changes the frequency of the scattered light. RRS is proposed to be the most probable cause for the broadening and reduction of depth of the Fraunhofer lines, the so-called Ring effect. The magnitude of RRS is a function of pressure, temperature, aerosol, ground albedo and scattering angle. Thus, the RRS structure in the OS limb-scattered spectra varies with tangent height. As a consequence, the Fraunhofer lines of the measured spectra do not entirely cancel out when computing the DOD and could mask the weak absorption of some trace gases if the Ring effect is not properly accounted for. Before performing the DOAS LSQ fit, an iterative backward Ring model (Sioris et al., 2002) is used to remove the Ring effect from OS limb spectra. When the Ring effect is considered, the residual RMS are even larger and  $\chi^2_{doas}$  values increase away from one for almost all the cases, indicating a poorer fit. This is consistent with the results found by Haley et al. (2004) and Sioris et al. (2003) when retrieving NO<sub>2</sub>. An explanation for this could be that the 403–427 nm window does not contain strong Fraunhofer lines and the use of a high tangent height reference from within the scan leads to a large cancellation of the effect.

### 3.3.4. Polarization

Solar radiation becomes partially polarized when it is scattered by air molecules and aerosol particles in the Earth's atmosphere. Like most grating spectrometers, OS sensitivity is dependent on the polarization state of the light; this dependence is larger for incident light polarized perpendicular to the grooves of the grating. Since the scattering angle is often close to 90 degrees in the OSIRIS viewing geometry, the contribution of the perpendicular component is maximized. McLinden et al. (2002a) concluded that the linear polarization of OS limb radiances varies little for tangent heights larger than

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30 km since the entire path is above both the ozone and aerosol layers. At lower tangent heights, multiple scattering and scattering by aerosols become more important and the variation of polarization is stronger. Figure 5 shows the OS polarization efficiency parameter in the 403–427 nm window computed as described by McLinden et al. (2002b). Because this parameter is not completely removed by a second order polynomial, it is included as a pseudo-absorber in the LSQ fit at all tangent heights in the sensitivity analysis. However, as the analysis shows, the polarization correction can be ignored since it has a negligible impact on the OCIO columns and their relative errors as well as on the other statistics.

### 3.3.5. Tilt effect

The Fraunhofer lines observed in the reference tangent height spectrum and a lower tangent height spectrum can appear shifted and skewed to each other. This effect, denoted ‘tilt effect’, was discovered by Sioris et al. (2003) and is mainly explained by the undersampling of the OS spectra ( $\sim 2$  pixels/FWHM) in combination with Rayleigh and Mie trending (tilt) of the limb radiances. Because of the large efficiency of Rayleigh scattering in the short wave range, this effect is most pronounced in the UV and blue regions of the spectrum. This phenomenon can be roughly accounted for by introducing a pseudo-absorber in the DOAS LSQ fit (Sioris et al., 2003). If atmospheric absorption is ignored, the tilt pseudoabsorber  $t(\lambda, h_t)$  is calculated as (Haley et al., 2004)

$$t(\lambda, h_t) = \frac{I^{os}(\lambda, h_t^{ref})/I^{os}(\lambda, h_t)}{I^{hr}(\lambda, h_t^{ref})/I^{hr}(\lambda, h_t)} - 1 \quad (11)$$

where the ratio of the spectra convolved to the OS resolution and sampling,  $I^{os}$ , is related to the ratio of highly resolved and sampled spectra,  $I^{hr}$ , and  $h_t^{ref}$  is the reference tangent height. In this study, the LIMBTRAN radiative transfer model (see Sect. 3.4.1) is used to simulate spectral limb radiances at different tangent heights under Antarctic spring conditions (large SZA and high ground albedo). A set of tilt pseudoabsorbers

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is calculated at tangent heights between 10 and 40 km with a 2-km interval when the reference tangent height was set to 50 km. The pseudoabsorber at a specific tangent height  $h_t$  is linearly interpolated from this set of pre-calculated tilt pseudoabsorbers. Figure 6 displays the tilt pseudoabsorber at four tangent heights (i.e., 10, 20, 30 and 40 km) in the 403–427 nm window. The influence of this effect in the fit diminishes as  $h_t$  approaches  $h_t^{ref}$  since the slope difference of the spectra becomes smaller. A large improvement in the DOAS fit is observed for almost all the scans when the tilt effect is considered. The residual RMS decreases by as much as a factor of 1.5 whereas  $\chi_{doas}^2$  diminishes 24% in average. The improvement of the fit also leads to larger OCIO abundances in 71% of the cases with an average increase of 11%.

### 3.3.6. Wavelength shift

The wavelength calibration of OS has been determined by applying two methods. A Levenberg-Marquardt (L-M) (Levenberg, 1944; Marquardt, 1963) fit of a high resolution solar spectrum (Kurucz, <http://kurucz.harvard.edu/sun/IRRADIANCE/irradiancebins.dat>) to OS limb radiance spectra at mesospheric altitudes has been performed to the blue part of the spectrum. To the red end of the spectrum, the wavelength calibration was determined by using intense airglow features, Fraunhofer lines, and O<sub>2</sub> absorption features (Sioris and Haley, personal communication). However, this is only a nominal calibration and any wavelength misalignment between the measured limb-scattered radiance spectra and the absorption cross sections could affect the DOAS fit. An absolute shift in wavelength is determined through L-M non-linear iterations on the DOAS fit to the lowest tangent height measurement and then applied to all measurements in the scan. The fit minimizes the residuals with an emphasis on the dominant absorber (NO<sub>2</sub> in the 403–427 nm window). After processing the set of 122 scans, a 0.03 nm average shift was found, but with large standard deviations (i.e., 0.045 nm). As seen in Tables 3, 4, 5, and 6, the wavelength shift has no clear impact on the fit. It is likely that because of the low NO<sub>2</sub> concentration inside the polar vortex area, the derived shift is being dominated by the noise in the measurement. In light of this, the wavelength shift

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is not applied when retrieving the OCIO column densities.

### 3.3.7. Temperature dependence

The absorption cross sections of the trace gases are temperature dependent and the retrieved ECD could be influenced by the specific cross sections chosen for the fit. The Kromminga et al. (2003) OCIO differential cross sections show a large temperature dependence varying by up to 40% between 213 and 233 K in the 403–427 wavelength interval. Since limb-scattered radiance spectra contain contributions from different tangent heights and the temperature varies with height, the effective temperature at which the absorption occurred for each spectrum is not obvious. If the temperature dependence is not properly taken into account (i.e., incorrect fixed temperature is assumed) and the use of the wrong cross sections in the DOAS fit will lead to the retrieval of the wrong ECD. However, as described in Sect. 3.4.1, a forward model is employed to invert the ECD to number density. Any systematic error in the ECD derived from the measurements will be compensated for when ECD are calculated from the model radiances, if the temperature profile and cross sections used in the radiative transfer model are correct and the same method for accounting for temperature dependence in the DOAS fit is applied in the forward model. As a consequence, the absorption cross sections were selected at fixed temperatures: 203 K for O<sub>3</sub> (Bogumil et al., 2003), NO<sub>2</sub> at 220 K (Vandaele et al., 1998), OCIO at 213 K (Kromminga et al., 2003), and O<sub>4</sub> at 296 K (Greenblatt et al., 1990). Cross sections at the coldest temperatures available were chosen since the European Centre for Medium-range Weather Forecasts (ECMWF) analysis for 19–20 September 2002 suggests cold temperatures inside the polar vortex region (i.e., <200 K).

As a result of these sensitivity tests, Rayleigh scattering, I<sub>0</sub> effect, tilt effect and fixed absorption cross sections are the spectral corrections applied when retrieving OCIO in the 403–427 nm region. Figure 7 presents a typical OCIO fit showing the fitted and observed OCIO optical depths and the residual structures for scan 8565047 at 18.7 km

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tangent height inside the polar vortex area.

### 3.4. Inversion

The objective of the inversion is to convert the OCIO ECD as a function of tangent height, obtained from the DOAS analysis, to vertical number density profiles as a function of altitude. The problem is best approached with the use of a forward model  $F$  that relates the vector of OCIO ECD for a set of tangent heights  $\mathbf{c}$  to the number density vector  $\mathbf{n}$  by

$$\mathbf{c}(h_t) = F(\mathbf{n}, \mathbf{b}, h_t) + \varepsilon, \quad (12)$$

where  $\mathbf{b}$  is the vector of model parameters that are not retrieved and  $\varepsilon$  is the measurement error.

The present inversion problem is ill-posed, under-constrained and non-linear. The problem is ill-posed because Eq. (12) does not have a unique solution. Hence, the inversion algorithm has to select a physically acceptable solution from a range of mathematically valid solutions (Jiménez et al., 2000). It is under-constrained because the number density profiles of OCIO are continuous functions of altitude and the measurements were performed at discrete tangent heights. Additionally, since absorption is a linear process only for optically thin conditions, the problem becomes non-linear in the UV/blue region where the high Rayleigh scattering efficiency could lead to large optical depths at low tangent heights.

