

Answers to discussion contributions: Detection of O₄ absorption around 328 nm and 419 nm in measured atmospheric absorption spectra

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1 Introduction and general comments

We would like to thank the editor Rainer Volkamer and the two reviewers Ryan Thalman and Henning Finkenzeller for their comments, suggestions and corrections. Robert R. Ryan commented offline to the manuscript. All comments together improved greatly the discussion manuscript. We considered each of the points, which are answered below together with a description of the related changes to the manuscript. When reprocessing the data for the supplement of the manuscript, I realized that the relative shifts mentioned in Section 3.3 were slightly wrong due to an inconsistency in using air/vacuum wavelength calibrations for the shifted hypothetical O₄ absorption cross-sections. This is fixed now, the respective peak absorption cross-section values in the manuscript and the supplement file are updated. Furthermore I included now the estimate for the absorption peak of O₄ at around 419 nm in the supplement file as well, despite the large error of the estimate. Here the radiative transfer effect on the absolute magnitude due to the wavelength dependency of the AMF was previously not considered, but it is now.

(Numbers of equations, figures, lines and pages refer to the discussion manuscript, if not mentioned otherwise. **Authors' reponses are written in bold face**, the referees' text is shown in normal face.)

2 Review #1

Lampel and co-authors present evidence of oxygen O₂-O₂ collision induced absorption bands at 328 and 419 nm from a combined analysis of Multi Axis (MAX) and Long Path (LP) Differential Optical Absorption Spectroscopy (DOAS) field measurements. The work presents analysis of the effects of these minor absorption bands on the retrieval of other absorbers (HCHO, BrO, H₂O) in both MAX and LP-DOAS applications. The analysis utilizes high signal to noise retrievals to identify the band strengths in air to constrain interference with other fitted absorbers. This is especially true with regard to the application to satellite retrievals. The paper is well written and presents a compelling analysis that should be considered in trace gas measurements as well as motivate further laboratory studies to constrain these weak absorption bands. I recommend publication after a few minor corrections as noted below.

We thank the reviewer for the overall positive assessment.

2.1 Specific comments

1. The report of the cross-section value for the 419 nm band is only found in the Abstract, the estimate should also be included in the results. While the 419 nm band value in the analysis is definitely uncertain (a point well made by the authors), this should still be reported in the body of the paper.

We added the following sentence to the end of the paragraph about the observations around 419 nm: 'This then results in a peak value of the O₄ absorption cross-section of $(3.7 \pm 2.7) \times 10^{-48}$ cm⁵ molec⁻² at a wavelength of 419.02 ± 0.42 .'

2.2 Technical corrections

1. Page 2 line 21: Missing reference (?? in parenthesis).
?? is now replaced by [Wang et al., 2017].
2. Page 2 line 23-24: The Vogel 2013 ([Vogel et al., 2013]) is referenced as the retrieval method for the earlier 2012 ([Vogel, 2012]) paper, is this correct?
yes, this was the intended meaning of the sentence. The PhD-thesis ([Vogel, 2012]) was finished earlier than the final version of [Vogel et al., 2013]. The observations which led to the restriction of the fit range in [Vogel, 2012] were not included in [Vogel et al., 2013]. We restructured the sentence to make this clearer. It is now:

In addition to that, for the spectral retrieval of BrO, [Vogel, 2012] found a lower limit for the choice of reliable fit intervals at about 330.6 nm, which could have been caused by the neglected O₄ absorption at around 328 nm - the FWHM (Full Width Half Maximum) of the known absorption peaks at 344 and 360 nm amounts to 4 nm. The method from [Vogel et al., 2013] was applied here on measured atmospheric spectra along different light path lengths.

3. Page 3 line 26: reword as The spectrometer, an Acton 300i,
done
4. Page 4 line 3: This paragraph needs some work (as follows):
Thanks for pointing this out. It now reads as follows:
The measurement procedure was as follows: Spectra were acquired alternatingly on both light paths. For each light path, spectra were recorded at four different wavelength intervals. The region of interest for this study is between 271 nm and 355 nm. For each of those regions, 25 spectra with a saturation of 70% were recorded, with a maximum duration of 1 s per spectrum. Typical exposure times for one spectrum were between 6 ms and 500 ms depending on the wavelength range, visibility conditions and the used arc lamp.
5. Page 14 line 31: is obtained when ignoring. . . (remove the first actually).
done
6. Page 15 line 1: molec2 cm-5 goes into the margin.
done
7. Page 15 line 11: resolved (one s).
fixed
8. Page 15 line 29: was likely the O4 absorption which. . . Drop the first rather.
fixed

3 Review #2

This study applies regression analysis to data sets of atmospheric spectra to find evidence for the incompleteness of currently available oxygen associated absorption cross sections around 328nm and 419nm. Specifically, no spectrally resolved absorption cross sections are available for these bands. While the study does not claim to generate accurate new cross sections, it gives approximate values for the peak absorption strength and peak wavelength for the bands at 328nm and 419nm. The data sets and methods used seem to be well suited for the purpose of the study. Wavelength ranges are motivated from earlier studies. Band shapes are transferred from neighboring bands in a zeroth order approximation. I do not see a significant potential to extract more information from the data sets for the purpose of the study by using additional or other methods than those presented in the study. The study is a helpful contribution moving the remote sensing technique forward, underlining that better knowledge about oxygen collision induced absorption cross sections is necessary to overcome current limitations. I recommend publication after a few minor adjustments, as described below.

We thank Henning Finkenzeller for his evaluation and implemented most of his suggestions in the revised manuscript. We like to point out that the extraction of more detailed spectral information of the

absorption bands could be possible by regression analysis of residual spectra on a channel-by-channel basis. However, due to the low signal-to-noise ratio and the number of overlaying absorbers these attempts failed during the preparation of the manuscript.

3.1 Specific comments:

1. Given the scope of the article, the publications by Dianov-Klokov 1959, 1963, 1964, and 1965 seem to be relevant and should be included in the publication to give the reader a more complete overview of the available literature. The findings in this publication about absorption strengths (of liquid oxygen) are in agreement with the findings presented here.

Thanks for pointing this out, we now also cite [Dianov-Klokov, 1959, Dianov-Klokov, 1964] in the revised manuscript.

2. The assignment of absorption bands to transitions (e.g. in table 2) seems to be incorrect, following e.g. Salow and Steiner 1936, Dianov-Klokov 1959, or the mentioned Greenblatt et al 1990 reference. E.g., for the 328nm band, the initial state is $^3\Sigma_g^-$ & $^3\Sigma_g^-$ and the final state is $^1\Sigma_g^+$ & $^1\Sigma_g^+$ ($\nu = 3$). When updating the states throughout the paper, I would recommend to use the full state description for the sake of completeness.

yes, indeed, we made an error and interchanged the Σ and Δ s at some point. We fixed this and also used now the full state description in the revised manuscript.

3. Figure 3: The figure, respectively the analysis, would benefit from an additional fit where the offset is constrained to 0 (assuming the same light path at 328nm and 343nm).

We added an additional fit with an offset constrained to zero to the figure and additionally incorporated this information in the text and in table 3. The result of the fit which is constrained to zero for the reference measurements actually fits the MAX-DOAS observations better than the other, previous fit, which was not constrained for the reference measurements. This makes sense as reference measurements have by definition all column densities at zero.

4. The wording of the article is sometimes not ideal. While not essential for publication, it would benefit from being revised and fine tuned by a native English speaker. The comments below pertain to obvious glitches.

We read through the article again and removed some of these. We hope that this is now acceptable. Additionally the article will be copy-edited during the final preparation of the manuscript.

3.2 Technical corrections/suggestions:

1. page 2, line 16: extra parentheses, remove
done

2. page 2, line 21: incorrectly formatted reference
fixed
3. page 3, line 6: rephrase "play a role" to "are responsible for the observed structures" for more clarity
We replaced it by 'are responsible for the observed absorption structures'.
4. page 3, line 12: "... a measurement campaign in Antarctica was undertaken based at the New Zealand station Scott Base." Rephrase for more clarity.
We now write 'In 2012, a measurement campaign was undertaken based at New Zealand's research station Scott Base in Antarctica.'
5. page 10, line 1: rephrase "As can be seen, ... is visible.", and the following sentence
We removed 'As can be seen' in the revised manuscript.
6. page 15, line 29: correct "rather ... rather than"
Nothing to correct as far as I can see.

References

- [Dianov-Klokov, 1959] Dianov-Klokov, V. I. (1959). On the question of the origin of the spectrum of liquid and compressed oxygen (12.600 - 3.000 Å). *Opt. Spectrosc.*, 6:290–293.
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- [Vogel et al., 2013] Vogel, L., Sihler, H., Lampel, J., Wagner, T., and Platt, U. (2013). Retrieval interval mapping: a tool to visualize the impact of the spectral retrieval range on differential optical absorption spectroscopy evaluations. *Atmospheric Measurement Techniques*, 6(2):275–299.
- [Wang et al., 2017] Wang, Y., Beirle, S., Hendrick, F., Hilboll, A., Jin, J., Kyuberis, A. A., Lampel, J., Li, A., Luo, Y., Lodi, L., Ma, J., Navarro, M., Ortega, I., Peters, E., Polyansky, O. L., Remmers, J., Richter, A., Rodriguez, O. P., Roozendaal, M. V., Seyler, A., Tennyson, J., Volkamer, R., Xie, P., Zobov, N. F., and Wagner, T. (2017). Max-doas measurements of hono slant column densities during the mad-cat campaign: inter-comparison and sensitivity studies on spectral analysis settings. *Atmospheric Measurement Techniques Discussions*, 2017:1–38.

Detection of O₄ absorption around 328 nm and 419 nm in measured atmospheric absorption spectra

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Abstract.

Retrieving the column of an absorbing trace gas from spectral data requires that all absorbers in the corresponding wavelength range are sufficiently well known. This is especially important for the retrieval of weak absorbers, whose absorptions are often in the 10⁻⁴ range.

5 Previous publications on the absorptions of the oxygen dimer O₂-O₂ (or short: O₄) list absorption peaks at 328 nm and 419 nm, for which no spectrally resolved literature cross-sections are available. As these absorptions potentially influence the spectral retrieval of various trace gases, such as HCHO, BrO, OClO and IO, their shape and magnitude needs to be quantified.

We assume that the shape of the absorption peaks at 328 nm and 419 nm can be approximated by their respective neighboring absorption peaks. Using this approach we obtain estimates for the wavelength of the absorption and its magnitude. Using Long-
10 path Differential Optical Absorption Spectroscopy (LP-DOAS) observations and Multi-Axis (MAX)-DOAS observations, we estimate the peak absorption cross-sections of O₄ to be ~~(1.7 ± 0.2) × 10⁻⁴⁷~~ (1.96 ± 0.2) × 10⁻⁴⁷ cm⁵ molec⁻² and determine the wavelength of its maximum at ~~328.51 ± 0.15~~ 328.59 ± 0.15 nm.

For the absorption at ~~419.0 ± 0.4~~ 419.13 ± 0.42 nm a peak O₄ cross-section value is determined as ~~(3.7 ± 2.7) × 10⁻⁴⁸~~ (5.0 ± 3.5) × 10⁻⁴⁸ cm⁵ molec⁻².

15 1 Introduction

The collision induced absorption of the O₂-O₂ dimer (or short: O₄) needs to be considered in various wavelength regions for in-situ and remote sensing absorption spectroscopy of various atmospheric trace gases. Furthermore, the O₄ absorption governs the budget of tropospheric singlet oxygen O₂(¹Δ) (Schurath, 1986), which can potentially impact on the oxidation of atmospheric trace gases, like CO (Platt and Perner, 1980) and SO₂ (Sorokin, 2010). In addition, the absorption of O₄ itself
20 can be used to deduce information about the actually observed light paths for passive remote sensing applications by applying inverse modelling methods and radiative transfer models.

Ellis and Kneser (1933) and [Dianov-Klokov \(1959, 1964\)](#) reported absorption peaks observed for liquid oxygen at 328 nm and 419 nm (for an overview, see Table 2). Most of the absorption peaks in the UV/Vis range of liquid oxygen can be also found for gas phase oxygen, as measured by Janssen (e.g. 1885); Salow and Steiner (e.g. 1936); Greenblatt et al. (e.g. 1990); Hermans et al. (e.g. 1999); Thalman and Volkamer (e.g. 2013) and others. It was first observed in the atmosphere by Perner and Platt (1980). These absorptions are potentially shifted by less than a nanometre compared to the liquid phase.

5 Spectrally resolved cross-section data suitable for spectroscopy applications exists for the absorption peaks at 344, 361, 380, 447, 477, 533, 577 nm and continues further into the red spectral range. Due to instrumental limitations (detection limits and/or covered spectral range), spectrally resolved cross-section data for the absorption peaks at 328 nm (transition ${}^3\Sigma^3\Sigma \rightarrow {}^1\Delta^1\Delta; \nu = 3$ ${}^3\Sigma_g^- + {}^3\Sigma_g^- \rightarrow {}^1\Sigma_g^+ + {}^1\Sigma_g^+ (\nu = 3)$, see also Table 2) and 419 nm (transition ${}^3\Sigma^3\Sigma \rightarrow {}^1\Delta^1\Sigma; \nu = 2$ ${}^3\Sigma_g^- + {}^3\Sigma_g^- \rightarrow {}^1\Sigma_g^+ + {}^1\Sigma_g^+ (\nu = 2)$) are, to our knowledge, not reported in literature.

10 Salow and Steiner (1936) measured the intensity of the absorption at 328 nm to be 4.2 % of the O₄ absorption at 360 nm, i.e. 15% of the O₄ absorption at 344 nm. For an O₄ dSCD of 4×10^{43} molec² cm⁻⁵, as e.g. found in MAX-DOAS observations under low elevation angles, this corresponds to an optical depth of 1.7×10^{-2} at 360 nm (Thalman and Volkamer, 2013), and thus an optical depth of 7×10^{-4} at 328 nm. This could introduce systematic biases in the spectral retrievals of BrO, HCHO, OClO and SO₂, when this wavelength range is included in the respective spectral analysis, as e.g. in satellite
15 retrievals of HCHO (De Smedt et al., 2008), various observations of BrO in the boundary layer (see Vogel et al. (2013) and references therein) and ground based measurements of SO₂ (e.g. Schreier et al. (2015) and Wang et al. (2016)). Convoluted to a spectral resolution of 0.5 nm, the overlaying absorption structure of HCHO at 328 nm has a peak absorption cross section of 4.5×10^{-20} cm² molec⁻¹ (Chance and Orphal, 2011). Typical ground-based HCHO dSCDs observed on the tropical open ocean are about $1 - 3 \times 10^{16}$ molec cm⁻² (e.g. Peters et al., 2012) (and lower at higher latitudes, (e.g. De Smedt et al., 2008)),
20 which corresponds to an optical depth of $4 - 14 \times 10^{-4}$ at 329 nm. Therefore it is important to consider the possible O₄ absorption at around 328 nm if the retrieval wavelength range for HCHO is extended towards shorter wavelengths below 330 nm. The recommended HCHO setting from Pinardi et al. (2013) suggests a fit interval from 336.5–359 nm and thus does not include the O₄ absorption at around 328 nm. This recommendation is for an analysis with fixed Fraunhofer reference spectrum. If sequential references are used (as it is typically done today for the spectral retrieval of weak absorbers, as e.g. in ??), then the
25 spectral range can/should be extended towards shorter wavelengths (e.g. 323 nm).

In addition to that, for the spectral retrieval of BrO, Vogel (2012) found a lower limit for the choice of reliable fit intervals ~~using the method from Vogel et al. (2013)~~ at about 330.6 nm, which could have been caused by the neglected O₄ absorption at around 328 nm - the FWHM (Full Width Half Maximum) of the known absorption peaks at 344 and 360 nm amounts to 4 nm. [The method from Vogel et al. \(2013\) was applied here on measured atmospheric spectra along different light path lengths.](#) This
30 fit interval was then widely used e.g. in Lübcke et al. (2014); General et al. (2015); Gliß et al. (2015); Bobrowski et al. (2015) and Lübcke et al. (2016). Widening the spectral retrieval interval for both species could reduce the fit error of BrO and HCHO dSCDs, as relatively large absorption bands are found for both species below 330 nm.