The inversion algorithm employed in this work is the maximum a posterior estimation method (Rodgers, 2000). MAP combines measurements with a priori information about the profile to find the best estimate of the true profile and its error covariance. This is done by maximizing the a posteriori probability density function of the state  $\mathbf{n}$  given the measurement  $\mathbf{c}$ . If Gaussian statistics are assumed for variables and errors, the MAP estimator leads to the minimization of the following cost function  $J$  (Rodgers, 2000):

$$J(\mathbf{n}) = [\mathbf{c} - F(\mathbf{n}, \mathbf{b})]^T \mathbf{S}_\varepsilon^{-1} [\mathbf{c} - F(\mathbf{n}, \mathbf{b})] + [\mathbf{n} - \mathbf{n}_a]^T \mathbf{S}_a^{-1} [\mathbf{n} - \mathbf{n}_a], \quad (13)$$

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where  $\mathbf{n}_a$  is the a priori number density state vector,  $\mathbf{S}_a$  is the a priori covariance matrix, and  $\mathbf{S}_\varepsilon$  is the measurement error covariance matrix.  $\mathbf{S}_\varepsilon$  is a diagonal matrix since  $\varepsilon$  is assumed to be uncorrelated in tangent height. In order to avoid negative values that could lead to unstable retrievals, the natural logarithm of the concentrations  $\ln(\mathbf{n})$  is inverted instead of the concentrations  $\mathbf{n}$ . This positive constraint requires a non-linear retrieval.

If the inversion problem is linear the forward model can be expressed as  $\mathbf{F}=\mathbf{K}\mathbf{n}$ , where  $\mathbf{K}$  is the weighting function matrix, and the minimization of  $J$  can be analytically solved. However, if the problem is not linear, it must be solved numerically and iteratively. To this end, a simplified Levenberg-Marquardt iterative scheme has been chosen to minimize  $J$ , yielding the following solution:

$$\mathbf{n}_{i+1} = \mathbf{n}_i + \left[ (1 + \gamma_i) \mathbf{S}_a^{-1} + \mathbf{K}_i^T \mathbf{S}_\varepsilon^{-1} \mathbf{K}_i \right]^{-1} \left[ \mathbf{K}_i^T \mathbf{S}_\varepsilon^{-1} (\mathbf{c} - \mathbf{F}(\mathbf{n}_i, \mathbf{b})) - \mathbf{S}_a^{-1} (\mathbf{n}_i - \mathbf{n}_a) \right], \quad (14)$$

where the weighting function matrix  $\mathbf{K}_i$  is calculated for each iteration step  $i$  (see Sect. 3.4.1) and  $\gamma_i$  determines the step size of the iteration. The simplified L-M method is a combination of the steepest descent and Gauss-Newton (G-N) methods where  $\gamma_i$  is the parameter controlling the balance between them (Rodgers, 2000).

Two different strategies were applied in this investigation. The first one is to find the solution within 10 iterations using the G-N method. When an occasional fail in convergence occurs, the L-M scheme is applied. Large  $\gamma_i$  values are set during the first iterations of L-M to descend with small steps. Once the solution is closer to the minimum, small  $\gamma_i$  values are chosen because the G-N iteration converges faster. The iteration is halted when the size of the step  $(\mathbf{n}_{i+1} - \mathbf{n}_i)$  is smaller than the estimated error. Thus, the convergence criterion is expressed as

$$\frac{(\mathbf{n}_{i+1} - \mathbf{n}_i)^T \hat{\mathbf{S}}^{-1} (\mathbf{n}_{i+1} - \mathbf{n}_i)}{\rho} < \Delta n, \quad (15)$$

where  $p$  is the length of  $\mathbf{n}$ ,  $\Delta n$  is the absolute convergence tolerance, and  $\hat{\mathbf{S}}^{-1}$  can be approximated by

$$\hat{\mathbf{S}}^{-1}(\mathbf{n}_{i+1} - \mathbf{n}_i) \approx \mathbf{K}_i^T \mathbf{S}_\varepsilon^{-1} [\mathbf{c} - \mathbf{F}(\mathbf{n}_i, \mathbf{b})] - \mathbf{S}_a^{-1} [\mathbf{n}_i - \mathbf{n}_a]. \quad (16)$$

In this study,  $\Delta n$  is set to 0.001. Once Eq. (14) has converged to some value  $\hat{\mathbf{n}}$  with corresponding  $\hat{\mathbf{K}}$ , a standard  $\chi^2$  test is carried out to determine whether the difference between the retrieved and measured quantities is statistically significant at some appropriate level. Following Rodgers (2000), the reduced chi-squared statistic for the inversion is defined by

$$\chi_{inv}^2 = \frac{[\mathbf{c} - \mathbf{F}(\hat{\mathbf{n}}, \mathbf{b})]^T \mathbf{S}_{\delta\hat{\mathbf{c}}}^{-1} [\mathbf{c} - \mathbf{F}(\hat{\mathbf{n}}, \mathbf{b})]}{q}, \quad (17)$$

where  $\mathbf{S}_{\delta\hat{\mathbf{c}}} = \mathbf{S}_\varepsilon [\hat{\mathbf{K}} \mathbf{S}_a \hat{\mathbf{K}}^T + \mathbf{S}_\varepsilon]^{-1} \mathbf{S}_\varepsilon$  is the covariance matrix of  $\delta\hat{\mathbf{c}} = \mathbf{c} - \mathbf{F}(\hat{\mathbf{n}}, \mathbf{b})$  and  $q$  is the length of  $\mathbf{c}$ . The probability of obtaining a value of  $\chi_{inv}^2 > 4$  is one in a million for a  $\chi^2$  distribution with 30 degrees of freedom. Hence, profiles following this condition are ruled out.

#### 3.4.1. The forward model

A radiative transfer model (RTM) simulates the limb-scattered radiances to different tangent height for a specified wavelength range and a given vertical number density profile of the species of interest. The simulated optical depths are then calculated and subjected to a DOAS analysis. The resulting effective column densities constitute the forward model  $F$ . As described in Sect. 3.4, the forward model is used to invert ECD as a function of tangent height to number density as a function of altitude. Full spherical RTM models are not suitable for many repetitive calculations since they are slower than the simplified models. On the other hand, the error for models assuming a plane-parallel atmosphere is quite large in cases where SZA is larger than  $75^\circ$  (Herman et al.,

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1994). Moreover, multiple scattering (MS) represents 10–50% of the total radiance at visible wavelengths in the limb viewing geometry, depending on SZA, SSA, albedo and tangent height (Oikarinen et al., 1999). The ratio MS/total radiance is even higher at SZA larger than 90°. In a trade-off between computational efficiency and accuracy, the pseudo-spherical multiple scattering radiative transfer model LIMBTRAN (Griffioen and Oikarinen, 2000) is applied in the inversion procedure. LIMBTRAN takes into account the variation of SZA and single scattering angle (SSA) along the LOS and assumes horizontal homogeneity within its vertical layers. Temperature and pressure data used in this RTM are from the ECMWF analysis fields. The  $O_3$  mean state distribution is taken from the four-dimensional climatology of Li and Shine (1995) which is based on satellite and ozonesonde data sets. The  $NO_2$  information is taken from a climatology constructed using the PRATMO photochemical box model (Prather and Jaffe, 1990; McLinden et al., 2000) that accounts for the diurnal variation of this species. The OCIO a priori distribution is described in Sect. 3.4.2. The temperature-dependent cross sections employed in LIMBTRAN are the same as those used for the spectral fitting (see Sect. 3.3.2). A simple stratospheric aerosol model is included based on fitted parameters as a function of season and tropopause height (McCormick et al., 1996; McLinden et al., 2000). The ground albedo is derived from the climatology of GOME Lambertian-Equivalent Reflectivity of the Earth's surface (Koelemeijer et al., 2003). The reader is referred to Haley et al. (2004) for more details on the simulation of OS radiances with this model.

### 3.4.2. A priori information

The most satisfactory source of a priori information is from independent high spatial resolution measurements (Rodgers, 2000). However, a climatology of such measurements is not available for OCIO. Thus, the a priori information is simulated with the REPROBUS chemical transport model (Lefèvre et al., 1994, 1998). This three-dimensional model takes into account the heterogeneous chemical reactions produced on the surface of the PSCs and extends from the ground up to 0.1 hPa on 42 levels.

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In this work, the model was integrated from 1 July 2002 until 1 December 2002 in a 2° latitude by 2° longitude horizontal grid and 15-min time step. The kinetic and photochemical data are based on Sander et al. (2000) for this particular study. Temperatures, winds and ground pressure analyzed every 6 h by the ECMWF were employed in the simulations. The ozone field was initialized on 1 July 2002 from the three-dimensional ECMWF ozone analysis whereas other species were initialized from a June zonal mean computed from a REPROBUS long-term simulation. The generated vertical profiles are taken from the model grid points closest to the location and time of the selected OS measurements.

The OCIO vertical distribution is assumed to be log-normal and the species variability is modelled by (Rodgers, 2000)

$$S_a(i, j) = \rho^2 \exp \left[ \frac{-|z(i) - z(j)|}{l_c} \right], \quad (18)$$

where  $z$  is the altitude indexed by  $i$  and  $j$ ,  $\rho$  is the standard deviation of the diagonal components, and  $l_c$  is the correlation length of the off-diagonal elements. A reliable climatology of the vertical OCIO variability is essential to determine  $\rho$  and  $l_c$ . Since such a statistics do not exist, a sensitivity study was carried out by using different values of  $\rho$  (100%, 200%, 300%, and 400%) and  $l_c$  (3 km and 4 km). In a trade-off between vertical resolution and retrieval error,  $\rho$  was set to 300% and  $l_c$  to 4 km.