For the absorption at 419 nm no estimate for its intensity is known. ~~This~~ [However, this](#) spectral region is also known for uncertainties of the available water vapour cross-section as reported in Lampel et al. (2015b), which overlays potential O₄

absorptions. Using the same ratio of peak absorption cross-sections of O_4 at 477 and 446 nm, an absorption band at 419 nm could potentially have a peak OD of 2×10^{-4} for an O_4 dSCD of 4×10^{43} molec² cm⁻⁵. This spectral range is of interest, as it is typically included in the spectral analysis of IO (e.g. Großmann et al., 2013; Prados-Roman et al., 2015). The potential to obtain residual spectra with an RMS below 1×10^{-4} has been demonstrated (e.g. Lampel et al., 2015a; Zielcke, 2015) and allows to measure IO at sub-ppt concentrations, corresponding to an OD along 10 km lightpath of $< 7 \times 10^{-4}$. Such concentrations have been reported on the open ocean by Prados-Roman et al. (2015) and were found above their respective limit of detection by Zielcke (2015) in polar regions (0.2-0.4 ppt using LP-DOAS and MAX-DOAS observations).

In this work, spectral data from three different instruments and environmental settings, utilizing two different remote sensing geometries, is presented in order to estimate the magnitude of the O_4 absorption peaks at around 328 and 419 nm. The different techniques used and the different locations of the measurements make it very unlikely that instrumental artefacts or local atmospheric influences ~~play a role~~ are responsible for the observed absorption structures.

2 Measurement Campaigns

In this section we shortly describe the measurement campaigns, during which DOAS data ~~was~~ were collected and which ~~is~~ are used in this manuscript.

15 2.1 MAX-DOAS

2.1 Antarctica LP-DOAS 2012

In 2012, a measurement campaign ~~in Antareticia~~ was undertaken based at ~~the New Zealand~~ New Zealand's research station Scott Base in Antarctica. The station is situated on Ross Island at 78°S and the campaign lasted throughout austral spring, from the end of August until the end of November.

20 The LP-DOAS instrument used in this campaign has been used in previous studies and therefore has already been extensively described elsewhere, e.g. in Pöhler et al. (2010); Eger et al. (2017).

In brief, light is coupled in and out of a telescope using a Y-shaped fiber optic bundle consisting of 7 individual fibers. The common end is mounted near the focal point of the telescope, the single central fiber is connected to the spectrometer and the six outer fibers are attached to a 800 μ m mono fiber which leads to the light source. A diffuser plate can be driven into the light path in front of the telescope end of the fiber in order to record spectra of the lamp (so-called optical shortcut spectra). For most of the time of the campaign, a 75 W xenon arc lamp (Osram XBO, not ozone-free) was used as the light source. During the last two weeks, a 500 W arc lamp (PLI Hanovia HSAX5002) was used, which has a higher luminous density and thus leads to a lower limit of detection in the deeper UV region around 300 nm. Both lamps were coupled into the fiber using a single fused silica lens. Besides several color filters to reduce stray light, the lamp housing also featured a shutter in front of the fiber coupling to block the lamp, in order to be able to record background spectra with the telescope, i.e. spectra of the light entering the telescope due to scattering on the surface or air and not from the dedicated light source. ~~As~~ The spectrometer, an

Acton 300i_x was used with a resolution of 0.50 nm and spectra were recorded by a back-illuminated CCD camera from Roper Scientific (Spec-10:2KBUV).

Two light paths were set up approximately 1.5 m over sea ice, for which two retro reflector arrays were deployed. The retro reflector arrays reflecting the light back into the telescope consisted of 12 (short path) and 50 (long path) individual elements made of fused silica with a diameter of 63.5 mm each. One array was located closer to the station, to be able to measure during periods with fog or snow drift, the other one further away to achieve lower detection limits. They were located at distances of 1.46 km (short) and 4.01 km (long).

The measurement procedure was as follows: Spectra were acquired alternately on both light paths. For each light path, spectra were recorded at four different wavelength intervals. The region of interest for this study is ~~the one~~ between 271 nm and 355 nm. For each of those regions, 25 individual spectra with a saturation of 70% were ~~recorded~~ averaged to one measurement spectrum, with a maximum duration of 1 s per individual spectrum. Typical exposure times for one individual spectrum were between 6 ms and 500 ms depending on the wavelength range, visibility conditions and the used arc lamp. 32 measurement spectra are averaged afterwards to achieve an optimal signal to noise ratio.

2.2 MAX-DOAS

15 2.2.1 **Polarstern 2014–2016**

The MAX-DOAS instrument used during these cruises PS88-PS98 (ANT XXX, ARK XXIX, ANT XXXI¹) onboard R.V. Polarstern from October 2014 to April 2016 is described in Lampel et al. (2017a) and the same upper limits for the spectral stability of the instrument also apply here for each leg. As during previous cruises, the exposure time per spectrum was set to two minutes. Spectra were recorded at 7 elevation angles of 90° (zenith), 40, 20, 10, 5, 3, 1°, respectively, as long as solar zenith angles (SZA) were below 85°. To reduce RMS, four elevation sequences were co-added before the DOAS analysis.

2.2.2 **Penlee Point Atmospheric Observatory 2015–2016**

MAX-DOAS measurements were performed from 3 April 2015 to 3 March 2016 at the Penlee Point Atmospheric Observatory (PPAO) on the south-west coast of the UK (e.g. Yang et al. (2016)).

Similar to the instrument used in Lampel et al. (2015a) during the MAD-CAT campaign, the EnviMeS² MAX-DOAS instrument is based on an Avantes ultra-low stray-light AvaSpec-ULS2048x64 spectrometer ($f = 75$ mm) using a back-thinned Hamamatsu S11071-1106 detector. The spectrometer is temperature stabilized ($\Delta T < 0.02$ °C). The UV spectrometer covered a spectral range of 296–459 nm at a FWHM spectral resolution of ≈ 0.55 nm (at 334 nm) or ≈ 6 pixel. The spectral stability was sufficiently high with a diurnal shift maximum spectral shift within one day of less than ± 33 pm after correction for the tilt-effect (Lampel et al., 2017b). During the night, mercury discharge lamp spectra were recorded automatically in order to

¹The respective cruise reports can be found at <https://www.pangaea.de/expeditions/cr.php/Polarstern>

²now continued by Airyx GmbH, Eppelheim, Germany, <http://www.airyx.de>

30 measure the instrument's spectral response function. No significant change of the response function was observed during the campaign.

The elevation sequence included elevation angles of $-2^\circ, -1^\circ, 1^\circ, 2^\circ, 3^\circ, 5^\circ, 10^\circ, 20^\circ, 40^\circ$ and 90° heading towards an azimuthal south-westerly direction of 245° . After 22 January 2016, the azimuthal viewing direction was changed to a south-easterly direction of 147° . Spectra with a total exposure time of one minute were recorded at an adaptive integration time per scan
5 in order to obtain spectra with a maximum saturation of 50%. From 5 June to 27 August 2015 the total exposure time per spectrum was reduced to 10 s.

The inherent non-linearity of the measured intensity values with respect to the actual incoming intensity of the spectrometers was corrected for by multiplying all intensities with a non-linearity correction polynomial. This polynomial was determined from a set of spectra recorded at different exposure times, which were recorded previous to the campaign using a temperature
10 stabilized "white" LED light source.

In order to have a coherent dataset and to reduce the RMS noise of the fits, spectra of subsequent elevation angle sequences during one day were co-added during preprocessing in order to obtain a consistent MAX-DOAS data set with spectra with a total exposure time of 4 minutes.

3 Method

15 Two DOAS methods were applied to quantify the O_4 absorption around 328 nm. The MAX-DOAS measurements have often longer effective light paths, which is however not initially known. LP-DOAS measurements have the advantage that the absolute light path length is known, but often yield larger fit residuals.

3.1 MAX-DOAS

The MAX-DOAS elevation sequences were evaluated against a current Fraunhofer reference using the sum of the two nearest
20 zenith sky spectra in order to minimize the effect of stratospheric absorbers. At the same time, this approach minimizes the effect of instrumental instabilities on the data evaluation.

The literature absorption cross-sections listed in Table 1 were convoluted with the measured Mercury (Hg) emission line at 334 nm. The Ring spectrum was calculated using DOASIS (Kraus, 2006), the correction spectrum for vibrational Raman scattering of molecular nitrogen (VRS, Lampel et al., 2015a) was calculated from the Fraunhofer reference itself, shifting the
25 spectrum by the corresponding vibrational energy quantum.

HONO and SO_2 were not detected in significant amounts, neither was OCIO. Water vapour absorption in the UV as reported in Lampel et al. (2017a) is small below 358nm ($\sigma < 3 \times 10^{-28} \text{ cm}^2 \text{ molec}^{-1}$) and thus negligible, especially in polar regions.

3.2 LP-DOAS

The ~~recorded spectra from the LP-DOAS were co-added over 32 measurement sequences to achieve a higher signal-to-noise ratio.~~ The optical depth was ~~then~~ calculated by dividing atmospheric and optical shortcut spectra after their respective back-
30

		MAX-DOAS			LP-DOAS	
		O ₄ 328 nm	O ₄ 419 nm	O ₄ 477 nm	O ₄ 328 nm	
Wavelength interval		322.5/311.5	410	450	320	
nm		358	439	490	347.5	
O ₃	223K	×	×	×	×	Serdyuchenko et al. (2014)
	223K	(×)				Taylor expansion terms (Puķīte et al., 2010)
	243K	×				
HCHO		×			×	Chance and Orphal (2011)
BrO		×			×	Fleischmann (2004)
NO ₂	293K	×	×	×	×	Vandaele et al. (1998)
O ₄		×	×	×	×	Thalman and Volkamer (2013)
SO ₂		(×)				Vandaele et al. (2009)
HONO		(×)				Stutz et al. (2000)
OCIO		(×)				Kromminga et al. (2003)
H ₂ O	298K		×	×		HITRAN 2012 (Rothman et al., 2013) corrected (Lampel et al., 2015b)
IO			×			Spietz et al. (2005)
Glyoxal			(×)			Volkamer et al. (2005)
Ring Spectrum at 273K		×	×	×		DOASIS (Kraus, 2006)
Ring Spectrum at 243K		×				
Ring Spectrum · λ ⁴		×	×	×		Wagner et al. (2009)
VRS (N ₂)		(×)	×			Lampel et al. (2015a)
Background & Shortcut Spectrum					×	
Polynomial degree		5	5	3	4	
Add. Polynomial degree		1	1	1		

Table 1. Retrieval wavelength intervals for DOAS measurements. Values in brackets were used for sensitivity studies only.

ground spectra ~~had been~~ were subtracted. The optical densities were then high-pass filtered ~~before~~ and afterwards the fit was applied. The applied fit scenario settings are ~~detailed~~ shown in Table 1. As for the MAX-DOAS evaluation, the literature cross-sections were convoluted with a measured Hg emission line at 334 nm.

3.3 Hypothetical O₄ absorption cross-sections

The absorption peak shape of the O₄ absorption at 328 and 419 nm cannot be deduced directly from field measurements, as a large number of other absorbers (HCHO, BrO, SO₂, HONO, OClO, NO₂, O₃, H₂O and others) potentially overlay the respective O₄ absorption peak. Their abundance is unknown in field observations. Additionally, their absorption cross-sections may not be known precisely enough (e.g. water vapour, Lampel et al. (2015b, 2017a)) to determine their abundances in other spectral ranges and thus constrain their overall absorption in order to obtain an extended O₄ absorption cross-section from MAX-DOAS or LP-DOAS field measurements. Dedicated laboratory studies will be needed.

The shape of the O₄ absorption peaks at 344, 360, 380 and at 446 and 477 nm is similar as shown in Figure 1 (top) when plotting the absorption cross-section (here from Thalman and Volkamer (2013)) over the difference in wavenumbers to the peak absorption. We therefore guessed the shape of the potential absorption bands at 328 nm and 419 nm by shifting the O₄ absorption peaks at 344 and 446 nm by 1414 cm⁻¹ and 1476 cm⁻¹, respectively. These shifts were chosen arbitrarily based on previous publications (Salow and Steiner, 1936; Ellis and Kneser, 1933) which list the wavelength of the respective absorption peaks.

This approach is reasonable, as the width of the O₄ absorption peaks is defined by the lifetime of the collision complex (Long and Ewing, 1973; Thalman and Volkamer, 2013) and is thus related to the energy of the respective absorption peak. The absorption peak shape at 477 nm was parametrized by Snee and Ubachs (2003), but we are not aware of parametrizations or quantum-mechanical calculations yielding absorption peak shapes at other wavelengths at room temperature.

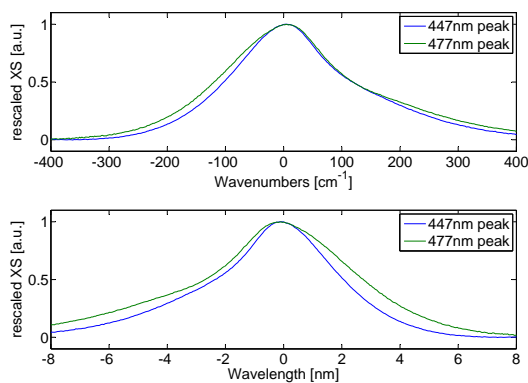


Figure 1. Shifted (top: by wavenumber; bottom: by wavelength) and normalized O₄ absorption cross-sections at 446 nm and 477 nm according to Thalman and Volkamer (2013).

Transition	Wavelength			
	[ElKn]	[SaSt]	[ThVo]	This study
	[nm]	[nm]	[nm]	[nm]
${}^3\Sigma^+ + {}^3\Sigma^- \xrightarrow{{}^3\Sigma_g^- + {}^3\Sigma_g^-} \rightarrow {}^1\Delta + {}^1\Delta(\nu=4) \xrightarrow{{}^1\Sigma_g^+ + {}^1\Sigma_g^+(\nu=4)}$ $\rightarrow {}^1\Delta + {}^1\Delta(\nu=3) \xrightarrow{{}^1\Sigma_g^+ + {}^1\Sigma_g^+(\nu=3)}$ $\rightarrow {}^1\Delta + {}^1\Delta(\nu=2) \xrightarrow{{}^1\Sigma_g^+ + {}^1\Sigma_g^+(\nu=2)}$ $\rightarrow {}^1\Delta + {}^1\Delta(\nu=1) \xrightarrow{{}^1\Sigma_g^+ + {}^1\Sigma_g^+(\nu=1)}$ $\rightarrow {}^1\Delta + {}^1\Delta(\nu=0) \xrightarrow{{}^1\Sigma_g^+ + {}^1\Sigma_g^+(\nu=0)}$		315.0 ± 0.6		
	328.9 ± 1.5	328.2 ± 0.3		328.51 ± 0.15 <u>328.59 ± 0.15</u>
	343.9 ± 1.5	343.6 ± 0.2	343.8 ± 0.1	
	360.7 ± 2	360.7 ± 0.2	360.86 ± 0.01	
	380.7 ± 2	380.3 ± 0.2	380.21 ± 0.01	
${}^3\Sigma^+ + {}^3\Sigma^- \xrightarrow{{}^3\Sigma_g^- + {}^3\Sigma_g^-} \rightarrow {}^1\Sigma + {}^1\Delta(\nu=3) \xrightarrow{{}^1\Sigma_g^+ + {}^1\Delta_g(\nu=3)}$ $\rightarrow {}^1\Sigma + {}^1\Delta(\nu=2) \xrightarrow{{}^1\Sigma_g^+ + {}^1\Delta_g(\nu=2)}$ $\rightarrow {}^1\Sigma + {}^1\Delta(\nu=1) \xrightarrow{{}^1\Sigma_g^+ + {}^1\Delta_g(\nu=1)}$ $\rightarrow {}^1\Sigma + {}^1\Delta(\nu=0) \xrightarrow{{}^1\Sigma_g^+ + {}^1\Delta_g(\nu=0)}$	392.5 ± 5			
	419.0 ± 1			419.02 ± 0.42 <u>419.13 ± 0.42</u>
	447.0 ± 1	446.4 ± 0.5	446.39 ± 0.01	
	476.0 ± 2	477.0 ± 0.1	476.89 ± 0.01	
${}^3\Sigma^+ + {}^3\Sigma^- \xrightarrow{{}^3\Sigma_g^- + {}^3\Sigma_g^-} \rightarrow {}^1\Sigma + {}^1\Sigma(\nu=4) \xrightarrow{{}^1\Delta_g + {}^1\Delta_g(\nu=4)}$ $\rightarrow {}^1\Sigma + {}^1\Sigma(\nu=3) \xrightarrow{{}^1\Delta_g + {}^1\Delta_g(\nu=3)}$	462.0 ± 1			
	495.0 ± 1.5			

Table 2. Relative intensities of O₄ absorption peaks below 500 nm, [SaSt] (Salow and Steiner, 1936) [ElKn] (Ellis and Kneser, 1933) [ThVo] (Thalman and Volkamer, 2013). The column of relative intensities for [ThVo] at a temperature of 293K is given in 10⁻⁴⁶ cm⁵ molec⁻². Transitions according to Greenblatt et al. (1990).