### 3.4.3. Weighting functions

$\mathbf{K}$  is the  $q \times p$  weighting function matrix that represents the forward model response to changes in the atmospheric state. The rows of  $\mathbf{K}$  are called weighting functions and the computation of the elements of  $\mathbf{K}$  requires the derivation of the forward model:

$$K(i, j) = \frac{\partial F[\mathbf{n}, \mathbf{b}, h_t(i)]}{\partial n[z(j)]}, \quad (19)$$

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where the forward model is evaluated at tangent height  $h_t(i)$  and  $n[z(j)]$  is the number density at altitude  $z(j)$ . The relationship between the derivatives of the RTM and the derivatives of  $F$  is not obvious because of the intermediate DOAS step. Hence, the weighting functions are determined numerically by using finite differences with sequential perturbation (5% in this case) of the elements of  $\mathbf{n}$ . An element of the  $\mathbf{K}$  matrix is approximated as

$$K(j, j) \approx \frac{F[\tilde{\mathbf{n}}, \mathbf{b}, h_t(i)] - F[\mathbf{n}, \mathbf{b}, h_t(i)]}{\tilde{n}[z(j)] - n[z(j)]}, \quad (20)$$

where  $\tilde{\mathbf{n}}$  is the perturbed number density vector.

This perturbation method is computationally expensive since the forward model has to be run  $p$  times to estimate  $\mathbf{K}$  for every iteration. As a result, two simplifications have been implemented when calculating  $\mathbf{K}$ . The first approximation is to reduce the number of spectral elements by using a two-wavelength DOAS approach as proposed by Haley et al. (2004). For the OCIO retrieval in the 403–427 nm window, the wavelengths 412 and 409 nm were selected as the strong and weak OCIO absorption wavelengths, respectively. This simplification does not lead to any significant differences when compared to a full DOAS analysis. The second simplification is to assume an aerosol-free atmosphere when simulating limb-scattered radiance spectra with the LIMBTRAN model. This approximation leads to negligible errors in the OCIO retrievals. A selection of wavelengths is also applied to compute  $F$ , and a 2 nm wavelength grid is found to be suitable in the 403–427 nm spectral range.

Figure 8 depicts the OCIO weighting functions computed with these simplifications for spring Antarctic conditions. Each plotted profile exhibits how much the OCIO ECD [molecule  $\text{cm}^{-2}$ ] at a given tangent height would change if the number densities [molecule  $\text{cm}^{-3}$ ] at the various profile levels were changed. For instance, if the OCIO number density at 24 km were to increase by 1 molecule  $\text{cm}^{-3}$ , the OCIO ECD at 24 km tangent height would increase by  $6.7 \times 10^7$  molecule  $\text{cm}^{-2}$ . The OCIO ECD at tangent heights above 20 km are mostly influenced by OCIO concentrations near

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and slightly above the tangent point. The weighting functions show a pronounced step directly below the tangent height because the layers below have a small contribution in the limb viewing geometry. At lower tangent heights, the weighting functions become broader and peak around 22 km altitude, indicating contributions from higher altitudes than from the tangent point region. Due to the different shape of the weighting functions below 20 km, it is still possible to retrieve OCIO down to 12 km of altitude. The rapid decrease observed in the weighting functions at low tangent heights is due to the increasing Rayleigh-scattering optical depths.

#### 3.4.4. Error analysis

The total retrieval error is composed of the smoothing error, retrieval noise, forward model error, and forward model parameter error (Rodgers, 2000). The retrieval error can only be estimated on a statistical basis, using covariance matrices because the exact values of  $\mathbf{n}$ ,  $\mathbf{b}$ , and  $\varepsilon$  are unknown (Jiménez et al., 2000). The limited vertical resolution of the observing system causes the smoothing error, whose covariance matrix  $\mathbf{S}_s$  is calculated by

$$\mathbf{S}_s = (\mathbf{A} - \mathbf{1})\mathbf{S}_a(\mathbf{A} - \mathbf{1})^T, \quad (21)$$

where  $\mathbf{A}$  is the averaging kernel matrix ( $p \times p$ ) and  $\mathbf{1}$  is the identity matrix. The  $\mathbf{A}$  matrix is computed as  $\mathbf{A} = \mathbf{G}\mathbf{K}$  where  $\mathbf{G}$  is the gain matrix defined as

$$\mathbf{G} = \mathbf{S}_a \mathbf{K}^T \left[ \mathbf{K} \mathbf{S}_a \mathbf{K}^T + \mathbf{S}_\varepsilon \right]^{-1}. \quad (22)$$

The retrieval noise is usually the easiest component to estimate and its covariance is given by

$$\mathbf{S}_m = \mathbf{G} \mathbf{S}_\varepsilon \mathbf{G}^T. \quad (23)$$

The forward model error arises due to the imperfections and approximations of the forward model. The forward model parameter error is related to the parameters specified

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in the RTM such as ground albedo, stratospheric aerosol loading, atmospheric pressure and temperature profiles, and absorption cross sections of the trace gases. The estimation of the forward model and forward model parameter errors is not carried out in this study. The total retrieved error covariance is obtained by adding the covariance matrices of the four error sources. Note that the covariance matrix of the solution,  $\hat{\mathbf{S}}$ , is the sum of  $\mathbf{S}_s$  and  $\mathbf{S}_m$ .

### 3.4.5. Inversion characterization

The vertical resolution of the retrieval is characterized by the width of the averaging kernel functions, defined as the rows of the  $\mathbf{A}$  matrix. In this work, the spread  $s$  (Backus and Gilbert, 1970) is used as a measure of this width

$$s(z) = 12 \frac{\int (z - z')^2 \mathbf{A}^2(z, z') dz'}{[\int |\mathbf{A}(z, z')| dz']^2}, \quad (24)$$

where  $z$  is the altitude of the nominal peak of the averaging kernel function. The measurement response  $w$  is given by the area of the averaging kernel functions and evaluates the relative contribution of the measurements and a priori information to the retrieved profile. Values close to one indicate that most of the information comes from the measurement and thus the retrieval is considered to be efficient. In this study, an efficient retrieval is chosen to be characterized by  $w$  larger than 0.7.

Figure 9 illustrates the OCIO averaging kernel functions, measurement response, spread, retrieval noise and smoothing error for limb spectra measured on 19 September 2002 over the Antarctic region. Between 14 and 18 km altitude, the averaging kernel functions peak at their corresponding altitude. This is consistent with the small smoothing error and low a priori contamination observed at the same altitudes. Hence, the vertical resolution approximates well the retrieval grid of 2 km for this altitude range. The averaging kernel for the 10 km level has a broad peak at the wrong altitude (i.e., 12 km). The measurements thus contain little useful information on this level as indicated by the low measurement response. The averaging kernel for the 12 km level

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peaks at the correct altitude, but the contributions from the neighbouring levels cause larger smoothing errors and larger spread. The influence of the a priori information is however rather small since the measurement responses are larger than 0.8. All of the averaging kernels above 18 km have broad peaks at 18 km altitude yielding large values of spread and smoothing error and low measurement response. As a result, the error of the solution (denoted by  $S$ ) increases quickly with altitude for these layers. Therefore, the altitude of good measurement sensitivity (i.e.,  $w > 0.7$ ) lies between 12 and 20 km for the OCIO retrievals. In this altitude range, the retrieval noise varies from 27 to 52% with a 2–5 km altitude resolution. This example is generally representative of the entire set of Antarctic OCIO data measured on 19–20 September 2002.

Summarizing, Table 7 presents the specifications of the spectral window used to retrieve OCIO in this study.

#### 4. Comparison

Several difficulties arise when trying to validate the OCIO vertical profiles. The high photolysis frequency prevents the build-up of appreciable concentrations of OCIO during daylight. Therefore most measurements have been performed during twilight and at night. In OSIRIS' case, measurements are carried out only close to the terminator when the chlorine system is not in a steady state. As a consequence, the profiles are very sensitive to differences in time, location, viewing geometry and gradients along the LOS. Thus, a comparison with independent observations is difficult.

In order to assess whether the retrieval method is appropriate and produces reasonable results, the computed OCIO vertical concentrations are tested in three ways: a) comparison to coincident OCIO values simulated using the REPROBUS model initialized on 1 July 2002, b) comparison to OCIO vertical profiles measured in Arctic balloon campaigns, and c) interpretation of the OS OCIO abundances with respect to the atmospheric conditions in the lower stratosphere.

Figure 10 shows the a priori OCIO profile, the observed OS OCIO profile with its as-

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sociated retrieval error and the coincident profile calculated by the REPROBUS model for scan 8565047 on 19 September 2002. Even though the profiles are displayed between 10 and 30 km altitude, the OCIO measurement response is larger than 0.7 only between 12 and 20 km altitude. The REPROBUS profile peaks at 16 km of altitude while the OS maximum is observed at 18 km, with a difference between peak values of less than 3%. There is a good agreement between the modelled and observed OCIO abundances within the retrieval error between 14 and 18 km. Similar agreements between measurements of OCIO performed during the THESEO 2000 campaign and model calculations were found in the lower stratosphere (Rivière et al., 2003).