4 Results

4.1 Peak positions

As we assume the maximum of the O₄ absorption peak at 328.2 nm (Salow and Steiner, 1936) and at 419 nm (Ellis and Kneser, 1933), its exact wavelengths needs to be determined again. ~~This can be from the measurements. This was~~ done based on experimental MAX-DOAS data, here from PPAO: ~~When included in~~ If introduced as a free parameter in the a DOAS fit, the individual shift of the hypothetical O₄ absorption cross-section can be used in order to ~~give~~ derive a more accurate estimate for the spectral position of the absorption peak. Measurements, which showed a ratio of fitted dSCD and dSCD fit error of more than 8 were considered for this analysis. The resulting peak position was found at ~~328.51 ± 0.15~~ 328.59 ± 0.15 nm and thus results in an overall shift of the absorption at ~~344 nm of +1366 ± 13~~ 344 nm of +1359 ± 13 cm⁻¹. In the blue wavelength range it was found at ~~419.32 ± 0.4~~ 419.13 ± 0.4 nm and thus results in an overall shift of the absorption at 446 nm of ~~+1458 ± 23~~ +1469 ± 23 cm⁻¹. For the absorption around 419 nm a larger scatter of shift values was observed, probably due to uncertainties of the overlaying water vapour absorption.

4.2 Absorption band at 328 nm

4.2.1 LP-DOAS

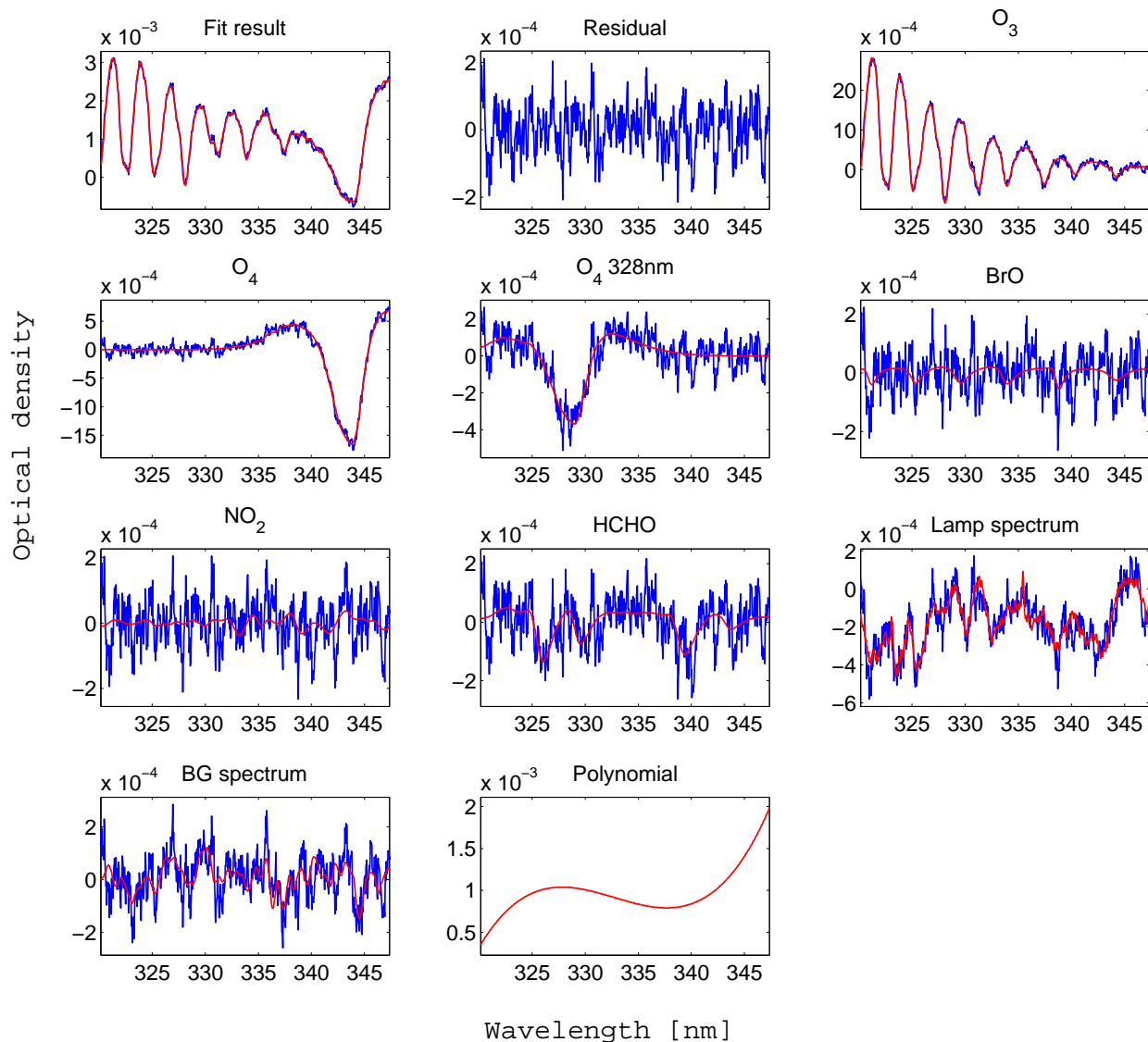


Figure 2. Exemplary LP-DOAS fit result of a measurement from 22nd November 2012 on the 8 km light path. The O_4 absorption at 328 nm is clearly visible. The retrieved column densities are: O_4 $(2.67 \pm 0.04) \times 10^{43} \text{ molec}^2 \text{ cm}^{-5}$ and O_4 328 nm $(6.09 \pm 0.38) \times 10^{42} \text{ molec}^2 \text{ cm}^{-5}$.

The LP-DOAS data evaluation reveals the suspected absorption structure at 328 nm nicely, given the extensive averaging of the data as described in Section 3.2. An exemplary DOAS fit is shown in Figure 2. Compared to the ozone and O_4 absorption,

the other species feature only a negligible optical depth in this [instance example](#). Besides ozone and the O_4 absorption band at [344nm](#)[343.8nm](#), the 328 nm absorption [however of \$O_4\$](#) is the most prominent absorption feature in this case and spectral region.

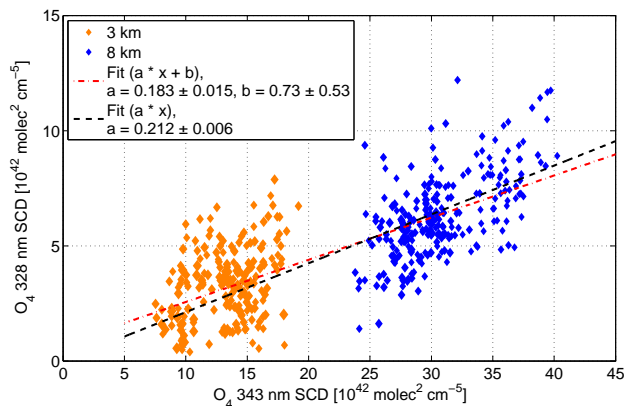


Figure 3. LP-DOAS correlation of the suspected 328 nm absorption feature with the known absorption at [344](#)[343.8](#) nm. Data for the short light path is shown in orange, for the long path in blue. [Linear regression results are shown with and without for a constant offset term.](#)

In order to compare the relative absorption strength of the 328 nm and 344 nm bands, the entire dataset was filtered for evaluations with a residual RMS better than 1.2×10^{-4} since the structure of interest can only then be retrieved with [relative sufficient](#) accuracy. Typical optical densities of the 328 nm absorption are between $4 - 6 \times 10^{-4}$ along the 8 km light path and column densities reach up to a maximum of around 20 times the instrumental detection limit.

Figure 3 shows the correlation of the LP-DOAS column densities of the suspected 328 nm absorption feature with the well known absorption feature at 344 nm. Data for the short light path is shown in orange, while data for the long path is shown in blue. [As can be seen, a](#) correlation between the suspected and the known absorption is visible. As expected, higher column densities for the longer light path and lower ones for the shorter light path. A linear fit performed on the entire dataset indicates a relative absorption strength of 0.183 ± 0.015 (see also Table 3) [, where cross-section values are listed\) at 328 nm](#) compared to the known 344 nm band [-when allowing for a constant offset. Fixing this offset to zero results in a slightly larger relative absorption strength of \$0.212 \pm 0.006\$. The given error is the error of the linear regression analysis and does not reflect the actual measurement error of each individual observation.](#)

A variation of the total O_4 SCD along both light paths can be observed, which is found simultaneously for both O_4 absorption bands at 328 nm and 344 nm, leading to the distribution of the measurements shown in Figure 3. This points towards a general property of the absorber O_4 and can be explained by temperature variations (up to 35K within the measurement period) and pressure variations. We estimate that almost two thirds of the observed variation are due to the changing absorption cross-section with temperature (Thalman and Volkamer, 2013), one third due to the change in number density according to the ideal gas law. Pressure variations between 962 and 1006 hPa during the observations also contribute. Variations depending on temperature and pressure were also reported by Wang et al. (2016) and Wagner (2017) for ground-based MAX-DOAS

observations and simulated for satellite observations by Park et al. (2017) and Dörner et al. (2017). A further and more detailed analysis of these dependencies is not within the scope of this publication.

10 4.2.2 MAX-DOAS

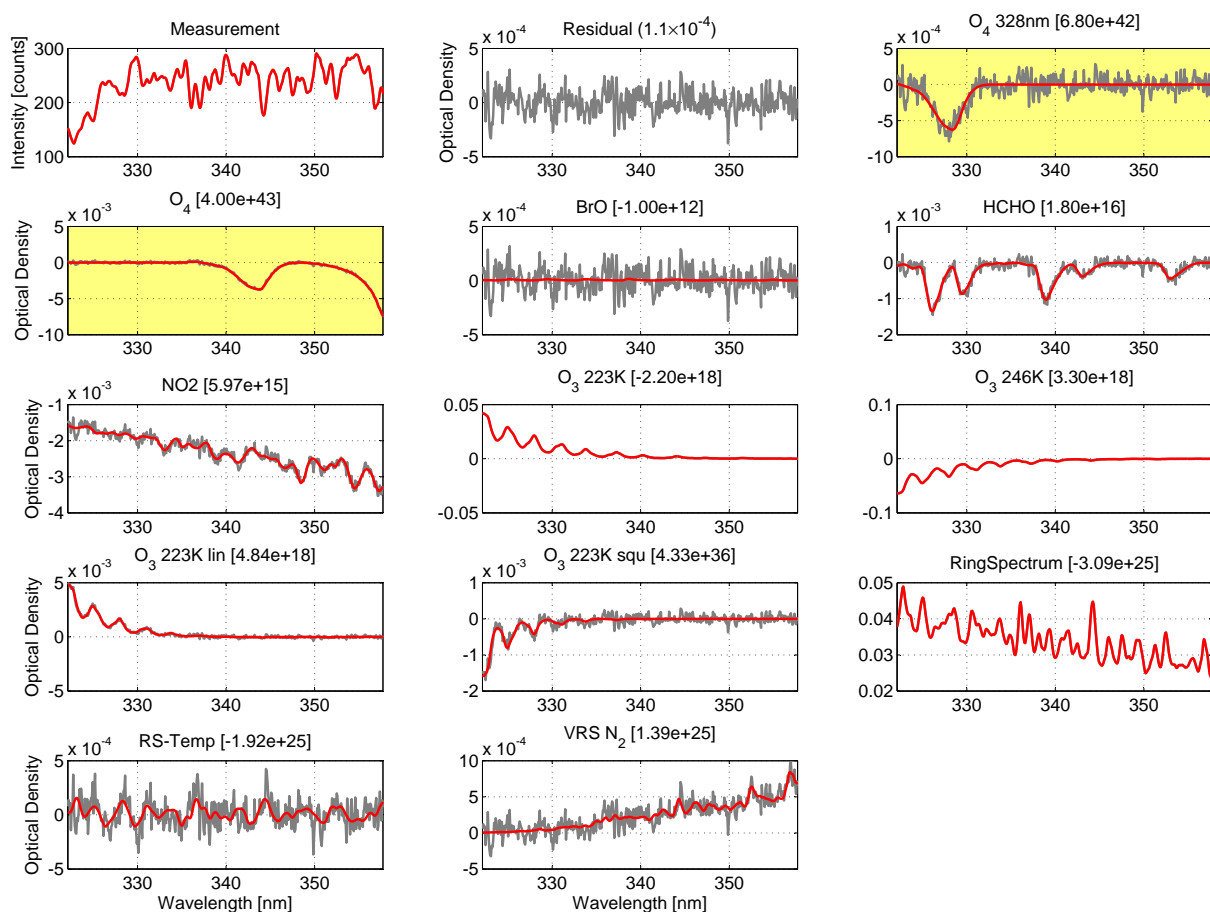


Figure 4. MAX-DOAS fit from PPAO, 6/7/2015, 11:18 UTC at 3° elevation and a 90° elevation reference spectrum. Spectra were co-added to obtain a total exposure time per spectrum of 4 minutes. The [328 nm](#) O_4 absorption structure is found here ~~at a dSCD which~~ is 14 times as large as the DOAS fit error. ~~The plot for the residual shows the residual in grey for the fit considering the O_4 absorption at 328nm.~~ Without considering this absorption, the HCHO dSCD in this case is larger ($+2.5 \times 10^{14}$ molec cm^{-2} or 1.4%), ~~as is and~~ the RMS of the residual ($+2.5 \times 10^{-5}$ or increases by +22%). ~~'RS-temp' denotes the difference between Ring pseudo absorption spectra calculated at 273K and 243K as listed in Table 1.~~

For the PPAO dataset, several sensitivity studies were performed in order to estimate the effect of ozone absorption and the contribution of vibrational Raman scattering (VRS) on the results.

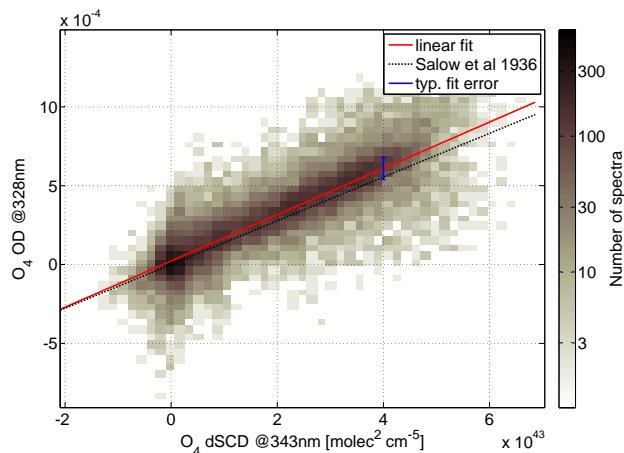


Figure 5. Correlation of O_4 dSCD at 344 nm and the fitted O_4 OD at 328.5 nm assuming the same shape of the absorption cross-section as at 344 nm, using the PPAO [MAX-DOAS](#) dataset. [The wavelength dependence of the \$O_4\$ AMF was not corrected here.](#)

To account for non-linear effect of strong ozone absorption, we also included a wavelength-scaled version of the ozone absorption as well as its square term as suggested in Pu \check{c} ite et al. (2010) and Pu \check{c} ite and Wagner (2016). This was mainly
 15 necessary when extending the fit interval below 320 nm to include additional absorption bands of HCHO. One part of the absorption of ozone is due to changes in the slant stratospheric ozone column during the [recording-measurement](#) of the elevation sequence and thus assumed to be symmetric and not introduce a systematic bias on the evaluation of the O_4 absorption band. The tropospheric contribution is of similar magnitude.