As already mentioned, a few OCIO vertical profiles have been measured with other instruments inside the polar vortex area. Table 8 summarizes the peak value and corresponding altitude, location, date and time of the OCIO measurements reported by Pommereau and Piquard (1994), Renard et al. (1997) and Rivière et al. (2003), and for OS scan 8565047. The altitude of the OCIO peak value and the shape of the profiles (not shown) are similar while the concentration values differ depending on location and time. The maximum OCIO number density from OS is larger than the peak value detected by Pommereau and Piquard (1994) inside the Arctic polar vortex. This is consistent with the larger OCIO column found above Antarctica where the polar vortex is more persistent and colder, allowing the formation of PSCs over a longer period of time (e.g. Miller et al., 1999). On the other hand, nighttime OCIO slant column abundances were found higher than diurnal measurements since photolysis is the main destruction mechanism for this species (e.g. Wahner et al., 1989). This is coherent with the lower OS OCIO peak value compared to the maximum values retrieved by Renard et al. (1997) and Rivière et al. (2003).

Using the potential vorticity isoline of  $-48 \times 10^{-6} \text{ K m}^2 \text{ kg}^{-1} \text{ s}^{-1}$  at the 475 K isentropic level to define the edge of the polar vortex (e.g. Braathen et al., 1994), Fig. 11a shows the OS  $\text{O}_3$  and  $\text{NO}_2$  concentrations – retrieved following Haley et al. (2004) – inside (scan 8565047) and outside (scan 8565037) the polar vortex area. Figure 11b displays the OS OCIO and ECMWF temperature profiles for scan 8565047. Due to their

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low measurement response, OCIO profiles outside the Antarctic vortex are not shown. Large OCIO number densities are observed inside the polar vortex over areas where reduced  $O_3$  and  $NO_2$  number densities are also found. Low  $NO_2$  concentrations in the ozone hole area are expected due to denitrification and denoxification processes that remove and sequester reactive nitrogen compounds. Temperatures below the threshold of the PSC formation (i.e., typically  $<196$  K) are observed between 14 and 23 km of altitude where the largest OCIO concentrations are detected. Thus, the OCIO profile shows the expected relation to the atmospheric conditions in the lower stratosphere.

## 5. Results and conclusions

To illustrate the OS capabilities of OCIO detection, two figures with OCIO profiles as well as concentrations of other related species are presented. OCIO ECD measurements along the Odin orbit 8565 on 19 September 2002 are shown in Fig. 12 (top panel) together with two number density profiles for two scans (middle panel) inside the ozone hole area. The bottom panel depicts the Southern Hemisphere total ozone content from EP/TOMS ([http://jwocky.gsfc.nasa.gov/ozone/ozone\\_v8.html](http://jwocky.gsfc.nasa.gov/ozone/ozone_v8.html)) for the same day. A clear core region of high OCIO ECDs is observed in the region where the total ozone column is the lowest (i.e.,  $<200$  DU).

The mean OCIO ECD for the orbit 8565 inside the polar vortex region is statistically significantly larger than the mean OCIO ECD outside the vortex at 95% confidence level. The ECDs outside the vortex area are statistically significantly different from zero at 95% confidence level for the same orbit. However, these concentrations are very low and their location coincides with areas where very low abundances of OCIO are expected. As a result, OCIO number density retrievals are limited to chlorine activation regions. The morning OCIO profile (scan A) peaks at 14 km with an estimated retrieval error of 52% while the evening profile (scan B) peaks at 16 km with an estimated retrieval error of 19%. The evening twilight concentrations are larger than the morning abundances, in accordance with the results found by several authors (e.g., Sanders et

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al., 1989; Perner et al., 1991).

Figure 13 displays the number density profiles of  $O_3$ ,  $NO_2$ ,  $OCIO$ , and  $ClO$  along the Odin orbit 8565 for latitudes south of  $40^\circ S$ . All of these measurements were performed at twilight conditions with SZA ranging from  $91^\circ$  to  $92.1^\circ$  when Odin was pointing off of the orbital plane into the sunlit region.  $O_3$  and  $NO_2$  profiles were derived from OS measurements according to Haley et al. (2004). The “SMR retrieval group” at “Chalmers University of Technology” retrieved the  $ClO$  profiles from Odin/SMR spectra (J. Urban, personal communication). The white lines in the plots indicate the lowermost and uppermost altitudes of significant measurements. A large ozone depletion is mainly detected between 16 and 30 km, associated with an important denitrification and denoxification of the lower stratosphere as shown by plots a) and b). This is consistent with an  $OCIO$  enhancement observed in the 10–22 km altitude range where a cold temperature core is also found with temperatures lower than the PSC threshold formation (i.e.,  $<196 K$ ). An area with large  $ClO$  concentrations is observed at altitudes below 20 km (panel d), adhering well with the  $OCIO$  abundances. The sunrise  $OCIO$  concentrations are lower than the sunset abundances as depicted in panel c) since the diurnal variation is largely driven by the diurnal cycle of its photolysis rate (Solomon et al., 1990).

In summary, an algorithm for retrieving stratospheric  $OCIO$  profiles from limb-scattered sunlight radiances has been described and applied to OS measurements.  $OCIO$  profiles were retrieved inside the Antarctic polar vortex region with a measurement response above 0.7 and a vertical resolution of 2–5 km in the altitude range 12–20 km. The estimated retrieval error is better than 60% at the peak of these profiles. This unique data set of  $OCIO$  profiles is very promising for the study of the seasonal and interannual variability of this species and for inter-hemispheric comparisons. Further characterization of the forward model and forward model parameter errors has to be carried out. Also, further comparisons with other  $OCIO$  measurements are desirable for data validation.

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## Glossary of symbols

*	convolution.
$\sim$	perturbation.
$\hat{\phantom{x}}$	MAP estimate.
$\chi_{doas}^2$	DOAS reduced chi squared.
$\chi_{inv}^2$	reduced chi squared of the inversion.
$\Delta n$	absolute convergence tolerance.
$\varepsilon$	measurement error of OS (STD) [ $\text{photon cm}^{-2} \text{ s}^{-1} \text{ nm}^{-1} \text{ ster}^{-1}$ ].
$\varepsilon_{\tau'_{obs}}$	error in $\tau'_{obs}$ (STD).
$\varepsilon_I$	measurement error of I (STD).
$\varepsilon_{I_o}$	measurement error of $I_o$ (STD).
$\gamma$	step size of the iteration.
$\eta$	number of pixels in the spectral window.
$\lambda$	wavelength [nm].
$\rho$	STD of the a priori profile [ $\text{molecule cm}^{-3}$ ].
$\sigma$	absorption cross section [ $\text{cm}^2 \text{ molecule}^{-1}$ ].
$\sigma'$	differential absorption cross sections [ $\text{cm}^2 \text{ molecule}^{-1}$ ].
$\tau$	optical depth.
$\tau'$	differential optical depth.
$\tau'_{obs}$	observed differential optical depth.
$\tau_M$	Mie optical depth.
$\tau_R$	Rayleigh optical depth.
<b>A</b>	averaging kernel matrix.
<b>b</b>	forward model parameter.
<i>c</i>	effective column density [ $\text{molecule cm}^{-2}$ ].
<b>c</b>	effective column density profile.
d	degrees of freedom.
<b>F</b>	forward model vector.

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<b>G</b>	gain matrix.
<i>g</i>	instrumental filter function.
<i>h<sub>r</sub></i>	highly resolved.
<i>h<sub>t</sub></i>	tangent height [km].
<i>h<sub>t</sub><sup>ref</sup></i>	tangent height of reference [km].
<i>I</i>	radiance [photon cm <sup>-2</sup> s <sup>-1</sup> nm <sup>-1</sup> ster <sup>-1</sup> ].
<i>I<sub>o</sub></i>	radiance of unattenuated spectrum.
<i>J</i>	cost function.
<b>K</b>	weighting function matrix.
<i>l<sub>c</sub></i>	correlation length [km].
<i>m</i>	number of species.
<i>n</i>	number density [molecule cm <sup>-3</sup> ].
<b><i>n</i></b>	number density profile.
<b><i>n<sub>a</sub></i></b>	a priori number density profile.
<i>P</i>	atmospheric pressure [hPa].
<i>ρ</i>	number of heights in <b><i>n</i></b> .
<i>ρ<sub>eff</sub></i>	polarization effectivity pseudoabsorber.
<i>q</i>	number of tangent heights in <b><i>c</i></b> .
<i>r</i>	DOAS fitting residual.
<i>r<sub>RMS</sub></i>	residual RMS.
<b>S</b>	covariance matrix of the solution.
<b>S<sub>a</sub></b>	covariance matrix of the a priori.
<b>S<sub>ε</sub></b>	covariance matrix of the measurement.
<b>S<sub>m</sub></b>	covariance matrix of the retrieval noise.
<b>S<sub>s</sub></b>	covariance matrix of the smoothing error.
<i>s</i>	spread.
<i>T</i>	temperature [K].
<i>t</i>	tilt pseudoabsorber.
<i>w</i>	measurement response.

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z	altitude [km].
DN	data number.
DOAS	differential optical absorption spectroscopy.
DOD	differential optical depth.
ECD	effective column density.
FWHM	full width at half maximum.
G-N	Gauss-Newton.
IRI	infrared imager.
L-M	Levenberg-Marquardt.
LOS	line of sight.
LSQ	least squares.
LST	local solar time [hours].
MAP	maximum a posteriori.
MS	multiple scattering.
OE	optimal estimation.
OS	optical spectrograph.
OSIRIS	Optical Spectrograph and Infrared Imager System.
PSCs	polar stratospheric clouds.
RMS	root mean square.
RRS	rotational Raman scattering.
RTM	radiative transfer model.
SMR	Submillimetre and Millimetre Radiometer.
SSA	single scattering angle [°].
STD	standard deviation.
SZA	solar zenith angle [°].
UV	ultraviolet.

*Acknowledgements.* The first author thanks P. Eriksson for helpful comments to set up the a priori constraint in the OCIO retrievals and J. Gumbel for valuable discussions on the manuscript. We also thank the SMR retrieval group at Chalmers University of Technology and

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the Odin/OSIRIS team for making the CIO vertical profiles and OSIRIS level 1 data available, respectively. This work was supported by the Swedish National Space Board, Chalmers University of Technology, and the Canadian Space Agency. Odin is a Swedish-led satellite project funded jointly by Sweden (SNSB), Canada (CSA), Finland (Tekes) and France (CNES).

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**Table 1.** Summary of the mission, spectral intervals and target species of the instruments onboard the Odin satellite.

Instrument	Mission	Interval	Target species (aeronomy)
SMR	astronomy/ aeronomy	486.1–503.9 GHz 541.0–580.4 GHz	O <sub>3</sub> , N <sub>2</sub> O, ClO, HNO <sub>3</sub> , H <sub>2</sub> O, CO, temperature.
OS	aeronomy	280–800 nm	O <sub>3</sub> , NO <sub>2</sub> , OCIO, BrO, aerosols, noctilucent cloud properties, temperature.
IRI	aeronomy	1.27 and 1.53 $\mu$ m	O <sub>2</sub> and OH airglows, mesospheric O <sub>3</sub> , subvisible cirrus properties.

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**Table 2.** Investigated spectral fitting windows for the OCIO retrievals.

Window [nm]	$\eta$	Excluded $\lambda$ [nm]	Interfering species
363–391	71	–	O <sub>3</sub> , NO <sub>2</sub> , O <sub>4</sub> , BrO
403–427	61	–	O <sub>3</sub> , NO <sub>2</sub> , O <sub>4</sub>
363–427	142	390.9–398.4	O <sub>3</sub> , NO <sub>2</sub> , O <sub>4</sub> , BrO

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**Table 3.** Positive and negative mean differences of OCIO ECD and their relative frequencies when including each of these spectral corrections: Rayleigh,  $I_o$ , Ring, tilt, polarization and wavelength shift.

Correction	Positive differences		Negative differences	
	Mean [%]	Frequency [%]	Mean [%]	Frequency [%]
Rayleigh	27	50	−31	31
$I_o$	8	64	−13	32
Ring	32	59	−45	18
Tilt	11	71	−10	26
Polarization	3	61	−4	38
$\lambda$ -shift	11	43	−11	45

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**Table 4.** Positive and negative mean differences of OCIO ECD relative error and their relative frequencies when including each of these spectral corrections: Rayleigh,  $I_o$ , Ring, tilt, polarization and wavelength shift.

Correction	Positive differences		Negative differences	
	Mean [%]	Frequency [%]	Mean [%]	Frequency [%]
Rayleigh	25	35	−26	47
$I_o$	14	28	−8	69
Ring	47	10	−29	73
Tilt	8	25	−10	73
Polarization	4	39	−3	60
$\lambda$ –shift	10	48	−11	45

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**Table 5.** Positive and negative mean differences of residual RMS and their relative frequencies when including each of these spectral corrections: Rayleigh,  $I_o$ , Ring, tilt, polarization and wavelength shift.

Correction	Positive differences		Negative differences	
	Mean [%]	Frequency [%]	Mean [%]	Frequency [%]
Rayleigh	0.1	3	−1	97
$I_o$	1	43	−1	57
Ring	4	97	−1	1
Tilt	0	0	−12	100
Polarization	0.1	3	−1	97
$\lambda$ -shift	4	51	−2	47

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**Table 6.** Positive and negative mean differences of reduced chi squared and their relative frequencies when including each of these spectral corrections: Rayleigh,  $I_o$ , Ring, tilt, polarization and wavelength shift.

Correction	Positive differences		Negative differences	
	Mean [%]	Frequency [%]	Mean [%]	Frequency [%]
Rayleigh	1	66	−3	34
$I_o$	2	44	−1	56
Ring	9	97	−2	1
Tilt	1	13	−24	87
Polarization	1	70	−3	30
$\lambda$ –shift	8	51	−4	47

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**Table 7.** Summary of the specifications of the spectral window used to retrieve OCIO.

Retrievals	OCIO window
Wavelengths	403–427 nm
Fitted species	O <sub>3</sub> , NO <sub>2</sub> , OCIO, O <sub>4</sub>
Closure polynomial	2nd order
Spectral corrections	Rayleigh, I <sub>o</sub> , tilt, fixed cross sections
Retrieval range	10–40 km
Reference spectrum height	40–70 km average
Estimating <b>K</b>	2λ, MS, no aerosol
Estimating <b>F</b>	2-nm grid
A priori STD	300%
Correlation length	4 km

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**Table 8.** Observations of maximum OCIO vertical concentrations.

Reference	Altitude [km]	n [cm <sup>-3</sup> ]	Location	Date	Time
Pommereau and Piquard (1994)	21	1.4×10 <sup>7</sup>	68° N, 20° E	Jan. 92	twilight, SZA 93°
Renard et al. (1997)	19	8.7×10 <sup>7</sup>	68° N, 20° E	Feb. 95	night
Rivière et al. (2003)	18	8.7×10 <sup>7</sup>	68° N, 22° E	Jan. 00	night
OSIRIS (scan 8565047)	18	7.3×10 <sup>7</sup>	82° S, 36° E	Sep. 02	twilight, SZA 92°

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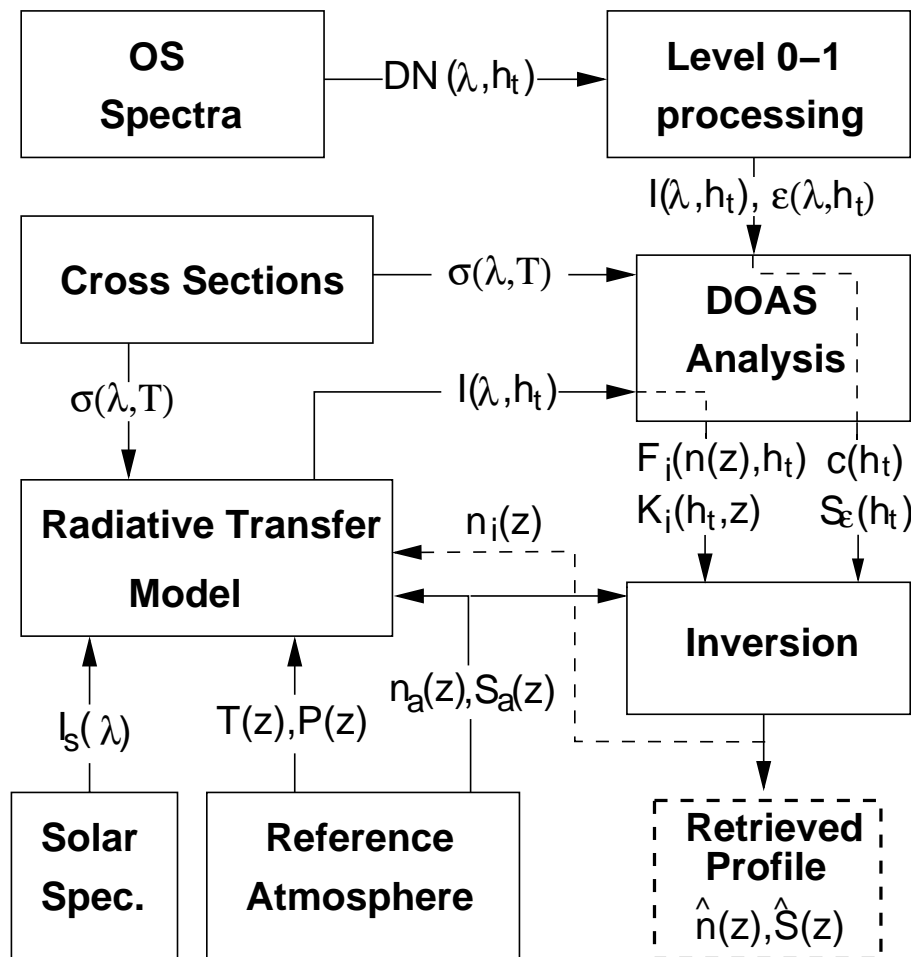
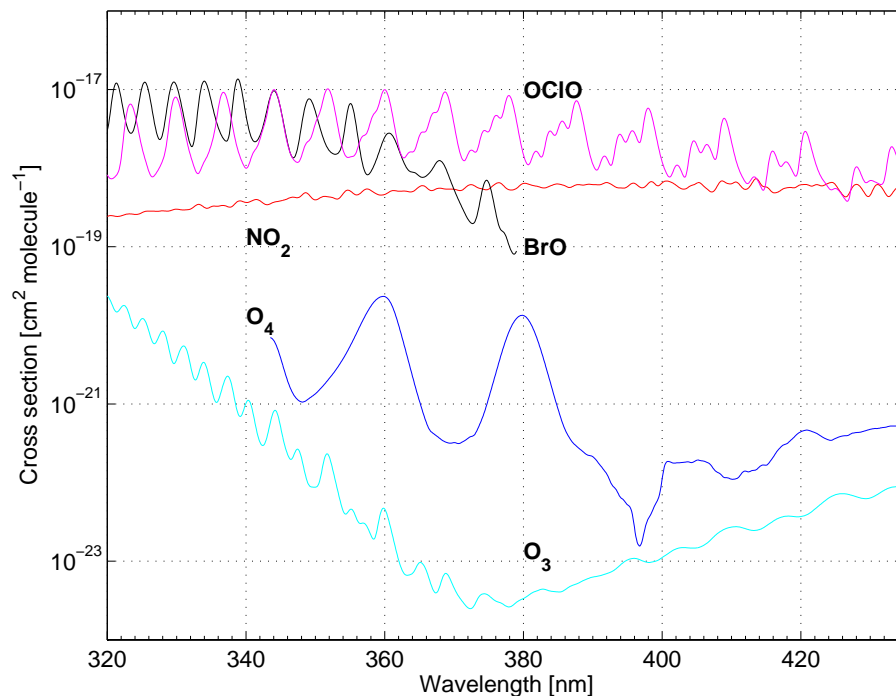


Fig. 1. Schematic description of the retrieval process.