The additional intensity caused by VRS did not significantly change the result as seen from Table 3.

20 BrO was analysed in the spectral range from 332–358 nm and not found above the detection limit (1×10^{13} molec cm^{-2}) at PPAO. During the Polarstern cruises the amount of HCHO (evaluated in the same spectral range) was typically smaller than at PPAO, however, also significant amounts of BrO were observed during Arctic spring (May, June, up to 1.4×10^{14} molec cm^{-2} at 3° elevation) and Antarctic spring (December, January, up to 5×10^{13} molec cm^{-2} at 3° elevation). We therefore exclude the possibility that the absorption at 328 nm is caused by erroneous BrO or HCHO absorption cross-sections.

5 As the MAX-DOAS measurements took place in regions without strong anthropogenic pollution, tropospheric NO_2 absorption does not significantly contribute to the overall magnitude of the observed residual spectra.

The resulting estimates for the absorption cross-section of O_4 at 328 nm can be found in Table 3. Good correlations of the absorptions at 328 nm and 344 nm can be found for LP-DOAS observations as well as for both MAX-DOAS data sets. For MAX-DOAS different settings for the spectral retrieval were tested and yielded similar results, however, for the larger fit
 10 interval slightly larger (+10%) absorption cross-section peak values are estimated. The low correlation for the setting not using the Taylor expansion approach by Pu \check{c} ite et al. (2010) on the large fit interval was expected as here strong ozone absorption can produce significant residual structures, which can interfere with other fitted species.

<u>Evaluation</u>	Lowest <u>fit</u> wavelength [nm]	Settings	R^2	n	$\sigma_{328\text{ nm}}$ [$10^{-47}\text{ cm}^5\text{ molec}^{-2}$]	
1	Antarctica (LP-DOAS)	320.0	<u>regression with offset</u> <u>without offset</u>	0.56 <u>0.56</u>	1921 <u>1921</u>	1.69 ± 0.15 <u>1.74 ± 0.15</u>
2		322.5		0.76	23573	1.59 ± 0.01
3		322.5	+ VRS	0.73	23597	1.55 ± 0.01
4	PPAO (MAX-DOAS)	322.5	no Taylor expansion	0.66	22491	1.76 ± 0.01
5		311.5		0.90	20297	1.76 ± 0.02
6		311.5	no Taylor expansion	0.29	18090	1.94 ± 0.03
7	Polarstern (MAX-DOAS)	322.5		0.68	18888	1.47 ± 0.01

Table 3. Results for the O_4 absorption at 328nm for different fit ranges and settings. MAX-DOAS data was selected according to $RMS < 4 \times 10^{-4}$, LP-DOAS data below an RMS of 1.2×10^{-4} , which then results in a different value for n, the number of valid observations. The correlation coefficient R^2 was calculated in each case. The peak magnitude of the absorption cross-section at 328 nm was calculated using the O_4 cross-section published by Thalman and Volkamer (2013) using the maximum cross-section value of $9.5 \times 10^{-47}\text{ cm}^5\text{ molec}^{-2}$ at ~~344.0~~343.8 nm. The wavelength dependence of the O_4 AMF for the MAX-DOAS observations was not corrected here.

4.2.3 Uncertainties

For PPAO, the distribution of fit errors of the O_4 absorption at 328 nm has its maximum at $5 \times 10^{41}\text{ molec}^2\text{ cm}^{-5}$ (similar as
 15 in Figure 4, corresponds to a peak OD of 4.6×10^{-5} using the shifted absorption peak from 344 nm), while the distribution of O_4 dSCDs at 328 nm has its maximum at $6 \times 10^{42}\text{ molec cm}^{-2}$. Thus most observations are above the detection limit.

The influence of strong ozone absorption is largely compensated for by the Taylor expansion approach and even allows fits at sufficiently low RMS down to 311.5 nm. The deduced magnitude of the O_4 absorption at 328 nm is slightly larger for larger fit intervals, compare Table 3.

5 The effect of VRS is negligible especially at the lower end of the fit interval, as can be also seen from Figure 4. It is however correlated with the Ring signal as previously reported for the blue spectral range and increases slightly the number of valid observations while the deduced magnitude of the O_4 absorption stays constant within the fit error.

The difference in MAX-DOAS air mass factors ~~of O_4 at (AMF) of O_4 for~~ low elevation angles at ~~wavelengths~~ of 328 nm ~~and compared to~~ 344 nm is expected to lead to an underestimation of the absolute O_4 absorption cross-section at 328 nm ~~in~~
 10 ~~MAX-DOAS observations using with~~ the approach presented above. Using a set of 10 representative aerosol profiles with aerosol optical thicknesses ranging from 0–5 and simulating the resulting O_4 dSCDs at 328 nm and 344 nm using SCIATRAN (Rozanov et al., 2014) yields an underestimation of 14%. This is slightly less than one could have expected for the pure

Rayleigh case, yielding $\approx 1 - (328/343)^4 = 16\%$. Applying this ~~to~~ correction of 14% the observed data from Table 3, this means that ~~either~~ the LP-DOAS ~~values underestimate or the result for the regression without allowing for an offset fits best the~~ corrected MAX-DOAS ~~results overestimate the real ratio~~ result of $1.72 \times 1.14 = 1.96$. This makes sense as for the reference measurements (at a light path length of 0 m), the column density is by definition zero. Estimating the potential systematic measurement errors by the measurement error itself, LP- and MAX-DOAS results ~~would however still~~ agree with each other with and even without the correction for the wavelength dependence of the AMF, as the measurement errors and therefore the scatter of data points are of the same magnitude as the expected difference between the two DOAS measurement types.

20 4.3 Absorption band at 419 nm

~~For~~ If assuming a large O_4 dSCD of 1×10^{44} molec² cm⁻⁵ and using the ratio of the magnitudes of the other ~~$^3\Sigma^3\Sigma \rightarrow ^1\Delta^1\Sigma$~~ $^3\Sigma_g^- + ^3\Sigma_g^- \rightarrow ^1\Sigma_g^+ + ^1\Delta_g$ absorption bands at 446 nm and 477 nm of about 12.7 (Thalman and Volkamer, 2013), the peak magnitude of the O_4 absorption at 419 nm could be expected to ~~amount to reach an optical density of~~ 4×10^{-4} . It is however unclear, if this extrapolation is valid. For the ~~$^3\Sigma^3\Sigma \rightarrow ^1\Delta^1\Delta$~~ $^3\Sigma_g^- + ^3\Sigma_g^- \rightarrow ^1\Sigma_g^+ + ^1\Sigma_g^+$ absorption bands at 361, 344 and
 25 329 nm this is approximately the case as seen in subsection 4.2.

The absorption structure reported by Ellis and Kneser (1933) around 419 nm is overlaid by water vapour absorption at around 416 nm with a peak absorption of 3×10^{-3} for a water vapour dSCD of 4×10^{23} molec cm⁻² at a spectral resolution of 0.5 nm using the HITRAN2012 line list (Rothman et al., 2013). From MAX-DOAS and LP-DOAS observations it was reported that these absorption lines are overestimated by a factor of two in HITRAN2012 (Lampel et al., 2015b), while the overall shape
 30 is relatively well reproduced. Thus the water vapour absorption contains some uncertainty, which could have an effect on the detection of the O_4 absorption band at 419 nm. This is the main reason why the wavelength of the maximum O_4 absorption around 419 nm is difficult to estimate.

Therefore the absorption band at 419 nm was fitted in different wavelength intervals, including and excluding the larger water vapour absorption peaks around 442 nm. The variation of the absolute O_4 absorption at 419 nm in these two intervals was less than 25%.