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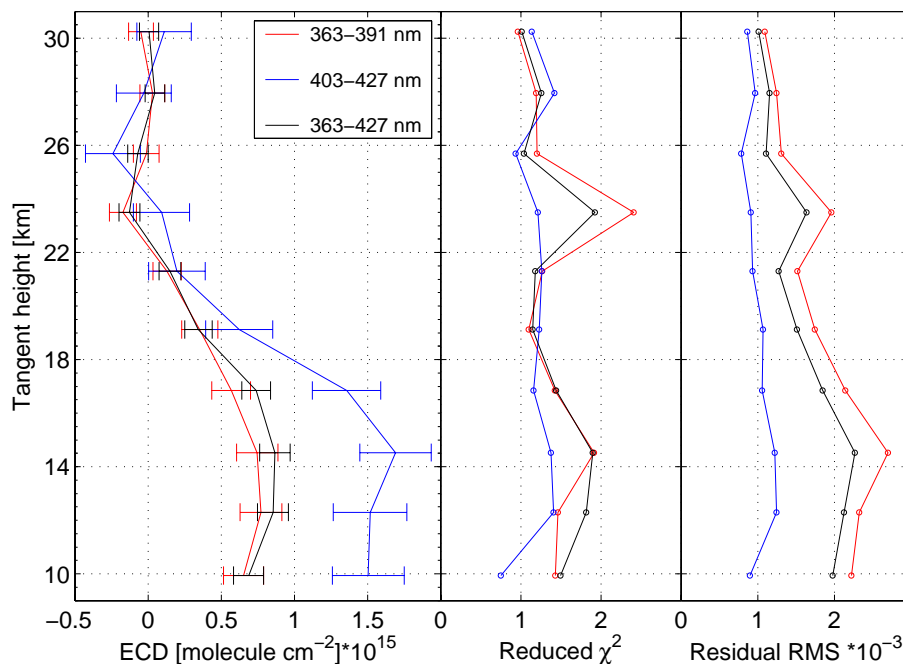
**Fig. 2.** Absorption cross sections of  $O_3$  (Bogumil et al., 2003),  $NO_2$  (Vandaele et al., 1998), OCIO (Kromminga et al., 2003), BrO (Wilmouth et al., 1999), and  $O_4$  (Greenblatt et al., 1990) convolved to the OS spectral resolution in the 320–435 nm region.  $O_4$  cross sections have been multiplied by  $10^7$  to fit on the same scale.

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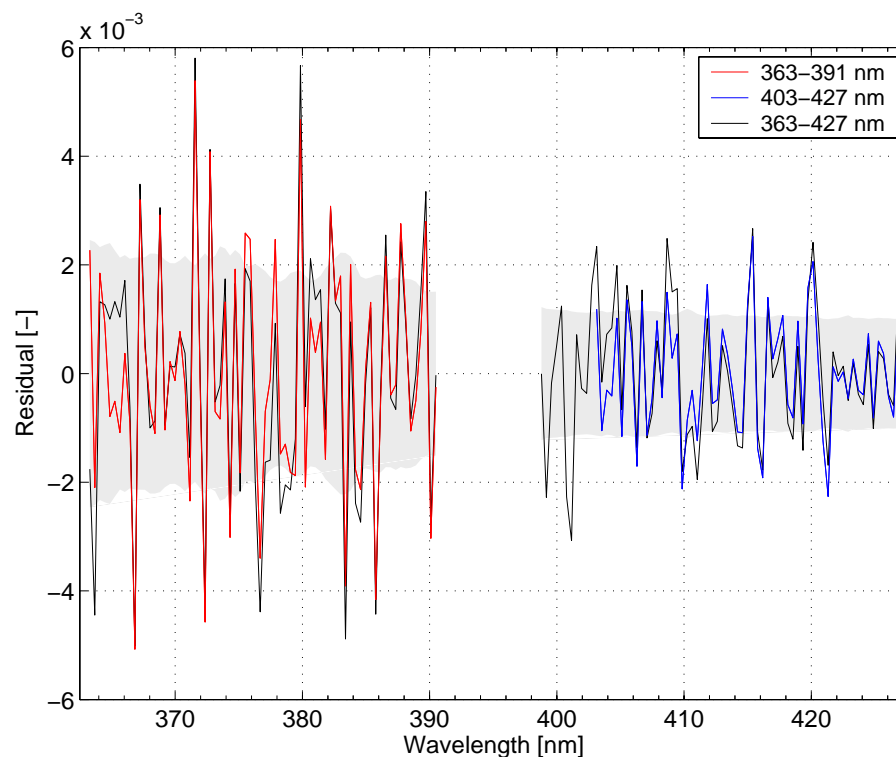
**Fig. 3.** Left panel: OCIO ECD profiles retrieved from OSIRIS spectra measured on 19 September 2002 (scan 8567046, latitude 79.2° S, longitude 18.2° W, SZA 91.0°, 17:47 LST) in the 363–391 nm, 403–427 nm, and 363–427 nm fitting windows. The error bars represent the uncertainties of the LSQ fit. Middle panel: reduced chi squared. Right panel: residual RMS.

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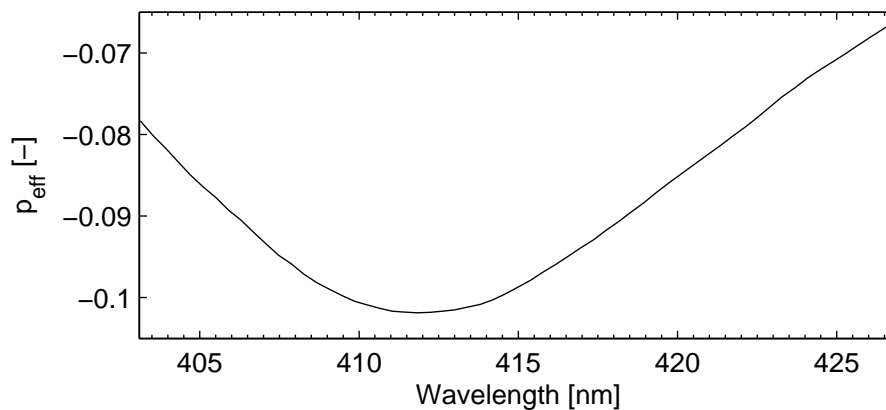
**Fig. 4.** Residual absorption spectra of scan 8567046 at the tangent height of 16.8 km in the wavelength regions: 363–391, 403–427, and 363–427 nm. The shaded region represents the estimated 1-STD error in the observed differential optical depth.

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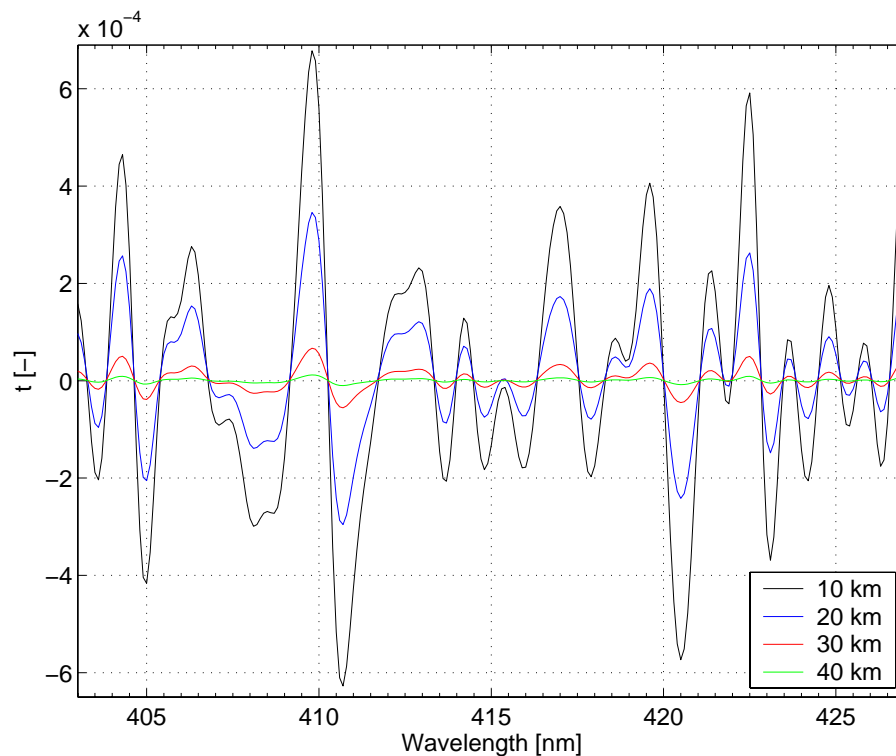
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**Fig. 5.** OS polarization efficiency parameter  $p_{eff}$  in the 403–427 nm window.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Print Version](#)[Interactive Discussion](#)

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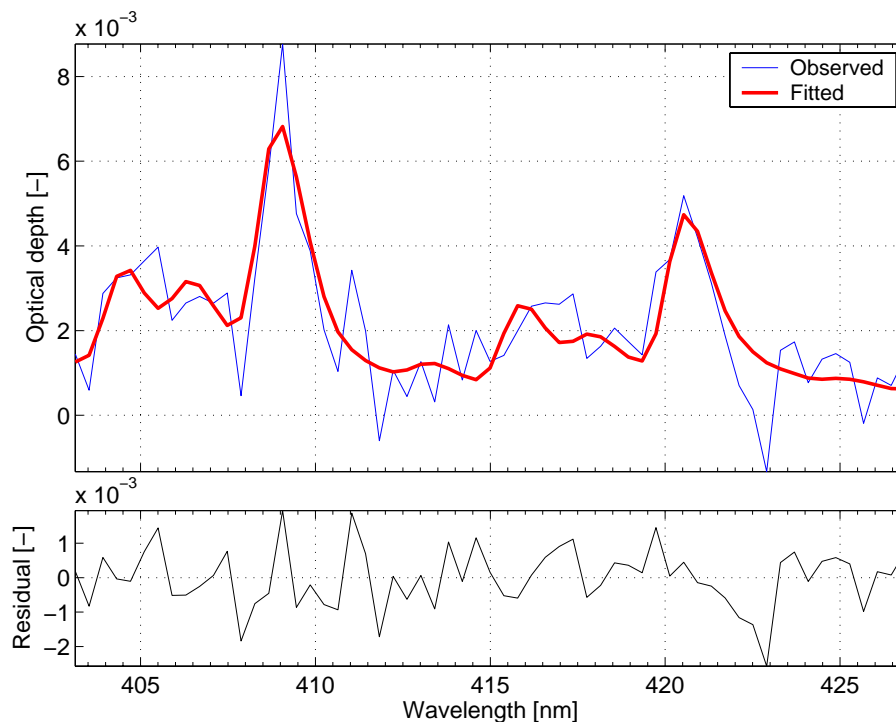
**Fig. 6.** Simulated tilt pseudoabsorber at 10, 20, 30, and 40 km tangent height in the spectral interval 403–427 nm.

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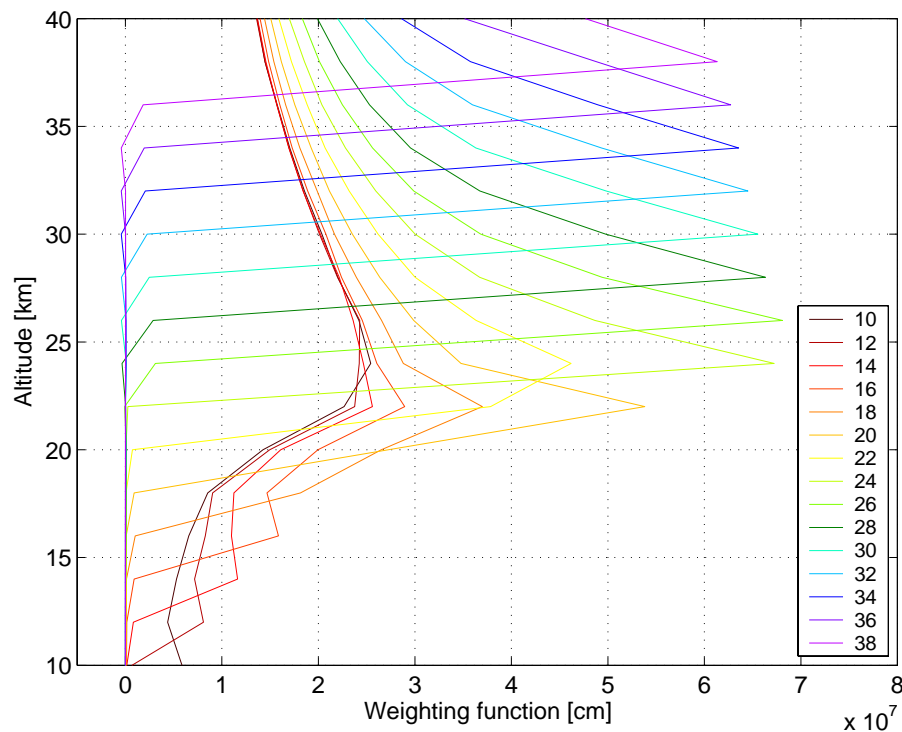
**Fig. 7.** Typical example of the fitted and observed optical depths of OCIO and residual structures in the 403–427 nm region. The corresponding OS measurement was performed at 18.7 km tangent height on 19 September 2002 (scan 8565047, latitude 81.7° S, longitude 36.4° E, SZA 92.0°, 18:10 LST).

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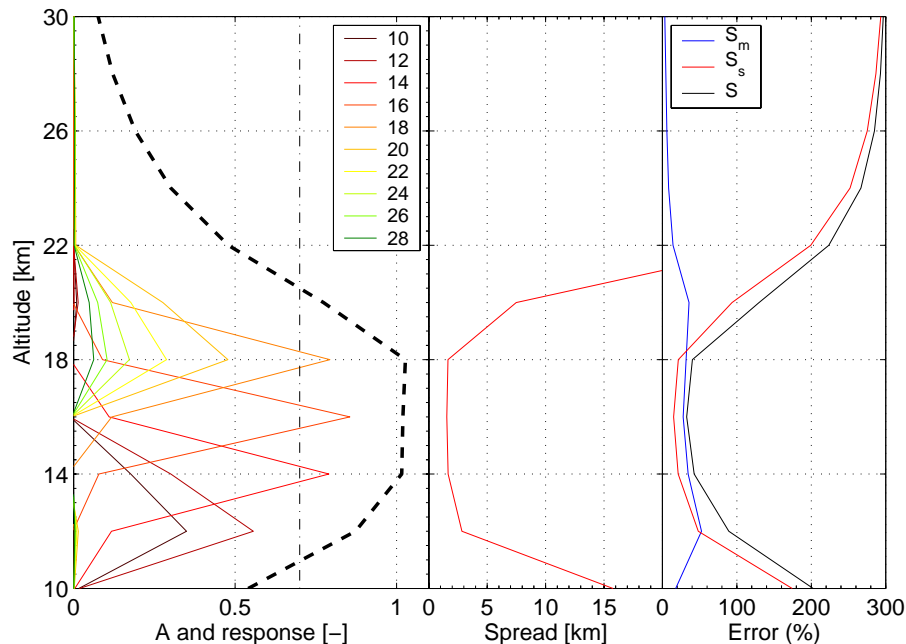
**Fig. 8.** OCIO weighting functions for DOAS effective column densities calculated by using radiances at 409 and 412 nm, 5% perturbation, SZA 91°, SSA 72°, ground albedo 0.8, multiple scattering and no aerosols. Tangent heights are expressed in km.

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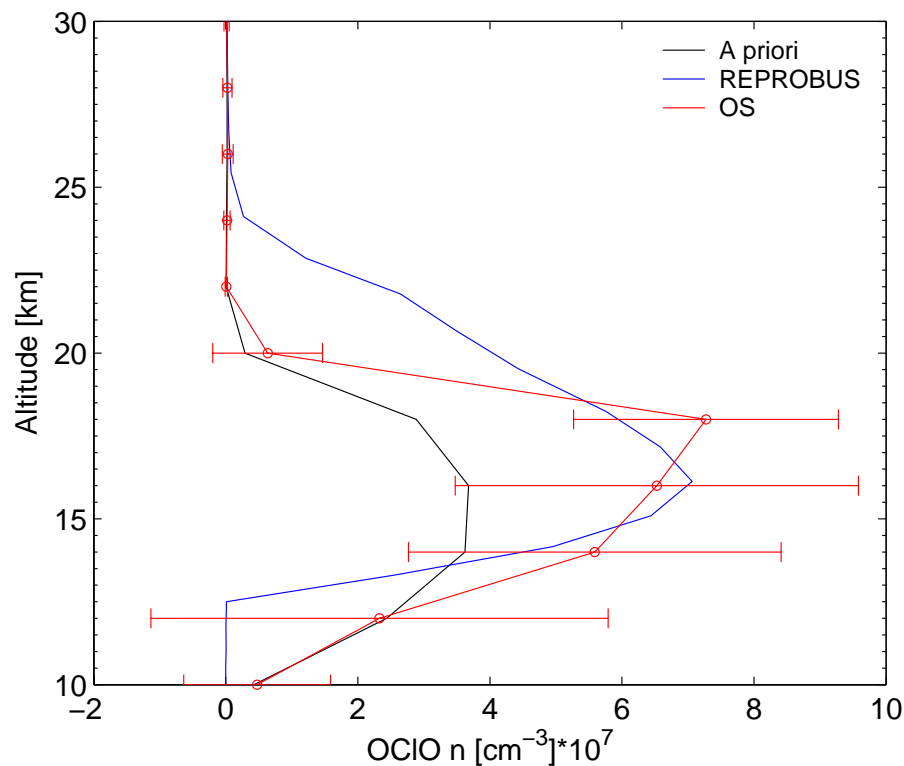


**Fig. 9.** Left panel: OCIO averaging kernel functions with corresponding tangent heights given in km, measurement response  $w$  (dashed line), and  $w=0.7$  (dashed-dotted line) for limb spectra measured on 19 September 2002 (scan 8567045, latitude  $83.9^\circ$  S, longitude  $18.5^\circ$  W, SZA  $91^\circ$ , SSA  $72^\circ$ , 17:44 LST).  $I_c$  was set to 4 km and  $\rho$  to 300%. Middle panel: spread  $s$ . Right panel: OCIO number density errors: retrieval noise  $S_m$ , smoothing error  $S_s$ , and retrieval error  $S = S_m + S_s$ .