To circumvent the potential influence of water vapour absorption in this spectral region, an overdetermined system of linear
 5 equations was set up in order to quantify the contribution of water vapour as well as O_4 absorption on the apparent O_4 absorption at 419 nm. The 'true' dSCDs S were determined at a wavelength close to the wavelength of interest, in this case for the water vapour absorption bands and the O_4 absorption band at around 477 nm. These are both more than 10 times stronger than their respective absorptions between 410-420 nm. This can be done as enough variation in water vapour concentrations is found for all MAX-DOAS campaigns included here, thus not leading to linear dependent data points of water vapour and O_4 dSCDs.

$$10 \quad c_{H_2O}^{442nm} * S_{H_2O} + c_{O_4} * S_{O_4}^{470nm} = S_{O_4}^{419nm} \quad (1)$$

The resulting c_{O_4} is 0.0785 ± 0.007 ~~or in~~. The correction for wavelength dependence of the AMF is estimated for the pure Rayleigh case, yielding $\approx 1 - (419.0/446.4)^4 = 22\%$. In other words, the absorption peak at 419 nm is ~~12.7 ± 1.2~~ 10.4 ± 0.9 times smaller than the absorption peak around 445 nm.

The resulting c_{H_2O} is $(3.4 \pm 1.0) \times 10^{18}$ molec cm^{-3} . This results for a H_2O dSCD of 3×10^{23} molec cm^{-2} in a change of the O_4 dSCD of 1×10^{42} molec² cm^{-5} , i.e. the main variation of the obtained O_4 dSCD is indeed caused by the O_4 dSCD variation. These show a mean value of 2.9×10^{43} molec² cm^{-5} and a standard deviation of 2.1×10^{43} molec² cm^{-5} at 3° elevation.

However, as the exact shift of the O_4 absorption structure is only poorly restricted from the MAX-DOAS measurements, the remaining uncertainty strongly depends on the position of the absorption peak. Using different fit settings and different positions of the absorption peak (± 0.3 nm) yields results for c_{O_4} within 0.08 ± 0.05 . 0.12 is ~~actually~~ obtained when ignoring the possible interference with water vapour absorption. This then results in a peak value of the O_4 absorption cross-section (after correction of radiative transfer effects) of $(5.0 \pm 3.5) \times 10^{-48}$ $\text{cm}^5 \text{molec}^{-2}$ at a wavelength of 419.13 ± 0.42 .

4.3.1 LP-DOAS observations

The O_4 absorption around 419 nm is close to its detection limit. The maximum of the distribution of O_4 fit errors is 7×10^{41} molec² cm^{-5} , the maximum of the distribution of O_4 dSCDs is 6×10^{42} molec² cm^{-5} .

Using the available data sets a reliable conclusion on the magnitude of the O_4 absorption is difficult to draw. With an estimated value of 0.07 ± 0.05 the ratio of magnitudes to the next larger O_4 absorption peak seems to be ~~similarly~~ similar as the ratio of the magnitudes of the other ~~$3\Sigma^3\Sigma^- \rightarrow 1\Delta^1\Sigma^-$~~ $3\Sigma_g^- + 3\Sigma_g^- \rightarrow \Sigma_g^+ + 1\Delta_g$ absorption bands at 446 nm and 477 nm of about 0.079 (Thalman and Volkamer, 2013).

5 Conclusions

We analysed atmospheric measurements of LP- and MAX-DOAS setups from different field campaigns in order to estimate the magnitude and wavelength of previously reported O_4 absorption peaks at 328 nm and 419 nm, for which no spectrally ~~resolved~~ resolved literature cross-sections are currently available and which have not been reported from atmospheric observations so far.

The main conclusion is that both O_4 absorption peaks at 328 nm and 419 nm can be observed using current MAX-DOAS ~~and LP-DOAS~~ setups and therefore have the potential to introduce biases in the spectral retrieval of weak absorbers. Further laboratory studies are needed quantify the magnitude of these small absorption peaks.

The O_4 absorption peak at 328nm was unambiguously identified. Its magnitude agrees with a previous publication by Salow and Steiner (1936) and is found to be ~~0.18 ± 0.02~~ 0.19 ± 0.02 of the magnitude of the next absorption peak at 344 nm ~~using LP and MAX-DOAS observations~~. This results in a maximum peak absorption cross-section based on Thalman and Volkamer (2013) of ~~$(1.7 \pm 0.2) \times 10^{-47}$~~ $(1.96 \pm 0.2) \times 10^{-47}$ $\text{cm}^5 \text{molec}^{-2}$ at ~~328.51 ± 0.15~~ 328.59 ± 0.15 nm.

The impact on incoming sun radiation in the spectral region from 323–331 nm is small and amounts to $7.8 \times 10^{-4} \text{ Wm}^{-1}$ for zenith sun and an O_4 VCD of $1.3 \times 10^{43} \text{ molec}^2 \text{ cm}^{-5}$ using the solar atlas by Chance and Kurucz (2010). It has therefore only a small impact on the radiative balance in the atmosphere.

15 It is interesting to note that the potential SO_2 oxidation by singlet oxygen (Sorokin, 2010) requires singlet oxygen molecules with the vibrational eigenstate $\nu > 2$. In particular these weak absorption near 328 nm (and near 315) leads to the formation of singlet oxygen molecules in the 3rd (and 4th) vibrationally excited state (see Table 2) and thus could play a role for SO_2 oxidation in the atmosphere.

20 The impact on trace gas retrievals depends on the fit settings of the respective trace gas and instrumental properties. For DOAS measurements in pristine to semi-polluted regions, a significant impact is expected for spectral retrievals of HCHO, BrO, SO_2 and OCIO, which could encompass this spectral region. Previous publications often avoided this spectral region. We suggest that the reason for the previously observed discrepancies was often ~~rather~~ the O_4 absorption which was not accounted for rather than the increasing influence of tropospheric and stratospheric ozone absorption towards shorter wavelengths.

25 Incorporating this O_4 absorption in the spectral retrievals of the above-mentioned absorbers will lead to a substantial improvement of the respective detection limits as additional absorption bands can be included in the spectral retrieval. In our evaluations, extending the fit range lower limit from 332.5 to 322.5 nm led to a reduction of the fit error by $\approx 35\%$ for HCHO and BrO. It furthermore significantly reduced the previously observed interferences between the BrO and HCHO absorption structures (Pinardi et al., 2013).

30 The O_4 absorption peak at 419nm was difficult to identify using the method presented here, as it is difficult to exclude the possible influence of water vapour absorption τ , which overlays the O_4 absorption structure ~~and is rather poorly constrained~~. For water vapour absorption in this spectral range significant uncertainties were reported by (Lampel et al., 2015b). Its magnitude is estimated to be about ~~0.07 ± 0.05~~ 0.08 ± 0.05 of the absorption peaks at 446 nm. No published data is available for the absorption at 419 nm. Based on Thalman and Volkamer (2013), it results in a peak absorption cross-section ~~at $419.0 \pm 0.4 \text{ nm}$ of $(3.7 \pm 0.2.7) \times 10^{-48}$~~ of $(5.0 \pm 3.5) \times 10^{-48} \text{ cm}^5 \text{ molec}^{-2}$ at a wavelength of 419.13 ± 0.42 .

Also in the case of the 419 nm absorption, the impact on trace gas retrievals depends on the fit settings for the respective trace gas and instrument parameters, but an influence can be expected for the spectral retrievals of weak absorbers in pristine regions, such as IO and NO_2 .

5 However, the O_4 absorption peak at around 419 nm cannot explain the observed differences between different water vapour absorption cross-sections in recent literature (compare Lampel et al. (2015b)), but could contribute to previously observed systematic residual structures.

Appendix A: Supplement

According to the procedure described above, a merged absorption cross-section of O_4 based on Thalman and Volkamer (2013) was calculated. The absorption peak at 344 nm was shifted by $+1366 \text{ cm}^{-1}$ to shorter wavelengths and scaled by ~~0.17~~ 0.1863 according to Table 3 and additionally the radiative transfer correction by 14% (as in subsection 4.2.3). These cross-section

10

values were then added to the original O₄ absorption cross-section at 293K below 331 nm. To avoid negative cross-section values below 337.5 nm after convolution to instrument resolution, absorption cross-section values between 331 and 337.5 nm were set to zero. ~~The~~ For the shifted absorption peak from 446.4 nm to 419.0 nm values between 409.25 and 426.0 nm were used, while the original O₄ absorption cross-section at 293K between 390.0 and 435.5 nm was set to zero. The peak was scaled by 0.0785 and corrected for radiative transfer dependence with wavelength by 22%. The resulting file is provided as a supplement. ~~As the magnitude of the O₄ absorption peak around 419 nm remains uncertain, this procedure was not repeated in the blue spectral range.~~

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