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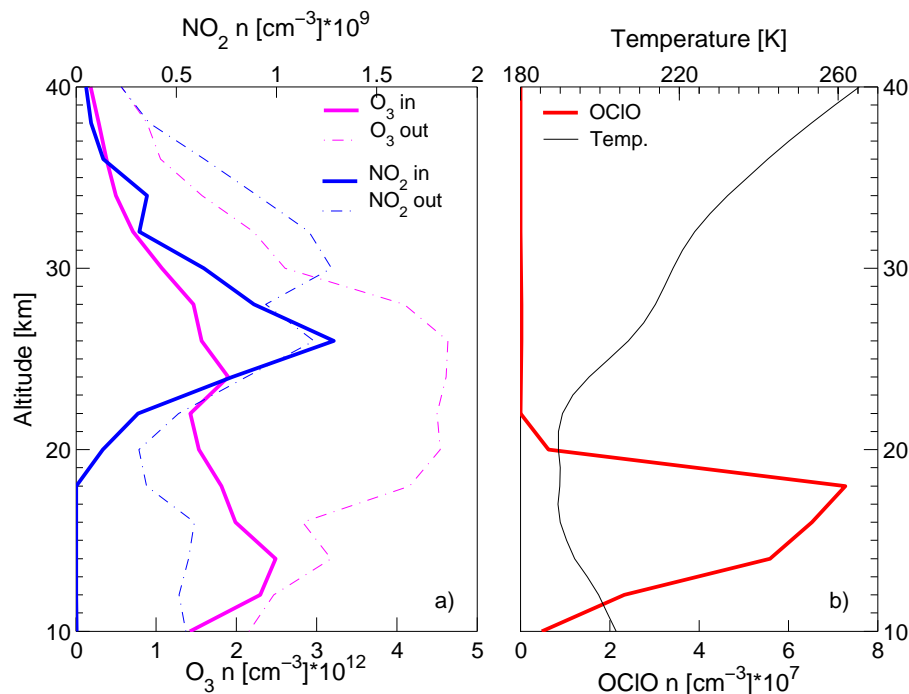
**Fig. 10.** OS OCIO profile (scan 8565047, latitude 81.7° S, longitude 36.4° E, SZA 92.0°, 18:10 LST), and the coincident profile calculated by REPROBUS model (SZA 92.2°). The a priori profile and the error bars of the estimated OS retrieval error are also shown.

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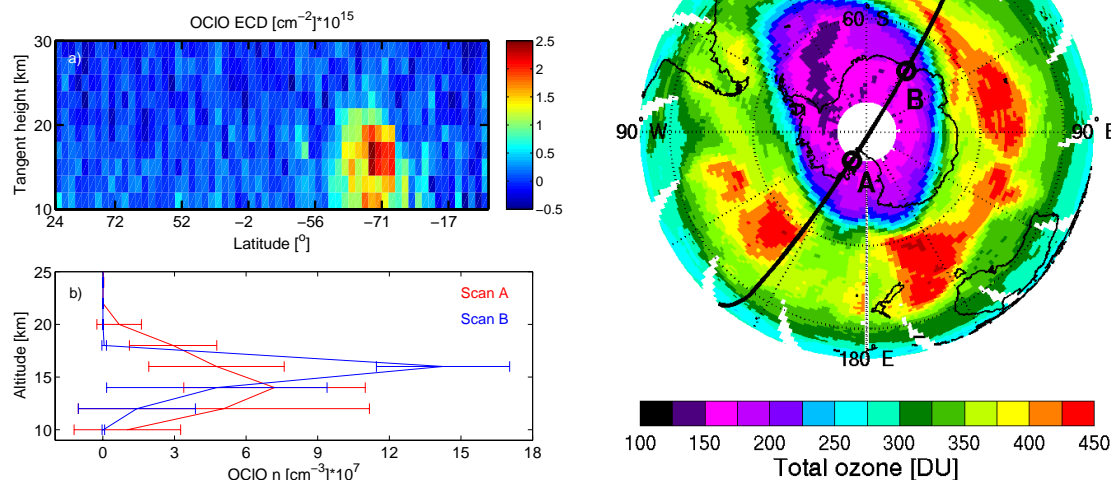
**Fig. 11. (a)** OS  $\text{O}_3$  and  $\text{NO}_2$  number density profiles inside (scan 8565047) and outside (scan 8565037, latitude  $45.1^\circ$  S, longitude  $145.7^\circ$  W, SZA  $91.9^\circ$ , 5:48 LST) the polar vortex region. **(b)** OS OCIO number density and ECMWF temperature profiles for scan 8565047.

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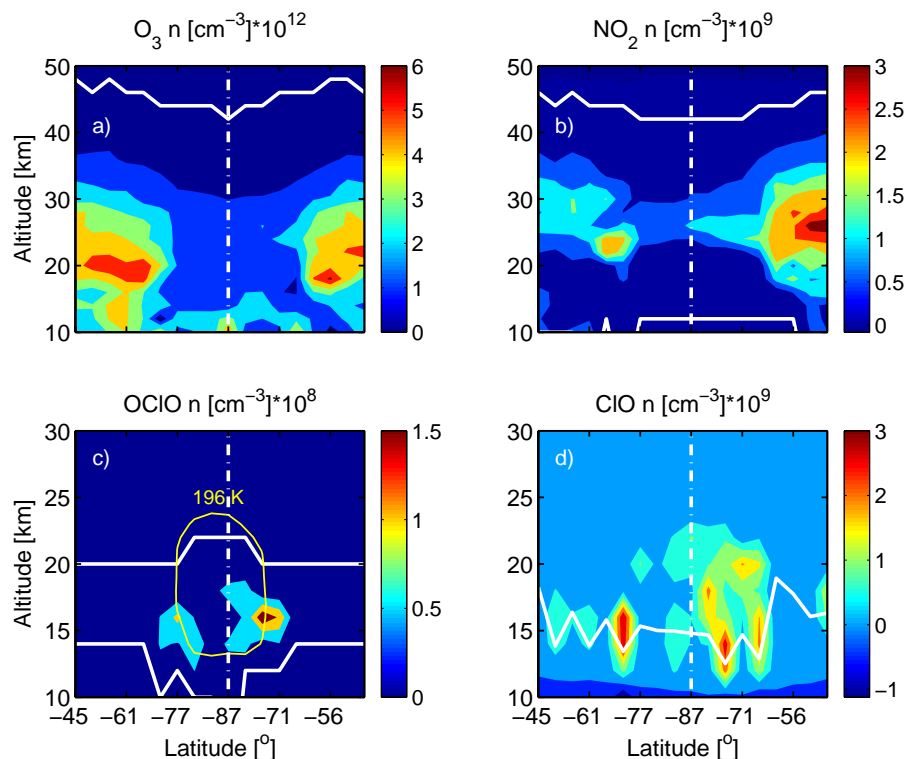
**Fig. 12.** Left panel: **(a)** Latitude vs. tangent height representation of OCIO ECD along the orbit 8565 on 19 September 2002 and **(b)** OCIO number density profiles for scans A (number 8565044, latitude 81.9° S, longitude 152.4° W, SZA 92.1°, 5:31 LST) and B (number 8565049, latitude 71.1° S, longitude 32.8° W, SZA 91.8°, 18:00 LST) with their corresponding retrieval error. Right panel: Austral total O<sub>3</sub> from EP/TOMS for the same day. The thick black line represents the OS tangent point path for orbit 8565, A and B indicate the average location of scans A and B, and the arrow shows the direction of Odin's movement. Sectors without measurements are not coloured. Note that Odin was pointing off of the orbit plane to achieve a better coverage.

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**Fig. 13.** Retrieved number density profiles of **(a)** OS  $\text{O}_3$ , **(b)** OS  $\text{NO}_2$ , **(c)** OS OCIO, and **(d)** SMR ClO along the Odin orbit 8565 for latitudes southward of  $40^\circ \text{S}$ . The white lines in each plot represent the lowermost and uppermost altitude of significant measurements (i.e.,  $w > 0.7$ ). The yellow line in plot (c) represents the isotherm of 196 K (threshold of the PSC formation). The dashed-dotted line in each plot separates the sunrise (left) and sunset (right) measurements.

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